Limiting sea state conditions for containerships

Seakeeping analysis and Summary Report

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Seakeeping analysis and Summary Report

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CONTENTS **PAGE**

REVIEW OF REPORTS

Table i-1: Deliverables of the current project phase[1]

Deliverable	Contains
MARIN report No. 33883-1-SEA	- the present report
MARIN report No. 33883-2-MO-rev.1	- network study
DELTARES report 11207734-002-HYE-0001	- metocean prediction accuracy

1 At the time of writing.

MANAGEMENT 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. 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.

As response to the report of the Dutch Safety Board, the Ministry of Infrastructure and Water Management of The Netherlands 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. In the first study, MARIN project 32558, three classes of container ships (Feeder, Panamax and ULCS) were model tested and calculations were performed.

This led to a preliminary limiting significant wave heights related to:

- consequence of exceeding transverse accelerations on containers,
- consequence of possible bottom contact of the hull with the seabed,
- consequence of green water exceeding the freeboard height and impact load on containers.

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:

Route	**FEEDER** **LPP < 200 m** Assumptions: GM=0.8 to 1.5m 0 to 8 knots 9.20 m draught Freeboard 3.0 m	**PANAMAX** **200 ≤ LPP < 300 m** Assumptions: GM=1.0 to 2.5m 0 to 10 knots 12.20 m draught Freeboard 9.2 m	**ULCS** **LPP ≥ 300 m** Assumptions: GM=6.0 to 9.25m 0 to 10 knots 12.40 m draught 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)[2] **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)

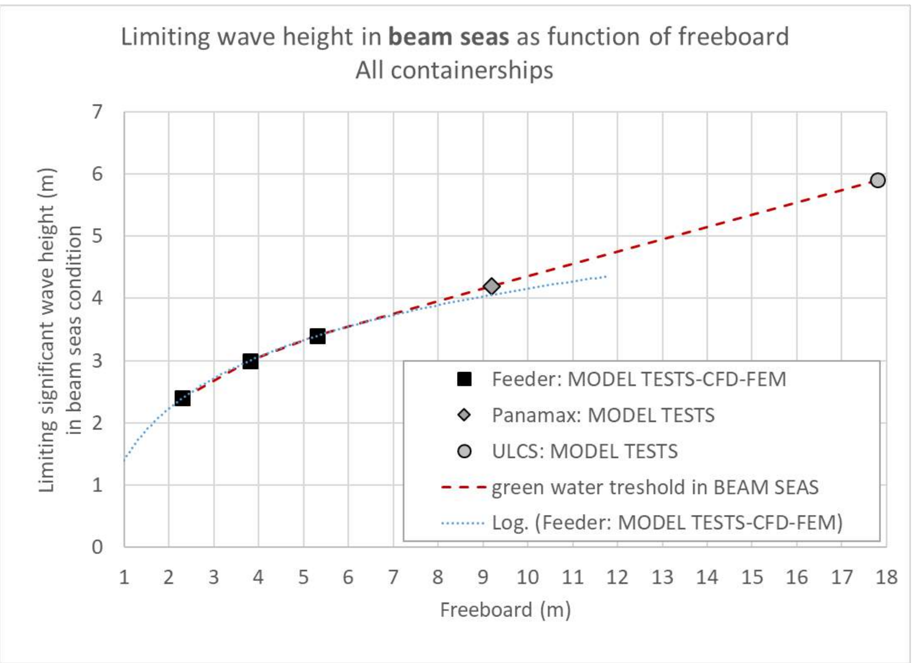
These results were the basis for a route advice from the Netherland Coastguard (Kustwacht) to prevent container loss above the Wadden Island, see https://kustwacht.nl/en/node/765#routeadvies.

[2] 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 a second study, MARIN project 33327, the green water consequences on Feeders were addressed by means of model tests and advanced calculations, leading to an updated limiting significant wave height as function of the Feeder freeboard height, freeboard type and water depth. The results applicable for both the routes is:

Freeboard height	**2.3 m**	**3.8 m**	**5.3 m**
135/225 deg (bow-quartering waves)	3.4 m	4.5 m	5.6 m
90/270 deg (beam waves)	*2.4 m*	*3.0 m*	*3.4 m*
45/315 deg (stern-quartering waves)	3.5 m	4.9 m	6.0 m

The risk for green water loading and loss of containers as a result depends strongly on the freeboard height. The risk can be mitigated by sailing more head into the waves. To obtain a green water limiting wave height as function of freeboard for all ships types, the limiting Hs values derived based on the observations and measurements in the model basin for the ULCS and Panamax vessel (project 32558) are combined with results for the Feeders:



The observed consistent trend can be understood when we realise that green water in beam waves in shallow water, despite the variation in ship motions, is dominated by the interaction of the steep (breaking) waves with the vertical side of the ship that acts like a wall (limited by the freeboard on the upper side). This observed trend can be used to estimate the susceptibility and sensitivity for green water of the larger ships types (Panamax and ULCS) with lower freeboard levels than tested freeboard in project 32558.

Based on these observations a common used risk table format is developed to describe the risk associated as function of significant wave height and freeboard. The risk description is indicative and separates the risk for ships sailing in beam seas and non-beam seas condition.

Risk for green water impact and damages of deck containers	Freeboard between 1.0 m and 2.3 m (cumm. < 2.3 m)	Freeboard between 2.3 m and 3.8 m (cumm. < 3.8 m)	Freeboard between 3.8 m and 5.3 m (cumm. < 5.3 m)	Freeboard between 5.3 m and 8.0 m (cumm. < 8 m)	Freeboard between 8 m and 12 m (cumm. < 12 m)	Freeboard between 12 m and 18 m (cumm. < 18 m)	Freeboard above 18 m
% of FEEDER ships on route TSS	9.3% (9.3%)	31.5% (40.8%)	32.5% (73.3%)	20.7% (94.0%)	6% (100%)	none	none
% of PANAMAX ships on route TSS	none	0.3% (0.3%)	2.6% (2.9%)	22.7% (25.6%)	71.6% (97.2%)	2.8% (100%)	none
% of POST-PANAMAX ships on route TSS	none	none	0.4% (0.4%)	4.6% (5.0%)	40.8% (45.8%)	54.2% (100%)	none
% of ULCS ships on route TSS	none	none	none	0.7% (0.7%)	10.3% (11.4%)	60.4% (71.4%)	28.6%
Hs > 6.0 m	extreme risk at all headings	extreme risk at all headings	extreme risk at all headings	high to extreme risk at all headings	high to extreme risk at all headings	unsafe in beam seas, expected safe otherwise	unsafe in beam seas, expected safe otherwise
4.5 m < Hs < 6.0 m	extreme risk at all headings	high to extreme risk at all headings	high to extreme risk at all headings	unsafe in beam seas, safe at other headings	unsafe in beam seas, safe at other headings	unsafe in beam seas, expected safe otherwise	safe at all headings
3.4 m < Hs < 4.5 m	high risk at all headings	unsafe in beam seas, safe at other headings	unsafe in beam seas, safe at other headings	unsafe in beam seas, safe at other headings	safe at all headings	safe at all headings	safe at all headings
3.0 m < Hs < 3.4 m	unsafe in beam seas, safe at other headings	unsafe in beam seas, safe at other headings	safe at all headings	safe at all headings	safe at all headings	safe at all headings	safe at all headings
2.4 m < Hs < 3.0 m	unsafe in beam seas, safe at other headings	safe at all headings	safe at all headings	safe at all headings	safe at all headings	safe at all headings	safe at all headings
Hs < 2.4 m	risk in beams seas for low freeboard ships	safe at all headings	safe at all headings	safe at all headings	safe at all headings	safe at all headings	safe at all headings

The scope of work in the present study can further be summarised by:

- An extensive sea keeping analysis is made for relevant containerships and draught conditions derived from a network survey covering the last 4 years of AIS data. The network study is separately reported.
- Based on the network analysis the length class of the Panamax ships is updated to LPP maximum 295 m.
- A metocean study (performed by DELTARES) is performed to investigate the accuracy of the wave height prediction. These findings are separately reported and briefly summarised in the present report. The impact of the wave model accuracy is discussed in relation to the accuracy in the seakeeping study.

In the first study (32558) the Panamax and ULCS vessel (in the model test and calculations) were given an average draught condition derived from a performed network study. In the present study the seakeeping study is extended to cover as well lower probability but realistic deep draught sailing conditions. A draught cover 95% of all containerships was used. The deep draught conditions lead to a more stringent limiting significant wave height. A Post-Panamax vessel was added to include a larger beam containership below 300 m.

The eastbound lane of the southern sailing route has a 9 nautical mile stretch of 19 m LAT depth, that cannot be avoided without leaving the lane. The consequence of this part of the route is for the first time assessed in the present study and it lowers the significant wave height for safe operation.

The probability of bottom contact is discussed and a limiting criterion for dynamic under keel clearance is derived. The class allowable accelerations on governing locations on board are calculated and compared to the calculated values.

The governing factor for the Panamax and ULCS vessels is the limited water depth under the keel on the 19 m LAT shallow part of the route, in beam seas. But even in 21 m water depth, the under keel clearance remains the governing parameter in the seakeeping assessment. Local accelerations impose a higher significant wave height limit. The risk – for both - can be mitigated by sailing into head seas condition.

Finally, update tables with limiting significant wave heights for the containerships are presented. They are dependent on the draught and freeboard of the ships:

Limiting wave height conditions for the ULCS, LPP > 295 m.

Relevant for beam seas sailing +/- 45 deg	**ULCS** sailing draught 14.5 m freeboard 15.8 m	**ULCS** sailing draught 12.4 m freeboard 17.9 m
Northern route (37 m)	**Hs ≈ 6.1 m (accelerations)** no risk on bottom contact Hs ≈ 7.4 m (green water)	Hs ≈ 6.1 m (accelerations) no risk on bottom contact Hs ≈ 7.4 m (green water)
Southern route westbound, min LAT = 21 m	Hs ≈ 6.6 m (accelerations) **Hs ≈ 4.8 m (bottom contact)**[3] Hs ≈ 5.5 m (green water)	Hs ≈ 6.1 m (accelerations) Hs ≈ 5.6 m (bottom contact) Hs ≈ 5.9 m (green water)
Southern route eastbound, min LAT = 19 m	Hs ≈ 6.6 m (accelerations) **Hs ≈ 4.0 m (bottom contact)**[4] Hs ≈ 5.5 m (green water)	Hs ≈ 6.1 m (accelerations) Hs ≈ 4.1 m (bottom contact) Hs ≈ 5.5 m (green water)

Limiting wave height conditions for the Panamax, 200 < LPP < 295 m.

Relevant for beam seas sailing +/- 45 deg	**Post-Panamax (beam 40 m)** sailing draught 13.8 m Freeboard 10.2 m	**Panamax (beam 32.3 m)** sailing draught 12.2 m Freeboard 9.2 m
Northern route (37 m)	**Hs ≈ 6.1 m (accelerations)** no risk on bottom contact Hs ≈ 6.5 m (green water)	Hs ≈ 6.1 m (accelerations) no risk on bottom contact Hs ≈ 5.7 m (green water)
Southern route westbound, min LAT = 21 m	Hs ≈ 5.3 m (accelerations) **Hs ≈ 4.0 m (bottom contact)**[4] Hs ≈ 5 m (green water)	Hs ≈ 5.5 m (accelerations) Hs ≈ 4.5 m (bottom contact) Hs ≈ 4.8 m (green water)
Southern route eastbound, min LAT = 19 m	Hs ≈ 5.3 m (accelerations) **Hs ≈ 4.0 m (bottom contact)**[5] Hs ≈ 5 m (green water)	Not derived, see 21 m LAT.

Limiting wave height conditions for the Feeders, LPP < 200 m.

Relevant for beam seas sailing +/- 45 deg	**FEEDERS** Sailing draught 9.2 m Freeboard 3.0 m	**FEEDERS** Freeboard covering 60% of all feeders (> 3.8 m)
Northern route (37 m)	Hs > 7.5 m (accelerations) No risk on bottom contact **Hs ≈ 3.3 m (green water)**	
Southern route westbound, min LAT = 21 m	Hs > 6.5 m (accelerations) Hs ≈ 5.5 m (bottom contact) **Hs ≈ 2.8 m (green water)**	**Hs ≈ 3.0 m (green water)**
Southern route eastbound, min LAT = 19 m	Hs > 6.5 m (accelerations) Hs ≈ 5.5 m (bottom contact) **Hs ≈ 2.8 m (green water)**	**Hs ≈ 3.0 m (green water)**

3 On the basis of < 1% risk on bottom contact in all possible occurring Hs – Tp sea states.

4 On the basis of accepting a risk > 1% on bottom contact in < 2% of the possible occurring Hs – Tp sea states.

5 On the basis of accepting a risk > 1% on bottom contact in > 13% of the possible occurring Hs-Tp sea states.

The conclusions from the DELTARES study are:

- The predicted nowcast and forecast significant wave heights are biased low, 12% underestimation with respect to the observations.
- A mean absolute error of -0.37 m with standard deviation of 0.32 m is found for the predicted significant wave heights between Hs = 2.5 m and Hs = 5.0 m.
- In order to correct the significant wave height forecast by the SWAN model, it is proposed by DELTARES to use the sum of the model bias plus half a standard deviation of the model, leading to a significant wave height correction by +0.53 m. Thus, when the SWAN model predicts an Hs of 4.0 m, it is safe to consider that the Hs value could be 4.5 m.

The accuracy of the seakeeping analysis is investigated based on the model tests (project 32558). This leads to the conclusion that the SEACAL results are biased high; that is the motions are typically over predicted. The metocean accuracy and seakeeping accuracy cancel each other out. Further reduction of the calculated limiting significant wave heights is not needed.

1 INTRODUCTION

1.1 Background

In the evening and night of January 1st to 2nd, 2019, the Ultra Large Container Ship (ULCS) MSC Zoe lost approximately 350 containers north of the Wadden Islands while sailing along the Terschelling-German Bight Traffic Separation Scheme (TSS) to next port of call Bremerhaven. In the wake of this accident the Dutch Ministry of Infrastructure and Water Management (Ministry) requested MARIN to qualify the seaworthiness 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.

In the first study for the Ministry (MARIN project 32558) three types of containerships were extensively model tested in shallow water conditions. Numerical seakeeping calculations were performed and benchmarked against these model tests. Preliminary limiting significant wave heights were derived for observed threats of under keel clearance in waves, accelerations on containers and green water. Below the limiting significant wave heights passage of the containerships over the TSS was considered safe. Soon after report delivery, the Netherlands Coastguard put a warning system in place when the forecasted significant wave height exceeded the preliminary derived limiting values.

In a second study (MARIN project 33327) the green water phenomenon on Feeder containerships with various freeboard heights and layouts were further investigated in the model basin. Computational Fluid Dynamics (CFD) simulations in irregular waves were performed to provide green water impact pressures on the containers for a structural FE assessment and safety consequences for the container stack. New limiting significant wave heights for the Feeder class were established to prevent container structural failure and loss of containers.

In the present study further numerical calculations are performed for the containerships sailing along the route using AIS data from the last 4 years. A representative deep draught condition is derived for the ships sailing regularly on route; whereas in the previous study a representative average draught was used.

In view of the warning system in place by the Netherlands Coastguard, the accuracy of the significant wave height (and peak period) forecast used in that route advice was investigated by DELTARES. The consequence of this for the final limiting wave heights is discussed in the concluding chapter.

The limiting wave height table for the containerships in the TSS above the Wadden Islands, for the first time derived in project 32558, is finally updated and discussed based on the conclusions from all three projects.

With respect to the loss of containers the following threats can occur:

- Exceeding structural loads on container securing systems (lashings) due to the high transverse accelerations on the containers. High accelerations are caused by excessive ship motions, and are in particular due to excessive roll motions. The acceleration level is a direct output of the seakeeping calculations. The maximum acceleration level that should be used to calculate the securing loads follow from the class rules.
- High impact loads on the containers itself due to wave crests exceeding the freeboard height. This can occur in (very) steep waves when ship motions are not that large or in the combination of less steep waves and more dynamic ship motions.

- High local hull vibrations in the ship due to wave impact loads against the ship side or impact loads due to seabed contact with the ship hull could translate to additional accelerations on the containers. This is a highly complex process and it is not possible at the moment to estimate the (whipping) acceleration level. Impact of the hull of the seabed must be avoided. It is a threat for high beam containerships and for deep draught conditions. The remaining under keel clearance in waves is a direct calculation output of the seakeeping analysis.

1.2 Preliminary limiting sea state conditions

In the previous study (MARIN project 32558) the limiting sea state conditions for three types of containerships were derived from a combination of model tests and seakeeping calculations. The limiting sea state heights are listed in Table i-1 with the associated seakeeping criteria for the Feeder class (LPP < 200 m), the Panamax class (200 ≥ LPP < 300 m) and ULCS class (LPP ≥ 300 m) container ships. 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[6].

The Feeder containerships are limited by green water freeboard exceedance with possible high impact loads on the containers. The green water exposure cannot be calculated (accurately) by any seakeeping tool. Therefore, a separate study was performed (MARIN project 33327) involving the combination of model tests, CFD and FEM to detail the green water impact loads and consequences for the containers. The obtained limiting significant wave height from that project is taken and further discussed in view of the present conducted network analysis.

For the ULCS the governing aspect is the calculated remaining dynamic under keel clearance in waves. The limiting conditions arise due to excessive rolling in beam seas condition under high, but not unrealistic, GM conditions. A safety margin of +2 m was used between the lowest hull point and the seabed. The allowable accelerations on the containers and the green water threat lead to a less stringent wave height limitation.

For the Panamax vessel the dynamic under keel clearance criterion gave the same limiting sea state height as for the ULCS. At low GM values the limiting wave heights are found in slightly off-beam seas conditions due to the combined effect of roll and pitch motions. In high GM conditions, the limiting wave height is obtained in beam seas condition.

In all studies performed so-far it was apparent that the containerships can mitigate the risk for green water, low under keel clearance or high accelerations on containers by sailing more head into the waves.

From the present study, Table 1-1 will be updated and presented in the concluding chapter. Note that the preliminary significant wave heights are derived on the basis of a given draught condition (as was used in the model tests) and for sailing in beam seas conditions.

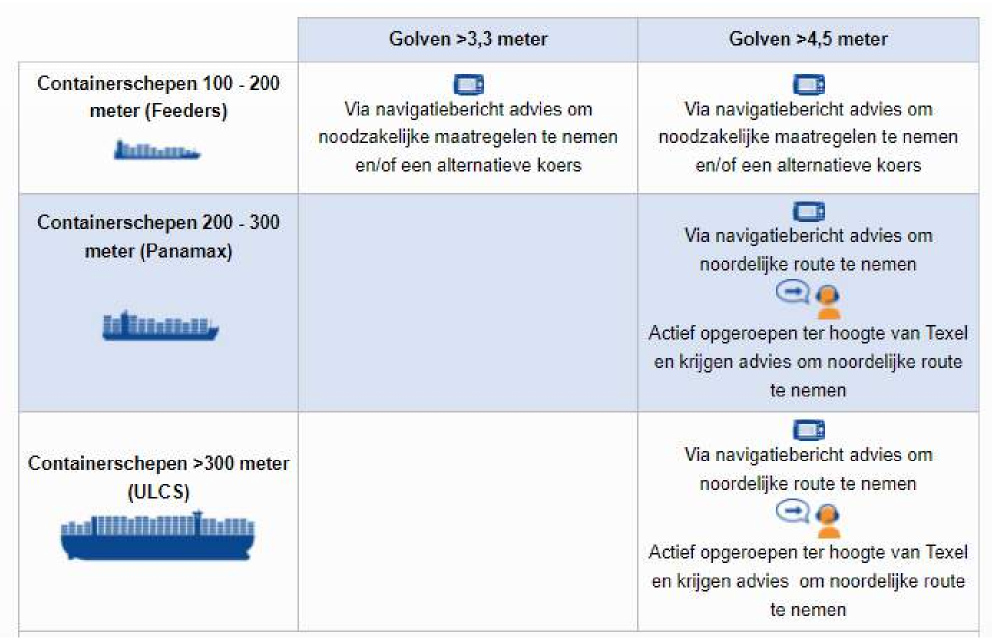
[6] For the limiting wave height for bottom contact the wave height is used at which the minimum dynamic UKC of 2 metres is reached, for the accelerations the lowest acceleration criteria of the 4 class societies is used and for green water the wave height at which the relative wave motions can reach 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.

Table 1-1: Preliminary limiting sea state conditions when sailing in beam-seas +/- 30 deg condition, as derived in previous investigations (project 32558)

Route	**FEEDER** **LPP < 200 m** GM=0.8 to 1.5m 0 to 8 knots 9.20 m draught Freeboard 3.0 m	**PANAMAX** **200 ≤ LPP < 300 m** GM=1.0 to 2.5m 0 to 10 knots 12.20 m draught Freeboard 9.2 m	**ULCS** **LPP ≥ 300 m** GM=6.0 to 9.25m 0 to 10 knots 12.40 m draught 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 ≈ 5.5 m (bottom contact)[7] **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)

1.3 Netherlands Coastguard route advice

The present warning system and route advice from the Netherland Coastguard (Kustwacht) is provided in Figure 1-1. Further information can be found in https://kustwacht.nl/en/node/765#routeadvies. The advice utilises the limiting sea states as given in Table 1-1 in bold font.



	Golven >3,3 meter	Golven >4,5 meter
Containerschepen 100 - 200 meter (Feeders)	Via navigatiebericht advies om noodzakelijke maatregelen te nemen en/of een alternatieve koers	Via navigatiebericht advies om noodzakelijke maatregelen te nemen en/of een alternatieve koers
Containerschepen 200 - 300 meter (Panamax)		Via navigatiebericht advies om noordelijke route te nemen Actief opgeroepen ter hoogte van Texel en krijgen advies om noordelijke route te nemen
Containerschepen >300 meter (ULCS)		Via navigatiebericht advies om noordelijke route te nemen Actief opgeroepen ter hoogte van Texel en krijgen advies om noordelijke route te nemen

Figure 1-1: Current route advice for containerships

It is noted that for the larger ships there is no Coastguard advice related to the limiting wave heights in the Northern route (Hs ≈ 5.7 m for the PANAMAX and Hs ≈ 6 m for the ULCS) as given in Table 1-1. In these conditions ships sailing in beam waves can also lose containers in the Northern route.

The current warning system and/or route advice to ships entering the TSS is based solely on the nowcast and forecast significant wave height in combination with the ship length. The broadcast warning is automatically generated based on the wave height predictions at several points along the route and

[7] 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.

Dutch coast. In the present project the accuracy of the forecast is investigated by DELTARES. Those findings are summarised in Chapter 3.

The underlying data that leads to the limiting significant wave height is deterministic. It is derived from model tests, calculations and class rules in combination with a stochastic interpretation of the influence of the (short-term statistics of) irregular waves. The seakeeping calculations so-far were done for the relevant containership classes (Feeder, Panamax, ULCS), but only for one draught condition in each class, based on an average observed draught from a past network analysis, combined with the conditions of the MSC ZOE accident and MARIN database information. At deeper sailing draught the risk for bottom contact can increase (most likely) so that a new network utilised to find a deeper relevant sailing draught.

The fleet of containerships sailing over the route varies from small to large, with significant varying loading conditions and stowage plans and thus significant draught and GM (stability) variations. It is clear that a single limiting significant wave height implies that a large portion of the fleet sails with more than sufficient safety margin. This is inherently the consequence of setting only a wave height limit to the complexity of seaworthiness in irregular seas which strongly vary with the wave heading and wave period. A quantitative risk analysis will be difficult since the probability of a certain draught and GM combination is unknown and it is not part of the present study.

In preparation of the present investigation a workshop meeting was held with all stakeholders involved (Ministry of Infrastructure and Water Management, Netherlands Coastguard, MARIN, DELTARES; Dec 2021). It became clear that the automatically generated first warning broadcast to ships based on the weather forecast is a practical (and desired) approach. After implementation, several containerships sailing eastbound were explicitly summoned/warned not to enter the southern route but to select the northern route instead for safer passage, and most of them did. The few that did not travelled safely without incidents on the route. This does not mean that the advice is too restrictive, as it is very likely that those ships had an actual draught and GM that would lead to a zero calculated risk in a seakeeping analysis under the given storm parameters and direction.

Following the outcome of the workshop the present investigations aimed at updating the existing table of limiting wave heights. Further discussion is presented on critical parameters that effect the safety of the containerships and their cargo, such as the freeboard height when it comes to green water risk.

1.4 Scope of work

The present study involved the following scope of work:

- An investigation on the accuracy of the wave height prediction around the critical significant wave height used in the present warning procedure. (DELTARES).
- A network analysis for the containership sailing through the southern and northern routes with a focus on actual vessel freeboard and draught in particular. (MARIN, 33883-2-MO-rev.1).
- Seakeeping analysis study (MARIN, 33883-1-SEA).
- Update of the preliminary limiting wave height table as shown in Table 1-1, including discussion and possible refinement to present realistic and practical advice possibilities (MARIN, 33883-1-SEA).

1.5 Report reading guide

Chapter 2 provides background information on the sailing route, the chartered water depth, and the metocean wave conditions.

Chapter 3 present the findings of the network analysis and the accuracy study on the significant wave height prediction.

Chapter 4 is an extensive chapter detailing the seakeeping analysis study approach. It discusses the accuracy of the motion prediction and the influence of shallow water. The correction method for the dynamic under keel clearance is presented. The seakeeping criteria are listed.

Chapter 5, 6 and 7 present the findings for the ULCS containership, the Post-Panamax and the Feeder. Each chapter concludes with a limiting wave height table. The green water results are summarised are taken together for all ships in Chapter 8. A green water risk matrix is presented.

Chapter 9 wraps ups the project investigation with final discussion and summary.

The table with preliminary limiting wave heights is included in Table 1-1, page 3.

The table with final limiting wave heights can be found in the management summary, page viii.

2 BACKGROUND INFORMATION SAILING AREA OF INTEREST

2.1 Introduction

A new seakeeping analysis was performed for representative containerships that sail in the shipping lanes above the Dutch Wadden Islands. The details of the used containerships are presented in the result chapters.

The sailing area of interest is detailed in Section 2.2. There are two distinct sailing routes: the northern TSS and the more shallow water southern TSS.

A network analyses utilising AIS transmitted data was used to quantify the fleet of containerships sailing on the TSS. In particular the freeboard height and the actual sailing draught were investigated for the different containership classes (length below 200 m, between 200 and 300 m, and above 300 m). The network study, which comprised the period 1-January-2018 until 28-February-2022, is reported separately (33883-2-MO). In Section 3.1 the findings are summarised in view of the present seakeeping analysis.

The metocean study on the accuracy of the wave prediction in the area of interest was performed by DELTARES and the findings are summarised in Section 3.4. The consequence of the forecast accuracy is detailed in the concluding chapter.

2.2 Sailing area of interest

The area of interest is the southern (Terschelling-German Bight TSS) and northern sailing route (East-Friesland TSS, Traffic Separation Scheme) along the Dutch Wadden Islands, as depicted in Figure 2-3. The northern route is also called the deep water (DW) route.

The southern route is about 60 nautical miles (nm) long, measured between the westerly entry point near Vlieland and the easterly crossing point with the German border. At an average speed of 10 knots, the distance is sailed in 6 hours. Continuation of the voyage towards e.g. Bremerhaven involves another 50 miles sailing on the German part of the TSS before exiting the TSS and turning south. The sailing time on the southern route is than about 11 hours in total at 10 knots average speed covering 110 nautical miles (nm).

If a containership, with the intention to sail the southern route, decides near Vlieland to take the northern route instead, the ship has to sail first 40 nm to the NNE before tuning east to follow the northern TSS. The distance to sail on the Netherlands part of the TSS is than 33 nm, that is about 3.5 hours at 10 knots speed. In storm conditions from the NW this means that the ships sails about 4 hours in bow quartering condition before reaching the northern TSS. Once on the TSS, the ship is exposed to beam or slightly stern quartering waves for about 3.5 hours, while on the southern route it would have been exposed 6 hours in beam to stern quartering seas.

Following the northern TSS, the distance to sail on the German bight Western Approach TSS is 50 nm before turning south, and the containerships reach the same crossing point (as the ship that followed the southern route) before harbour approach after another 13 nautical miles. The complete northern round trip has taken 136 nautical miles, or about 14 hours sailing at 10 knots average speed. This is 3 hours more than the original scheduled southern route, but the exposure to the more dangerous beam waves (in NW storm) has been reduced, while the ship constantly sails as well with more water under keel. A graphical representation of the exposure times when sailing 10 knots average and compass direction on the southern and northern TSS is shown in Figure 2-1.

The compass direction of the southern route is eastbound 70^0, equivalent to westbound 250^0. The northern route has direction 80^0 and 260^0, eastbound and westbound, respectively. The compass course from the southern to the northern TSS entry point is 20^0. Once on the TSS, the ship heading is thus nearly identical, so that, given a particular storm direction, the relative ship heading can be considered identical.

Concerning the warning system of the Netherlands Coastguard: a warning is broadcasted to the Feeders when the significant wave height increases above 3.3 m, independently from where they are on the TSS. The advice to change course (away from beam seas) is easier executed on the westbound lane as the ships can leave the TSS to the North. The same applies to the Panamax and ULCS ships above 4.5 m significant wave height. Once going eastbound a significant course change will be more difficult for all ships, but in particular for space to navigate is minimal for the larger ships. It is noted that for the larger ships (PANAMAX and ULCS) there is no Coastguard advice related to the limiting wave heights in the Northern route as given in Table 1-1 (around Hs=6m). In these conditions ships sailing in beam waves can also lose containers in the Northern route.

Given a south-westerly (SW) storm, the containerships sail in bow-quartering conditions westbound, and stern-quartering conditions eastbound; see Figure 2-1. Given a storm from the NW to NNW direction, the containerships sail in beam seas conditions are potentially more vulnerable for large roll motion, large accelerations and green water freeboard exceedance.

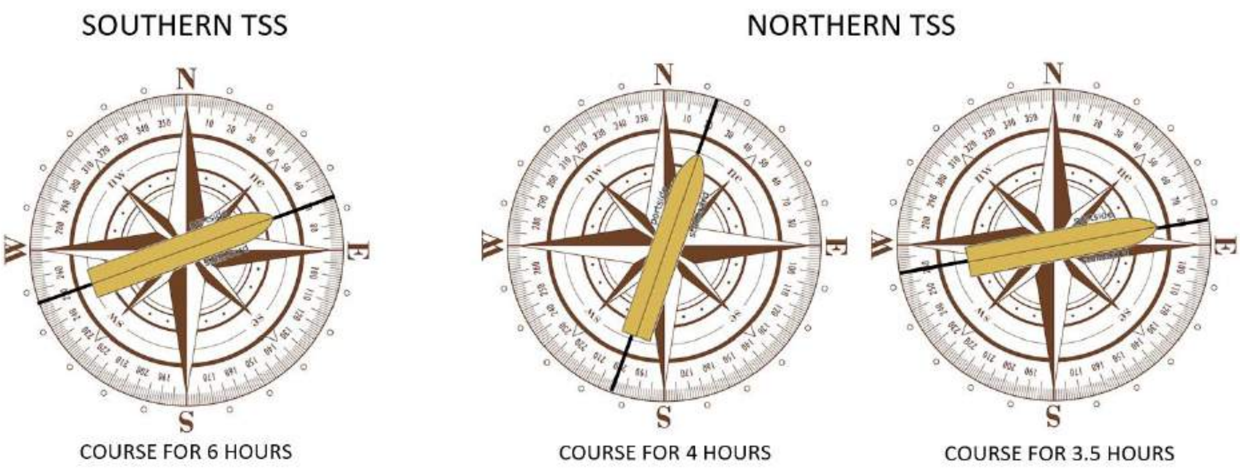


Figure 2-1: Exposure time and ship heading when sailing eastbound at 10 knots starting from the westerly entry point (decision point) of the southern route until the German border. When the northern route is selected, the ship first has to sail to the northern route.

At several locations on the TSS's the water depth (provided as a LAT, Lowest Astronomical Tide) is read from the (e.g.) nautical charts provided online by www.navionics.com. LAT is the lowest water depth possible due to tidal variations established over a long period (19 years). It is common seamanship practice (for the commercial ships) to respect the LAT water depth and not to rely on a possible additional tidal surplus of water. That is conceived as 'bonus' water under keel. The chart is shown in Figure 2-3. It is noted that the amount of reduction due to ship dynamics is the larger unknown to the sailing crew.

The water depth along the TSS's is further detailed in Figure 2-4 and Figure 2-5. As observed, the LAT water depth on the southern route for the Netherlands part varies between 19 and 23 m on the eastbound land, and is at least 21 m on the westbound lane. The shallower water part with water depth between 19 and 21 m eastbound is about 8 miles long (at 10 knots speed this will take < 1 hour). When the ship eastbound sails close to the separation zone, the minimum encountered water depth is 20.1 m LAT.

On the German TSS there are a number of sandbanks of 17 m depth that extend (only) through the southern eastbound lane for about 9 miles (Borkum riff). This German part of the route is not included in the metocean study nor in the seakeeping analysis, but it is a possible threat for deep draught ships eastbound on the southern route. The MSC ZOE, sailing that route, headed North before reaching this shallow water part as it was known at that time that containers had been lost.

Tidal motion will increase the LAT water depth. The tidal variation on the L9 platform location are retrieved for 2023 and presented in Figure 2-2. The tide reference plane is NAP (Normaal Amsterdams Peil). The figure gives a good indication on the time varying water depth on the whole TSS. The lowest low water (LW) in 2023 is predicted to be -1.2 m below NAP. The NAP reference plane is about 1.5 m above LAT, according to the information on charts of the sailing area (NV Atlas). Thus, the lowest water depth at the reference 19 m LAT will be 19.3 m in 2023. The highest HW level is about 1.2 m above NAP, leading to a water depth of 21.7 m at the 19 m LAT plateau.

A tide cycle is about 12 hours between two low tides. Given the sailing time of approximately 6 hours at 10 knots on the southern TSS (Netherlands part), the vessel will not encounter more than one low tide. It can experience one low tide, one high tide or sail during a falling or rising tide. Obviously, when sailing faster or slower this picture changes a bit.

Based on the above findings, the following is concluded:

- The LAT chartered water depth reflects the lowest possible water depth occurring about 1 / year (theoretically only 1 / 18.5 year as it is a calculated lowest tide in the lunar nodal tidal constituent).
- On the eastbound southern TSS there is a stretch of about 10 nm where water depth is below 21 m. For 8 nm it is below 20 m, reaching 19 m over about 4 nm. To the extreme north of the eastbound lane the water depth remains 20 m LAT over a 275 m wide strip. Once the shallow water part is passed, the LAT is eastbound at least 22 m.
- The LAT chartered minimum water depth on the southern TSS in the westbound lane is 21 m. Over 45 nm of the 60 nm track, the water depth exceeds 23 m.
- The representative water depth on the northern TSS is 37 m.
- Tidal variations are in the order of +/ 1.2 m around NAP reference level 1.5 m above LAT.

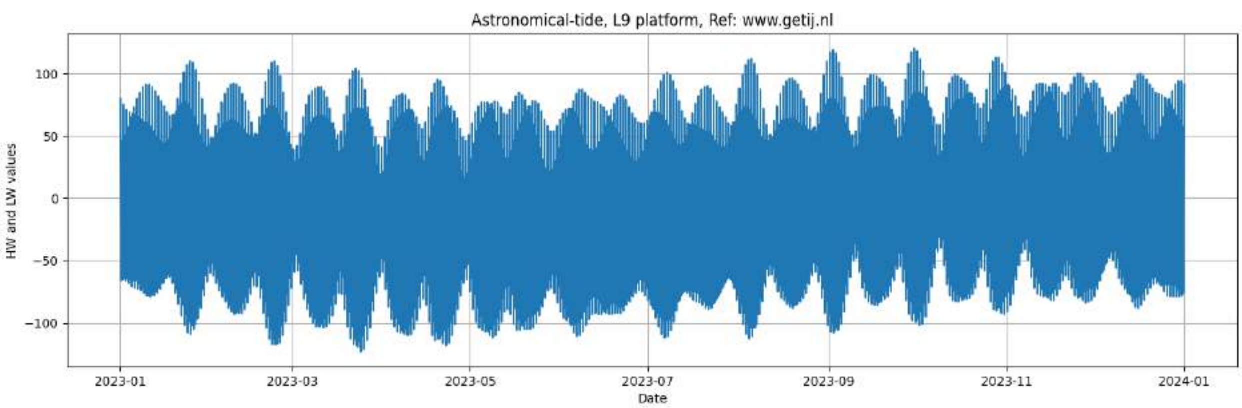


Figure 2-2: Astronomical tide prediction for 2023, platform L9 location.

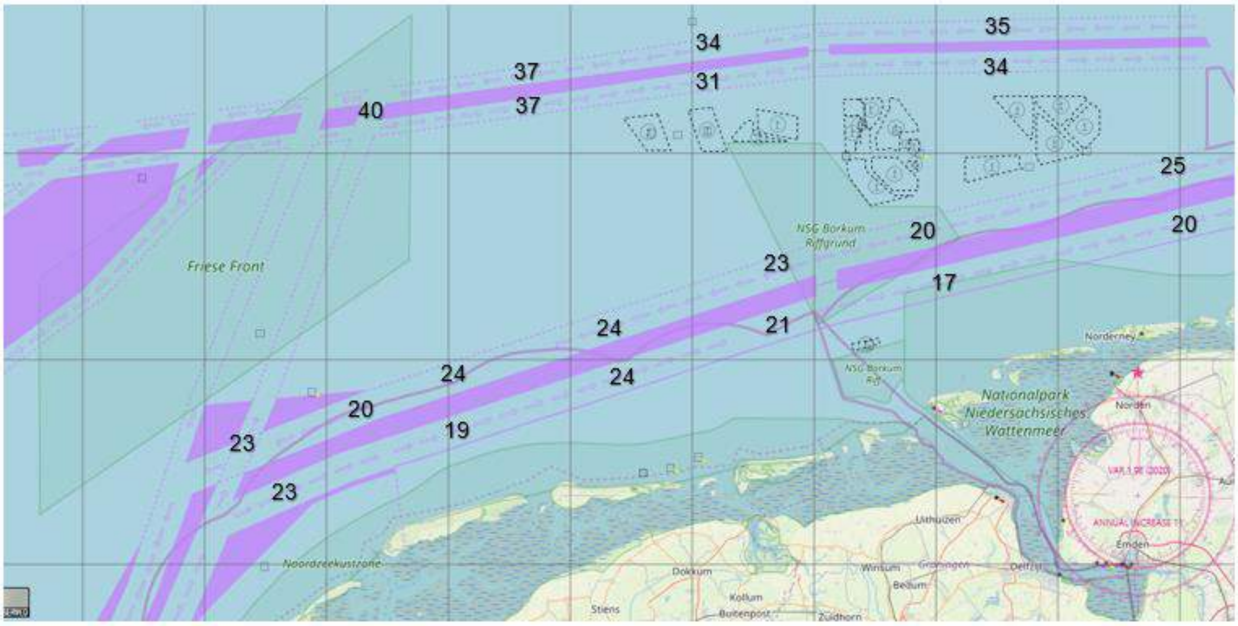


Figure 2-3: *Northern and Southern TSS sailing route with LAT water depth.*

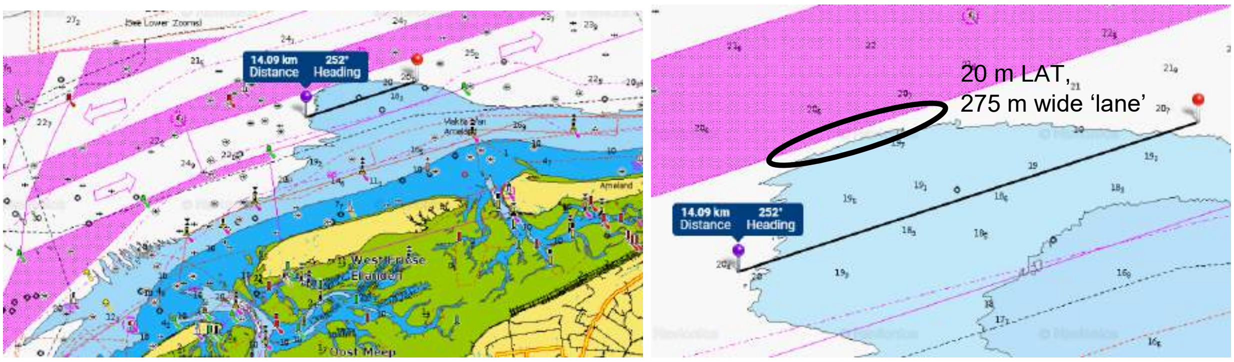


Figure 2-4: *Most shallow water depth part in the Southern TSS: 9 miles at LAT 19 m. Navionics website, March 2022.*

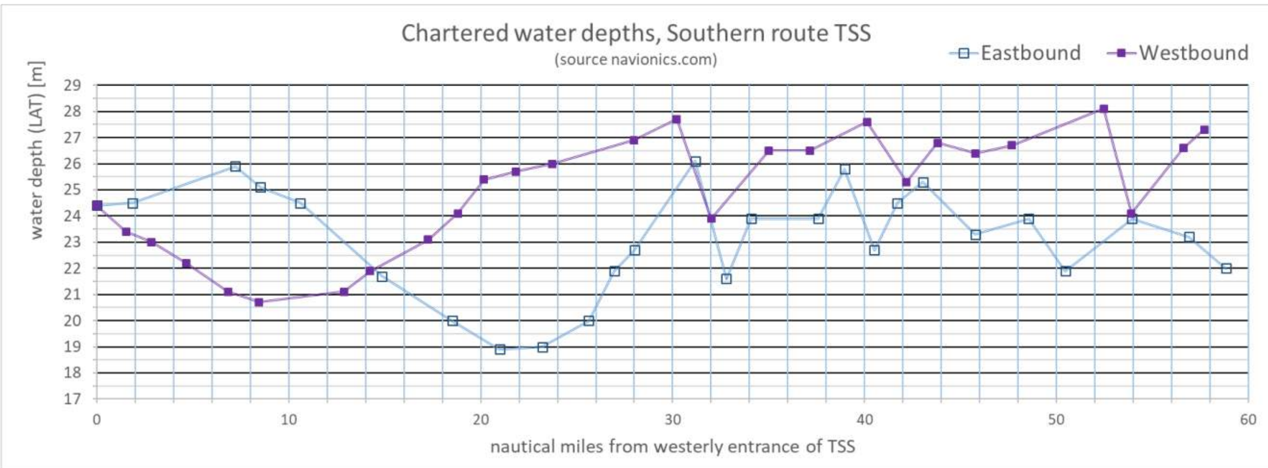


Figure 2-5: *Chartered water depths on the southern TSS versus distance from westerly entry point.*

2.3 Metocean conditions on the TSS

This section details the metocean data. A similar discussion can be found in 32558-3-SEA.

The metocean conditions typically include: wind speed, current velocity and sea state condition (wave height Hs, and wave peak period Tp). Only the wave conditions are used in the numerical assessment. Wind and current are neglected.

The ERA5 metocean hind-cast data for platform L-91 includes 40-year data (1979-2019). The hourly data leads to N=354264 sea state conditions. L-91 is positioned on the easterly departure of the northern and southern TSS. The scatter diagram of all occurring Hs (significant wave height) and Tp (peak spectral period) is given in Figure 2-6 together with a wind-rose of sea states coming from direction. The maximum sea states have a significant wave height of close to 8 m. The wave peak periods range from about 8 seconds up to 14 seconds, with a few exceptions of long swell sea states with associated significant wave heights below Hs of 4 m. There is a clear boundary of possible wave steepness (Hs –Tp combinations) on the left hand side of the scatter diagram.

In Figure 2-8 the percentage of occurring of a Hs-Tp sea state is shown. It shows that the dominating sea states in the area are below Hs of 2 m. Two sea state groups dominate, each with close to 10% probability of occurring (Hs [0.5 to 1.0] m with Tp [4 to 5] s, and Hs [1.0 to 1.5] m with Tp [5 6o 6] s).

Based on the earlier SWAN simulations and investigations by DELTARES for the OVV investigations on the MSC ZOE[8] accident the following wave conditions will be used in the sea keeping analysis:

- JONSWAP wave spectra with gamma 1.5,
- Short-crested sea states, spreading function cos 2s = 12,
- Wave periods up to 14 seconds.

Figure 2-7 shows the most probable wave periods at various H_S levels (red marker), and the bandwidth of 95% occurring sea states (red bands). The most probable wave period depends on the storm direction sector. The longer wave periods are due to storms from the NW direction. It shows that up to Hs of 4.5 m the wave periods above 12 seconds are rare. When the wave height increases, wave spectra with a peak period longer than 12 seconds are more common. Wave periods above 14 seconds are neglected in the analysis (low Hs swell sea state conditions).

In Table 2-1 the probability of occurring of a certain Hs value is calculated from the 40-year metocean data and expressed in terms of hours and days per year occurring. It shows e.g. that waves above Hs of 4.5 m occur only 0.5% of the time per year, which amounts to about 44 hours/year.

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[8] DELTARES report 11204419-002-HYE-0001, June 2020, for Dutch Safety Board, www.onderzoeksraad.nl

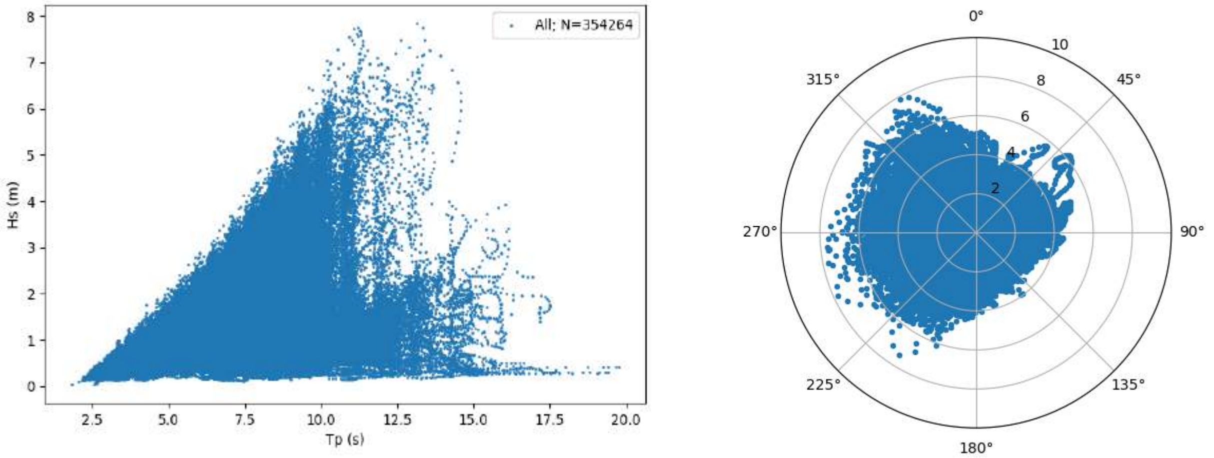

Figure 2-6: Left: Scatter diagram of Hs-Tp combinations, Right: sea state direction (coming from) as function of Hs.

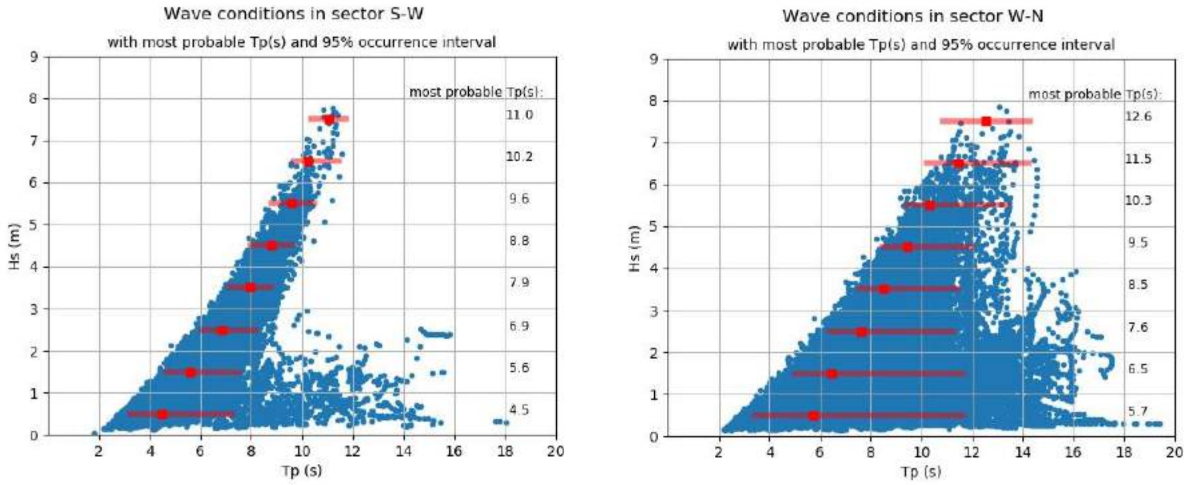

Figure 2-7: Wave scatter diagrams for storm sectors S-W and W-N. In red: most probable wave period and bandwidth of 95% occurring wave periods.

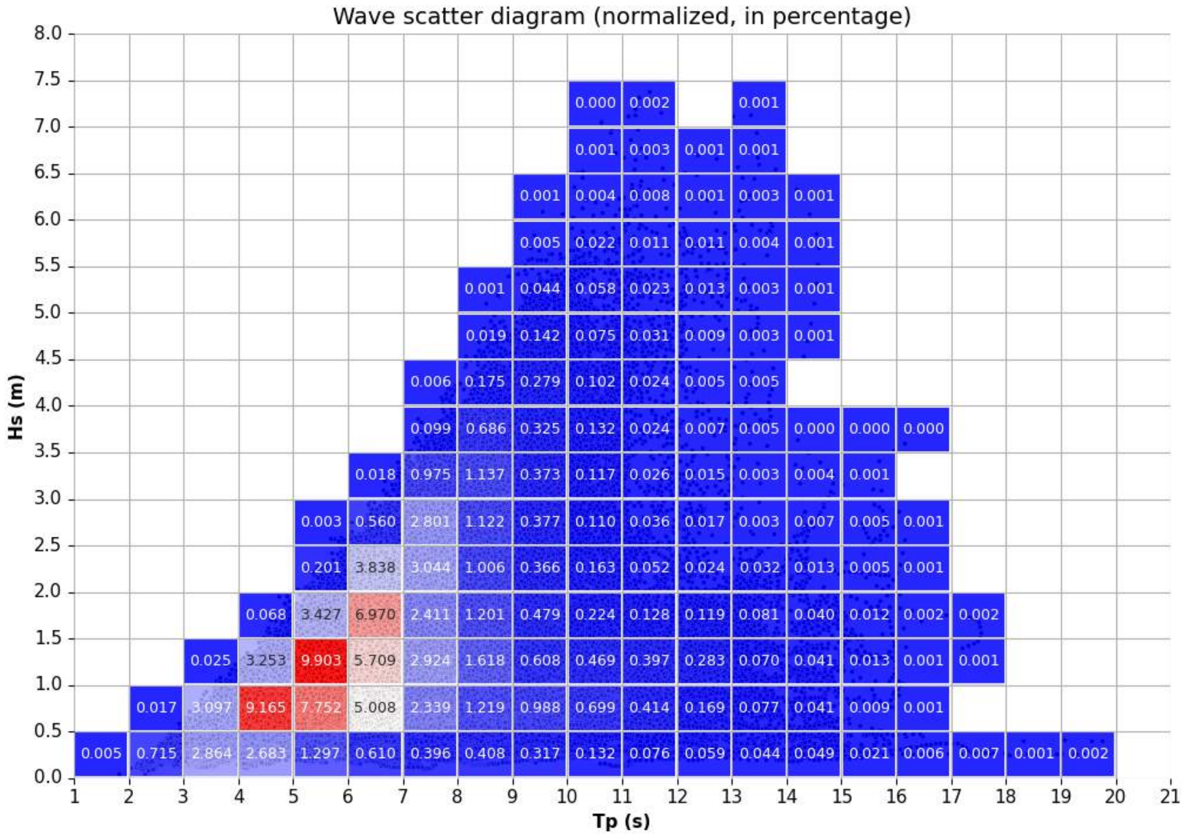

Figure 2-8: Normalised wave scatter diagram (40 years of data).

Table 2-1: Probability of occurring of the sea state (all periods) given a certain limiting wave height.

	% occuring per year of significant wave height Hs (m)							
storm direction	>2.5	>3.0	>3.5	>4.0	>4.5	>5.0	>5.5	>6.0
ALL	10.1	5.1	2.4	1.1	0.5	0.2	0.1	0.0
S to W	4.2	2.1	0.9	0.4	0.2	0.1	0.0	0.0
W to N	4.8	2.6	1.4	0.7	0.3	0.1	0.1	0.0

	hours per year of significant wave height Hs (m)							
storm direction	>2.5	>3.0	>3.5	>4.0	>4.5	>5.0	>5.5	>6.0
ALL	884	442	208	96	44	19	7	3
S to W	372	181	78	34	15	6	2	1
W to N	421	226	118	59	28	12	5	1

	days per year of significant wave height Hs (m)							
storm direction	>2.5	>3.0	>3.5	>4.0	>4.5	>5.0	>5.5	>6.0
ALL	37	18	9	4	2	1	0	0
S to W	15	8	3	1	1	0	0	0
W to N	18	9	5	2	1	1	0	0

3 ROUTE NETWORK AND METOCEAN STUDY

3.1 Containership classes

In the first study, 32558, three ships types were selected, which were denoted Feeder, Panamax and ULCS class. The naming was linked to the length of the ship:

Feeder containerships	LPP < 200 m
Panamax containerships	200 < LPP < 300 m
ULCS containerships	LPP > 300 m

For consistency, in the network study the AIS database was divided into above three groups based on the ship length.

The containership naming is however slightly more diverse.

The first Panama Canal locks had a length limitation of 294.4 m and a beam limitation of 32.3 m. Container ships that were able to travel through the Panama Canal were denoted Panamax containerships. The beam limitation allows for 13 containers across deck and the carrying capacity is typically between 3000 and 4500 TEU, with 6 to 8 tiers on deck.

The next generation of containerships was called Post-Panamax vessels as they could not travel through the Panama Canal. Their length was just below or above 300 m with a beam of 40 or 43 m carrying 15 or 17 containers across deck. The carrying capacity is 4000 to 8500 TEU, with 9 tiers high on deck.

In 2016 the new panamax locks came into operation. The length limitation for these locks is 370.3 m, the beam limitation is 51.2[9]. The older Post-Panamax vessels can now thus travel through the Panama Canal. A new class of ships was designed with about 12500 TUE carrying capacity that fits within the new lock dimensions. They are denoted New-Panamax or Neo-Panamax (NPX) vessels.

The even large containership are denoted ULCS containerships. They are close to 400 m in length carrying 23 or even 24 containers across deck with a carrying capacity beyond 18000 TEU. The beam is 59 m or 62 m. They cannot sail through the Panama Canal.

To reflect the various containership classes better it is recommended to change the length division from 300 to 295 m; with the notion that the Post-Panamax containerships in the usual context can be longer than 295 m. By setting the length division at 295 m, all ships with a beam beyond 43 m fall in the ULCS class. The class division is given in Table 3-1, the accompanying network analysis data is shown in Figure 3-1 (next section).

Table 3-1: Container ship class division (proposed for the new route advice).

Feeders	LPP < 200 m	Feeder containerships	
Panamax	200 < LPP < 295 m	Panamax containerships	Beam < 32.3 m
		Post-Panamax containerships	Beam < 44 m
ULCS	LPP > 295 m	ULCS containerships, including New-Panamax ships	(no beam restriction) Beam < 51 m

[9] www.pancanal.com; OP Notice to Shipping No. N-1-2022 (January 2022)

3.2 TSS route network study

3.2.1 Introduction

A network analysis was performed on the containerships sailing on the TSS above the Dutch Islands. The results are reported in 33883-2-M0. In the following section a summary is presented.

3.2.2 Summary of the study

In project 32558 three representative containerships were defined for model testing and seakeeping analysis. The dimensions of the three containerships are listed in Table 3-2. The three container ships are denominated by their usual type name which is linked to their dimensions and cargo carrying capacity. The given draught was the draught of the ships in the model tests and seakeeping analysis.

Table 3-2: Main properties of the three containerships used in project 32558 (preliminary advice stage).

Ship type	Length range (m)	Selected length (m) (LPP)	Beam (m)	Draught (m)	Indicative TEU
FEEDER	< 200 m	168	27.04	9.20	< 3000
PANAMAX	200 to 300 m	294	32.30	12.20	Approx. 4300
ULCS	> 300 m	395	59.08	12.40	Approx. 18000

The AIS network analysis in the present project provided further insight into the dimensions of the containerships, in particular the length to beam ratios, the freeboard height and the actual sailing draught. The network analysis comprised AIS data from January 2018 to February 2022. A normalised map (values in the map give percentage of occurring) of the all the containerships (both routes) is given in Figure 3-1 as function of length to beam. It shows that within the length class up to 297 m most ships are classical Panamax vessels with a beam of 32.3 m (6% of the total fleet), but that there are a number of ships with larger beam of about 40 m (3.7% of the fleet). In the length class beyond 297 m, three beam values dominate the fleet, of which 59 m is the largest (3.8% of the fleet).

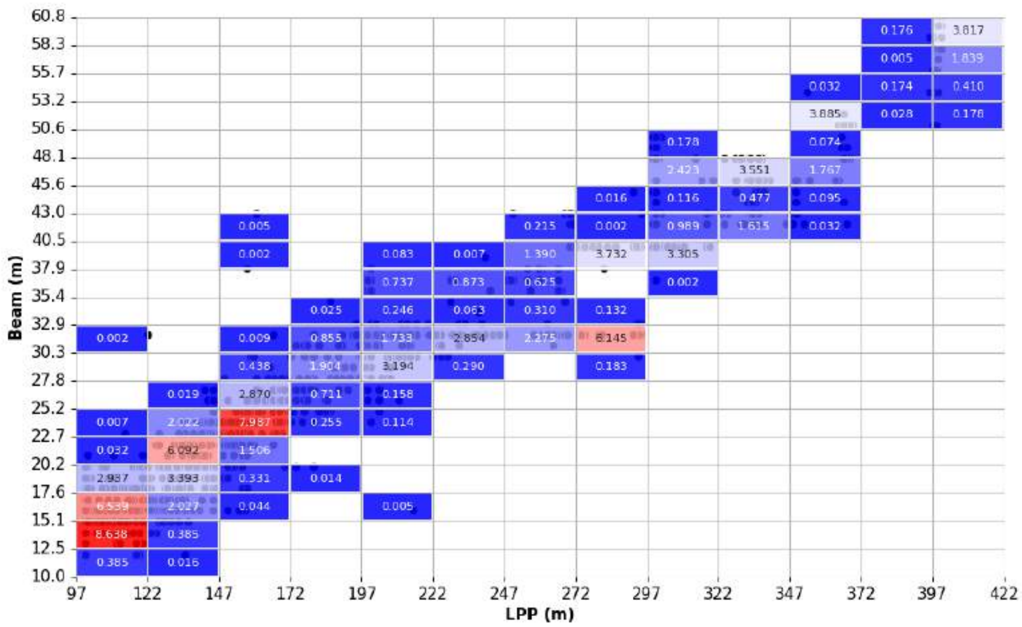

Figure 3-1: Normalise distribution of containerships. Length versus Beam. (Both routes = 100%).

The following is concluded from the network study (see report 33883-2-MO for more details):

- From all containerships on route: 12% selected the northern route and 88% the southern route.
- From the containerships in the ULCS class: 23% selected the northern route, 77% selected the southern route.
- From the containerships in the Panamax class: 14% selected the northern route, 86% selected the southern route.
- From the containerships in the Feeder class: 7% selected the northern route, 93% selected the southern route.
- From all containerships on the southern route, 10% of the ships had a draught above 12.4 m and most of these ships, 68%, fall in the ULCS class.
- Considering the ULCS vessels on the southern route: 53% of the vessels had a draught less than 12.4 m (previously used ULCS draught), and 95% of the vessels sailed with a draught less than 14.5 m. The ULCS vessels with a beam around 59 m sailed with a draught between 8.4 m and 15.8 m.
- Considering the Panamax vessel on the southern route: about 80% of the vessels had a draught less than 12.2 m (used in the previous study) and 95% of the vessel sailed with a draught less than 13.2 m. The maximum actual draught of 14.6 m was recorded twice.
- On the northern route the average draught of the ULCS vessels is typically higher than on the southern route, but not that much. The maximum recorded draught is the same.
- About 31% of the ships with a length between 200 and 297 m are Post-Panamax vessels with a beam larger than 32.3 m. The selected beam is 40 m for these ships. About 95% of the Post-Panamax vessels sailed at a draught up to 13.8 m.

In the present seakeeping analysis the Panamax and the ULCS class containership properties was updated to reflect the findings of the network analysis; the new calculation matrix is shown in Table 3-3.

For ships above 200 m the dynamic under keel criterion is the limiting factor for safe navigation on the southern route, and the dynamic UKC is mainly a function of the vessel beam and draught, hence:

- Within the Panamax ships length class up to 297 m, a Post-Panamax vessel with a beam of 40 m was selected in combination with a draught of 13.8 m.
- The draught of the ULCS class ships above 297 m was increased to 14.50 m.

It can be expected that the new selected sailing conditions will have an impact on the limiting significant wave since the gross under keel clearance (in calm water condition) significantly reduces; see the summary in Table 3-4.

Table 3-3: Main properties of the two containerships in the present numerical study.

Ship type	Length (m)	Beam (m)	Typical Draught (m)	95%-Draught (m)	B / T ratio (-)
POST-PANAMAX	278	40.00	12.20	13.80	2.90
ULCS	395	59.08	12.40	14.50	4.07

Table 3-4: Gross UKC (in calm water) in the present seakeeping study.

Vessel	Panamax Previous study	Post-Panamax **Present study**	ULCS Previous study	ULCS **Present study**
Vessel draught, Tm	12.2 m	13.8 m	12.4 m	14.5 m
Minimum water depth Eastbound southern TSS	21.3 m	19.0 m	21.3 m	19.0 m
Gross UKC	9.1 m	5.2 m	8.9 m	4.5 m

Vessel	Panamax Previous study	Post-Panamax **Present study**	ULCS Previous study	ULCS **Present study**
Vessel draught, Tm	12.2 m	13.8 m	12.4 m	14.5 m
Reference water depth southern TSS	21.0 m	21.0 m	21.0 m	21.0 m
Gross UKC	8.8 m	7.2 m	8.6 m	6.5 m

3.3 Containership GM loading conditions

There is no information of the actual sailing GM of the ships. This information is not broadcasted with the AIS data, but it is recorded on-board and known from the loading computer.

The selection of the GM conditions is thus based on other sources.

The natural roll period of the ship is the parameter that determines at which period the ship is most vulnerable for roll excitation. If the peak of the wave spectrum is near the natural roll period, the ship will experience a large excitation and the roll motions will be large. The further the wave peak period is away from the natural roll period the smaller the wave excitation to the ship is and the lower the motion response.

Given a ship draught the metacentre height above keel (KM) is known. And once the distance of the centre of gravity above keel is known, KG, the transverse stability parameter GM is known (KM = KG + GM). The KG of the ship is large depending on the container cargo on board. The ship loading computer is used to calculate the KG from which the GM follows. The GM is thus known at ship departure.

Once the GM condition is known the allowable maximum acceleration level according class rules can be calculated. Then the loads on the container securing equipment can be calculated from the mass times the acceleration. The obtained loads are verified against the structural capacity of the securing system, including load safety factors.

Each ship is designed and class approved with an accompanied stability booklet (load manual). In that booklet a range of envisioned loading conditions are prepared and verified, covering the extreme low and high GM conditions. The actual GM condition during the life time of the ship must vary between the minimum and maximum GM in the stability booklet. MARIN is often asked to perform model tests for a specific ship and a specific GM condition during the early phase of ship design, using typically averaged GM values. The more extreme values from the stability booklets are not known.

In general, when the GM increases the ships become “stiffer” with a shorter roll period (s). The shorter roll period (s) implies a higher natural roll frequency (rad/s), ω. The local accelerations are a function of the ω^2, so that the accelerations increase with increasing GM. There is thus a tendency to limit the GM to keep the acceleration levels on acceptable levels. In low(er) GM conditions the stability of the ship is less and the ship is more vulnerable for large roll angles given a small excitation. The effective gravity angle will then be an important part in the local acceleration. Hence, class requirement impose a maximum roll angle (30 deg) for the verification of container securing arrangements.

In general, the GM will increases when the ship beam increases due to the fact that the metacentre height above keel (KM) increases.

The following range of GM conditions is used in the present study. It is based on MARIN experiences from various projects:

- Present study, ULCS (beam 59 m): GM range of 4.0 m to 10.0 m
- Present study, Post-Panamax (beam 40 m): GM range from 2.0 to 6.0 m
- Previous study (32558): Panamax (beam 32.3 m): GM range from 1.0 to 4.5 m
- Previous study: Feeders (beam 27 m): GM range from 1.0 to 2.5 m.

According to the MSC ZOE accident investigation report[10], the MSC ZOE sailed with an operational GM of about 9.01 m, which was considered to be a very high GM. The GM limit of 10 m is therefore taken.

The CSS code[11] provides an acceleration correction table depending on the B/GM factor (Annex 13). The value range is B/GM=7 to B/GM=13. This amounts for B=40 m to a GM range of 3.1 m to 5.7 m; hence the selected Post-Panamax GM range 2.0 to 6.0 m. For the ULCS this would amounts to a GM range of 4.5 m to 8.4 m, and for the Panamax to a range of 2.5 m to 4.6 m. The above is combined with the MARIN project experience.

The other parameter that effects the natural roll motion period is the roll radius of gyration (k_{xx}). A typical value for the Kxx is 0.37B, where B is the ship beam. The findings in the TopTier JIP showed an average value of about 37% of the beam, with a variation of about +/- 4%. A typical value used in class regulations is 0.35B. In all calculations the Kxx ratio is kept the same, as the GM change is already large and in-house calculations done in an other research project (on containerships) showed that the effect of varying Kxx under given GM condition has minor influence on the overall response.

3.4 Metocean prediction accuracy study (DELTARES)

3.4.1 Introduction

A metocean study performed by DELTARES, reported in 11207734-002-HYE-0001, evaluates the accuracy of the significant wave height in the nowcast and forecast by comparing SWAN calculations/predictions with hind-cast data from several points along the TSS. The nowcast is the predicted significant wave height calculated on the actual recorded wind field. The forecast (+3 hours, + 6 hours) is the calculated significant wave height based on the forecasted wind field at that time.

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10 Internationale toedrachtsrapport MSC ZOE, “Loss of containers overboard from MSC ZOE”, June 2020, www.onderzoeksraad.nl

11 CSS-Code of safe practise for cargo stowage and securing, Res. A.714(17), MSC/Circ. 1026, IMO

3.4.2 Summary of the study

The conclusions from the study are:

- The predicted nowcast and forecast significant wave heights are biased low, 12% underestimation with respect to the observations.
- A mean absolute error of -0.37 m with standard deviation of 0.32 m is found for the predicted significant wave heights between Hs = 2.5 m and Hs = 5.0 m.
- In order to correct the significant wave height forecast by the SWAN model, it is proposed by DELTARES to use the sum of the model bias plus half a standard deviation of the model, leading to a significant wave height correction by +0.53 m. Thus, when the SWAN model predicts a Hs of 4.0 m, it is safe to consider that the Hs value could be 4.5 m.
- The above accuracy of the model was found to be independent of the location of analysis along the sailing route, and can thus be applied on both the southern and northern sailing route.

The accuracy study was limited to Hs values between 2.5 and 5.0 m since the present route advice threshold value is an Hs of 4.5 m for the Panamax and ULCS vessels and an Hs of 3.3 m for the Feeders.

Figure 3.2 from the DELTARES report is given in Figure 3-2 in this report. It shows the bias in the significant wave height as function of the measured significant wave height. The scatter points are clustered around -0.5 m for waves above Hs of 4.0 m. There are not that many severe storms in the time trace used so that the scatter is large. However, the trend is clear; the SWAN model in-use tends to under predict the measured significant wave height by a small amount. The bias of -0.37 m is mainly caused by the many waves below 3.0 m. This ‘coloured cloud’ of more occurring wave heights has a kind of constant bias between 2.5 and 3.5 m, so it is expected that the bias can be taken the same for all Hs values.

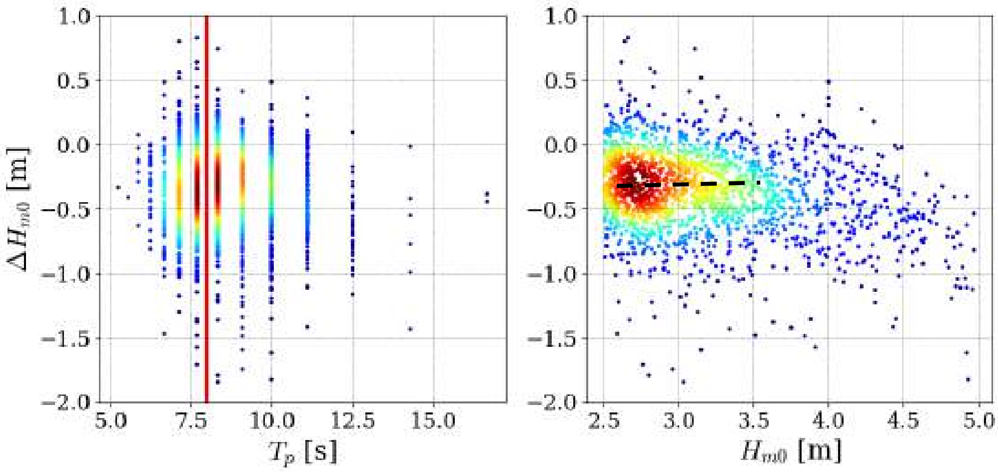

Figure 3-2: Scatter density plot of the wave peak period (left) and significant wave height (right). Data is taken from four locations during the period Oct 2020 and Jan 2022.

3.5 Conclusions

3.5.1 Metocean accuracy

The consequence of the derived accuracy of the metocean conditions, in particular the accuracy of the forecasted significant wave height need to be addressed in relation to the accuracy in the seakeeping analysis. This is discussed in other sections of this report.

3.5.2 Selection of containership and GM loading condition

Overall dimension of container ship

Based on the TSS network analysis the containerships selected for the present seakeeping analysis are listed in Table 3-5. The ships used in the previous study are listed in Table 3-2.

Table 3-5: Main properties of the two containerships in the present numerical study.

Ship type	Length (m)	Beam (m)	Typical Draught (m)	95%-Draught (m)	B / T ratio (-)
POST-PANAMAX	278	40.00	12.20	13.80	2.90
ULCS	395	59.08	12.40	14.50	4.07

GM loading conditions

Based on the investigations presented in Section 3.3, the following GM loading condition range is used:

- Post-Panamax vessel: GM between 2.0 m and 6.0 m
- ULCS vessel: GM between 4.0 m and 10.0 m

4 NUMERICAL SEAKEEPING ASSESSMENT IN SHALLOW WATER

4.1 SEACAL seakeeping calculations

4.1.1 3D seakeeping panel code

The numerical calculations were performed with MARIN's SEACAL program. SEACAL is a 3D potential flow seakeeping panel code developed in-house over the last 3 years. It is a so-called linear frequency domain seakeeping code. It is basically a merge of the long existing PRECAL code, with an approximate forward speed modelling, and the FATIMA seakeeping tool that solves the exact forward speed problem. Recently, SEACAL was extended with an advanced roll damping module for the prediction of bilge keel roll damping. SEACAL includes the first-order shallow water conditions, similar as available in the PRECAL and FATIMA.

Numerical calculations in project 32558 were performed with a combination of PRECAL and FATIMA and a roll damping value obtained from the model tests. The post-processing steps were rather complex at the time, and do not allow for generalisation to ship conditions for which no model tests have been done; as needed in the present project. In the present project the bilge keel roll damping from SEACAL is used without further calibration. This is based on an extensive in-house validation that included the Panamax and ULCS containership as model tested in project 32558.

The motion equations are solved in the (linear) frequency domain. The non-linear roll damping in waves is replaced by an equivalent linear roll damping, which leads to a series of response operators (RAOs) for various roll damping levels. In the post-processing phase, the equivalent linearised roll damping in the sea state is calculated and matched to the roll damping from the pre-calculated RAOs so that the applicable RAOs valid for that particular sea state can be selected.

All post-processing is based on the so-called Rayleigh probability distribution in which the positive and negative motion extremes are identical. The motion extremes are directly related to the motion response RMS value obtained in the wave spectrum. This is further detailed in Section 4.4.2.

The MARIN in-house SEACAL code version includes the modelling of first-order shallow water conditions code used in project 32558.

The SEACAL output is a set of response functions (RAOs) that allow calculation of the ship motions in any irregular sea state, including under keel clearance and point accelerations.

Appendix I presents a comparison between the present and past seakeeping analysis for the ULCS at 9.0 m GM in 21.3 m water depth. The results agree well for global ship motions, derived accelerations and dynamic under keel clearance.

4.1.2 Calculation reference system

The ship motions are always defined with respect to the centre of gravity (CoG) of the ship. The CoG location is specified with respect to the ship origin (0,0,0) that is specified at APP, Centreline, Keel, denoted as ACK reference point. The APP location usually aligns with the rudder stock location. The 6-degree-of-freedom (6-DOF) ship motion components are specified in Figure 4-1.

The x-location of the centre of gravity is equal to the x-location of the buoyancy point so that there is no trim. All calculations are done with even keel condition. The z-location of the centre of gravity above keel is the KG height. The ship stability parameter GM value follows from the ship stability KM value minus KG. The natural roll period in water follows from the GM the ship loading condition parameters. The so-called dry natural period can be calculated when the mass distribution is known. The natural period in water is obtained when the so-called roll added mass is accounted for which follows from the ship motion calculations.

The wave heading follows the usual seakeeping convention, see Figure 4-2: head seas are defined as waves from 180 deg, following waves come from 0 deg, wave from starboard are denoted as beam seas from 90 deg, wave from portside are denoted as waves from 270 deg heading. The ship motion calculations are done for every 7.5 deg wave direction variation between 0 and 360 deg. The ship is assumed symmetrical so that the response in beam seas from 90 and 270 will be identical. All headings are included in the calculation database because the calculations will be done in short-crested sea states; thus in the mean head seas condition the wave headings +/- 180 deg are used based on the wave spreading function.

The compass ship heading on the route is not an input to the calculations. All analyses results refer, when relevant, to the wave heading convention as specified above.

Accelerations or under keel clearance are calculated with reference to a ship-fixed position (X,Y,Z) defined w.r.t. the origin as described above, if not mentioned otherwise.

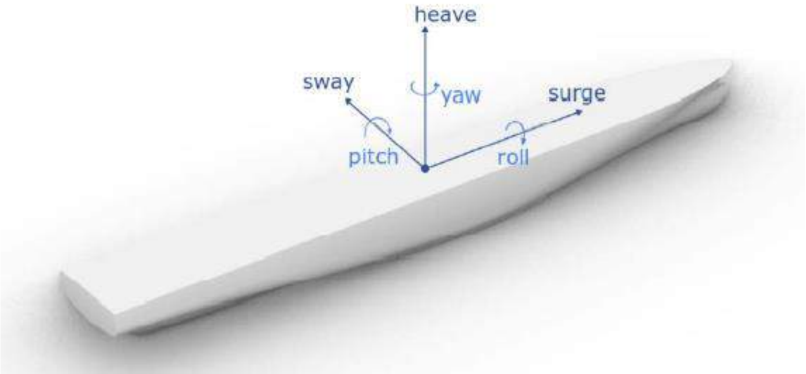

Figure 4-1: Ship motion definition with reference axis positioned in CoG.

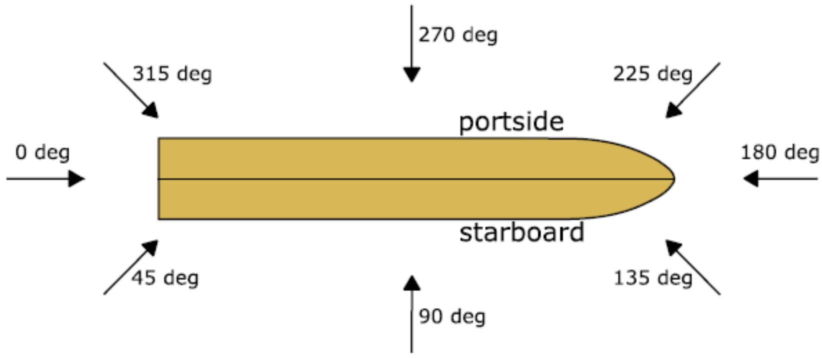

Figure 4-2: Wave heading convention.

4.1.3 Frequency domain post-processing

The ship 6-DOF motion response operators (RAOs) are calculated at the ship CoG. Rigid body motions are assumed so that the motions, velocities and accelerations can be calculated at any point on the ship by linear combination of the 6-DOF RAOs.

The post-processing is carried out using MARIN's OpCal software which calculates the response at the required locations in the prescribed short-crested sea states. Python scripts are used for further post-processing to a most probable maximum in the sea state, to generate the screening over all conditions via pivot tables and to generate the output tables.

4.2 Assessment of ship motions in shallow water

4.2.1 Measured wave and ship motion statistics (MPM)

Wind driven waves are created by the energy transmission between the wind field and the water. It takes time before there is a balance between the wind dissipation and the wave energy spectrum. During the build up of the wave spectrum the wave period gets longer. Short waves are first generated before longer waves. When the wind decays, the reverse is observed: long waves decay first and then the shorter waves.

The wind energy at the free surface leads to water velocities that mitigate downwards leading to so-called orbital wave velocities in the water column. The water velocities decay exponentially and at sufficient water depth below the free surface the water velocities become zero.

In shallow water conditions, the waves will start "to feel" the seabed and the water velocities at the free surface are affected, hence the free surface wave shape changes. As a result, the wave troughs will be less deep and the wave crests will be steeper and higher than in deep water for the same statistical wave properties (Hs – Tp).

The wave shape in deep water is sinusoidal and linear wave theory is applicable. The shallow water waves are nonlinear, and the nonlinear effects increase with decreasing water depth. Figure 4-3 shows a schematic drawing of deep and shallow water waves.

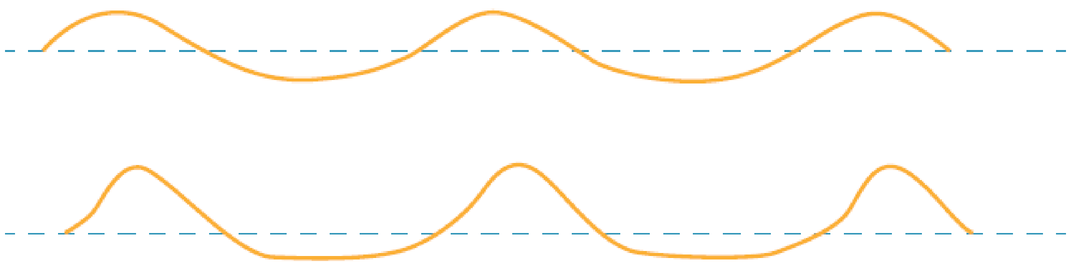

Figure 4-3: Deep water wave profile (above) versus shallow water wave profile (below).

There is a lot of attention in literature on the prediction of the height of the wave crests in shallow water conditions since this is important in the design of e.g. the airgap of platforms at sea. The nonlinearity of the shallow water waves is a function of the water depth, wave period and the wave height. And given these parameters, the wave crest distribution can be calculated from the Forristall (2000)[12] distribution. For the wave trough distribution the conclusion from Forristall (2000) can be used which states that the wave height (trough to crest) remains Rayleigh distributed. The MPM of the wave height can be calculated from the RMS of the wave spectrum, which relates directly to the significant wave height.

12 Forristall, G. (2000): Wave Crest Distributions: Observations and Second-Order Theory, Journal of Physical Oceanography 30(8): 1931-1943, August 2000

The nonlinear wave physics, the second or even higher order wave corrections, cannot be accounted for in the statistical post-processing of the linear frequency domain seakeeping results, which are all based on linear first order statistics, that is the Rayleigh distribution.

The effect of shallow water on the wave statistics and ship motion statistics are summarised in Table 4-1 and Table 4-2. These are important tables as they reveal the difference between the Rayleigh statistics and measured statistics.

In Table 4-1 the wave statistics are shown from the incident wave field. The measured through extremes are compared to the predicted trough extreme and it is observed that the troughs are 22% to 30% deeper in the calculations than measured and the measured wave crests are higher than predicted. All is according expectation.

Table 4-1: Wave statistics from 3 hour model tests, wave calibration phase, Project 32558.

21.3 m water depth	**Measured** WAVE extremes		**Calculated** WAVE properties	
Sea state	Max crest (m)	Max trough (m)	Min/Max MPM (m)	through error %
Hs = 6.5 m, Tp = 14.5 s, Tz = 10.8 s	8.9	-4.8	6.0	+25%
Hs = 6.5 m, Tp = 12.4 s, Tz = 9.3 s	7.8	-4.7	6.1	+30%
Hs = 5.2 m, Tp = 11.9 s, Tz = 8.9 s	6.0	-4.0	4.9	+22%

In Table 4-2 the motion statistics are given in RMS and measured MPM values, both for the positive and negative extremes. Positive heave is upwards, negative heave is downwards, positive roll amplitude is roll to starboards, negative roll is towards portside which is the windward side. The waves come from 270 deg heading.

The table lists the calculated MPM based on the measured RMS. If the numerical would predict the RMS as measured, the calculated MPM is the one used in the seakeeping analysis. The calculated MPM values are then compared to the measured extremes. The motion distributions reported in 32558 do not show outliers in the statistics at low probability, so that the measured extreme is a good measure for the MPM.

The comparison shows that *if* the heave RMS is well predicted, the heave troughs are predicted too low by about 21% to 34%. For the test in Hs of 5.2 m this difference amounts to +0.76 m, which is a very significant amount considering the under keel clearance. The shallow water effect is very pronounced visible in the heave prediction.

The comparison of the predicted and measured roll motion extremes shows a different trend. Based on the measured roll RMS, the roll MPM towards the approaching waves is typically over predicted, but only by a relatively small amount. The predicted MPM is in 3 out of 4 cases within 6% of the measured extreme. The roll MPM away from the waves shows on average a difference above 13%.

So, the effect of the wave non-linearity due to shallow water on the basic ship motions vary. The roll motions are most affected by the wave slope near the zero mean water level, and the effect of the wave nonlinearity is found to be smaller. The heave motions show a strong asymmetry, and the troughs are much less deep compared to the height of the crests.
The observed difference is significant for the prediction of the under keel clearance (+0.76 m in Hs of 5.2 m in the given example). The motion accelerations will be dominated by roll amplitude and static gravity angle, so the motion accelerations will not be much affected by shallow water wave nonlinearity.

Table 4-2: Motion statistics in 3 hour wave tests, ULCS at zero speed, 21.3 m water depth.

	Measured response		**Calculated MPM**	
Heading 270 deg	Heave motion	Roll motion	Heave motion	Roll motion
Sea state	RMS (m)	RMS (deg)	MPM (m)	MPM (deg)
Hs = 6.5 m, Tp = 14.5 s	1.58 / 1.57	4.65 / 4.73	5.94 / 5.90	17.48 / 17.78
Hs = 6.5 m, Tp = 12.4 s	1.32	3.29	4.96	12.37
Hs = 5.2 m, Tp = 11.9 s	1.00	2.23	3.76	8.38

	Measured		Difference % **calculated** MPM vs measured maximum	
	Heave motion extremes			
Sea state	Pos. Amax (m)	Neg. Amax (m)	Pos. Amax	Neg. Amax
Hs = 6.5 m, Tp = 14.5 s	5.8 / 5.7	-4.9 / -4.6	+2% / +4%	+21% / +28%
Hs = 6.5 m, Tp = 12.4 s	4.6	-3.7	+8%	+34%
Hs = 5.2 m, Tp = 11.9 s	3.7	-3.0	+2%	+25%

	Measured		Difference % **calculated** MPM vs measured maximum	
	Roll motion extremes			
Sea state	Pos. Amax (deg)	Neg. Amax (deg)	Pos. Amax (deg)	Neg. Amax (deg)
Hs = 6.5 m, Tp = 14.5 s	15.7 / 15.2	-17.2 / -11.7	+13% / +15%	+3% / +16%
Hs = 6.5 m, Tp = 12.4 s	10.4	-11.7	+19%	+6%
Hs = 5.2 m, Tp = 11.9 s	8.3	-8.6	+1%	-3%

4.2.2 Nonlinear shallow wave theory

Using the second-order wave crest distribution as given by Forristall (2000) and the fact that the wave height distribution remains Rayleigh distributed, the nonlinearity in the wave statistics can be assessed numerically. The Forristall equations for short-crested sea states is used.

Such investigations were reported in 32558-3-SEA for a water depth of 21.3 m and higher. In this section the investigations are extended to 19 m water depth, as this is the minimum LAT water depth on the eastbound southern TSS.

The results ae summarised in Table 4-3 for 21 m and 19 m water depth for a series of significant wave heights and an associated typical (most probable) wave period. An example distribution is given in Figure 4-4. The results point to about 15% to 38% reduction of the trough maximum due to shallow water conditions, depending on the wave conditions. This agrees rather well with the measurements in the model basin. At lower wave heights the reduction is less because the wave lengths are shorter since the peak period was reduced.

It can be concluded that the second-order wave theory provides a fair insight in the how the wave statistics change on shallow water.

Table 4-3: Trough reduction factors based on Forristall second-order wave theory for shallow water.

Trough reduction factor w.r.t. Rayleigh prediction						
Sea state	Hs = 2.0 m Tp = 7.0 s	Hs = 3.0 m Tp = 8.0 s	Hs = 4.0 m Tp = 9.0 s	Hs = 5.0 m Tp = 10.0 s	Hs = 6.0 m Tp = 11.0 s	Hs = 6.5 m Tp = 14.5 s
LAT 21 m	0.86	0.83	0.79	0.73	0.71	0.69
LAT 19 m	0.86	0.82	0.76	0.69	0.62	0.74

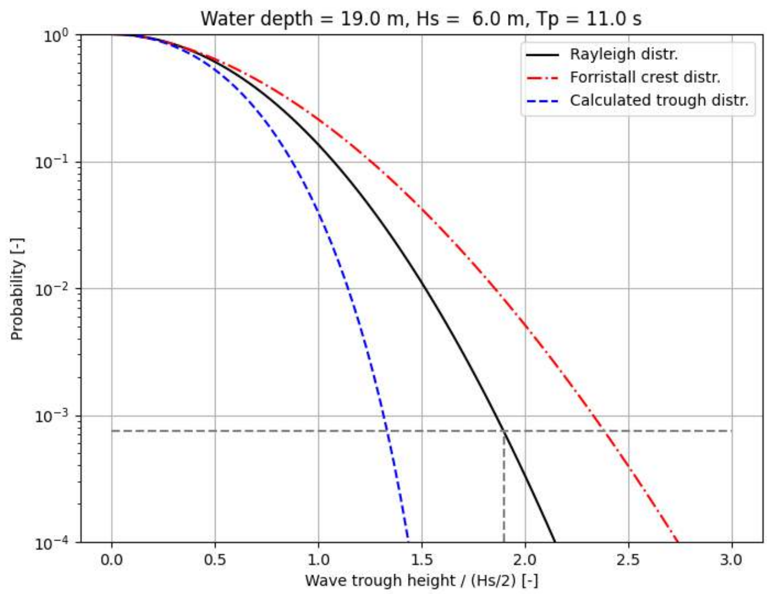

Figure 4-4: Rayleigh distribution, Forristall theoretical crest distribution, and derived trough distribution for shallow water short-crested sea state. Horizontal crossing line is the3 hours MPM probability.

4.2.3 SEACAL validation for the Panamax and ULCS

The model tests performed in project 32558 were used to validate the ship motion prediction by SEACAL in shallow water conditions. The roll damping is calculated by the CRS-RR2 method which is an advanced bilge keel roll damping prediction method based on the well-known IKEDA bilge keel roll damping model, improved on some fundamental aspects. The IKEDA method is published about 50 years ago, the new CRS-RR2 is recently developed at MARIN and findings are not yet published.

The results are shown without any further calibration on the roll damping.

The validation for the Panamax vessel, sailing at 10 knots, is shown in Table 4-4. In general, there is a good agreement in the heave and pitch RMS. The scatter in the roll motion RMS is larger, which is probable strongly effected by the limited test duration of only 30 minutes. Statistics are not fully converged, especially for roll where non-linear bilge keel damping is present. The correlation seen in shallow water of 21.3 m typically points to an over predicted roll response by about 15% on average. This is very often seen in roll damping validation studies.

The validation for the ULCS vessel, at zero speed, is shown in Table 4-5. The zero speed tests had a duration of 3 hours, and the model test statistics should have converged. There is a good agreement in the heave motion. The pitch motions are under predicted but the values are small in beam seas and pitch is not relevant in this case. The roll motions are under predicted in two lower sea states and over predicted by 13% in the higher sea state.

The shallow water case is (rather) difficult and challenging due to the fact that all wave non-linear effects are present in the model tests, but not in SEACAL apart from the first-order shallow water effects (the wave remain sinusoidal, which they are not anymore in shallow water, but the wave length is correct in SEACAL shallow water, as well as the orbital water velocities and thus the first-order wave loading). The motion extremes from the model tests, shown in Table 4-6, clearly show the lower heave amplitudes towards the seabed while the roll motions are more symmetrical in roll towards SB and PS.

The validation shows as well scatter results between the sea states; SEACAL sometimes under predicted the motions, and sometimes over predict the motions. Concerning a possible roll damping tuning to better match the model tests: this will be impossible with a single calibration factor on the bilge keel roll damping that either increases or decreases the roll damping.

Overall, it is concluded that the SEACAL motions capture the model test results rather well. The heave RMS values are typically predicted within 5% of the measured heave. The same is expected for the pitch RMS (when pitch motions are relevant). The roll motion RMS is typically predicted about 15% biased high. Larger and smaller differences are found and addressed to e.g. uncertainty in the statistics of the model tests due to limited test duration. The 15% is seen in other in-house validation studies.

Note that the validation is performed on the RMS value and not the MPM values from the model tests, which are clearly asymmetric due to shallow water nonlinear effects. Thus, even a good RMS correlation will not necessary lead to a good MPM correlation, in particular for heave. Overall, the heave troughs will be predicted to deep by SEACAL. This is further addressed in a section on the under keel clearance.

Table 4-4: SEACAL results against Model test experiments, Panamax vessel, 10 knots.

PANAMAX, B/T = 2.65, GM=2.50 m, Tphi=16.8 s	**HEAVE RMS (m)**			**Roll RMS (deg)**			**PITCH RMS (deg)**		
Conditions (short-crested, 2s, s=12)	Experiment	SEACAL	Difference in %	Experiment	SEACAL	Difference in %	Experiment	SEACAL	Difference in %
GM=2.5m, WTD=21.3m, V = 10 knots									
Hs=5.4 m, Tp=10.5 s, gamma=2.0, Heading=240 deg	0.69	0.73	6%	1.30	0.99	-24%	0.55	0.53	-3%
Hs=5.4 m, Tp=12.6 s, gamma=1.0, Heading=300 deg	0.68	0.71	5%	3.57	4.64	30%	0.53	0.54	3%
Hs=6.5 m, Tp=13.2 s, gamma=1.0, Heading=300 deg	0.87	0.89	2%	5.25	5.74	9%	0.72	0.67	-7%
Hs=7.7 m, Tp=13.7 s, gamma=1.0, Heading=270 deg	1.52	1.51	0%	5.33	6.11	15%	0.75	0.87	15%
GM=2.5m, WTD=37.5m, V = 10 knots									
Hs=5.4 m, Tp=10.5 s, gamma=2.0, Heading=240 deg	0.78	0.83	6%	1.15	0.94	-18%	0.59	0.60	2%
Hs=5.4 m, Tp=12.6 s, gamma=1.0, Heading=300 deg	0.61	0.76	25%	2.48	4.98	101%	0.51	0.56	9%
Hs=6.5 m, Tp=13.2 s, gamma=1.0, Heading=300 deg	0.79	0.94	20%	3.52	6.33	80%	0.64	0.68	7%
Hs=6.5 m, Tp=13.2 s, gamma=1.0, Heading=270 deg	1.30	1.30	0%	4.48	5.74	28%	0.65	0.72	10%

Table 4-5: SEACAL results against Model test experiments, ULCS vessel, 0 knots.

ULCS, Tm=12.5 m, GM=9.25 m, Tphi=17.1 s	**HEAVE RMS (m)**			**Roll RMS (deg)**			**PITCH RMS (deg)**		
Conditions (short-crested, 2s, s=12)	Experiment	SEACAL	Difference in %	Experiment	SEACAL	Difference in %	Experiment	SEACAL	Difference in %
WTD=21.3m, V = 0 knots									
Hs=5.21 m, Tp=11.92 s, gamma=1.5, Heading=270 deg	1.00	0.98	-2%	2.22	2.10	-5%	0.17	0.05	-71%
Hs=6.71 m, Tp=12.2 s, gamma=1.5, Heading=270 deg	1.32	1.30	-1%	3.29	2.93	-11%	0.28	0.06	-77%
Hs=6.90 m, Tp=14.53 s, gamma=1.5, Heading=270 deg	1.58	1.61	2%	4.65	5.26	13%	0.30	0.06	-80%

Table 4-6: Measured motion extreme values from the Model test experiments, ULCS vessel, 0 knots.

ULCS, Tm=12.5 m, GM=9.25 m, Tphi=17.1 s	**HEAVE MPM (m)**		**ROLL MPM (deg)**		**PITCH MPM (deg)**	
Conditions (short-crested, 2s, s=12)	Pos Amax	Neg Amax	Pos Amax	Neg Amax	Pos Amax	Neg Amax
WTD=21.3m, V = 0 knots						
Hs=5.21 m, Tp=11.92 s, gamma=1.5, Heading=270 deg	3.67	-3.02	8.25	-8.56	0.76	-0.65
Hs=6.71 m, Tp=12.2 s, gamma=1.5, Heading=270 deg	4.64	-3.72	10.14	-11.71	1.16	-1.06
Hs=6.90 m, Tp=14.53 s, gamma=1.5, Heading=270 deg	5.76	-4.48	15.72	-17.21	1.24	-1.06

4.2.4 Comparison between SEACAL and PRECAL-FATIMA results

A comparison between the SEACAL results and the PRECAL-FATIMA results from the previous study is shown in Appendix I for the case of the ULCS at 9.25 m GM at 21.3 m water depth.

In the appendix the results are discussed.

The overall conclusion is that the accelerations are within 5% between the two data sets, and that the under keel clearance is within 3%. This supports the use of both approaches in the seakeeping assessment.

4.2.5 Calculation procedure for the dynamic under keel clearance

Based on the above discussions and findings the following is concluded on the accuracy of the calculations and defined limits:

- The vertical motions of the ship is the combined effect of roll, heave and pitch. The largest vertical motions in beam waves occur on the windward side of the ship (due to the phase relationship between roll and heave).
- The squat due to forward speed of the containership has no noticeable effect on the draught around midship. In beam seas rolling condition the critical points are around midship and it is thus not necessary to account for squat.
- The seakeeping calculations are conservative in the prediction of the roll motions, typically up to 15% based on the performed validation with containerships. This implies that a lower under keel clearance is predicted; typically around 0.5 m. Due to the roll uncertainty, this conservatism in the calculations is not corrected for.
    - ULCS example, beam 59 m: If the roll angle is 15% too larger, and the vessel rolls 15 deg, the vertical induced motion at the side is predicted 8.7 m (17.25 deg roll) instead of 7.6 m. The difference is +1.1 m.
    - Post-Panamax example, beam 40 m: If the roll angle is 15% too larger, and the vessel rolls 15 deg, the vertical induced motion at the side is predicted 3.0 m (17.25 deg roll) instead of 2.6 m. The difference is +0.4 m.
- The shallow water second order wave kinematics lead to an over prediction of the heave motions downward by about 22% to 38%. It is observed in all model tests. The heave motion contribution in the dynamic under keel clearance will be corrected by 20%, leading to a correction in the order of 0.5 m.

An example calculation is shown in XX for the ULCS sailing at 21 m water depth. The figure shows the dynamic under keel clearance calculated following linear wave theory with the heave motion corrected for non-linear shallow water effects. In the given example for GM 9.0 m the non-linear correction leads to a raise of the limiting significant wave height by 0.46 m.

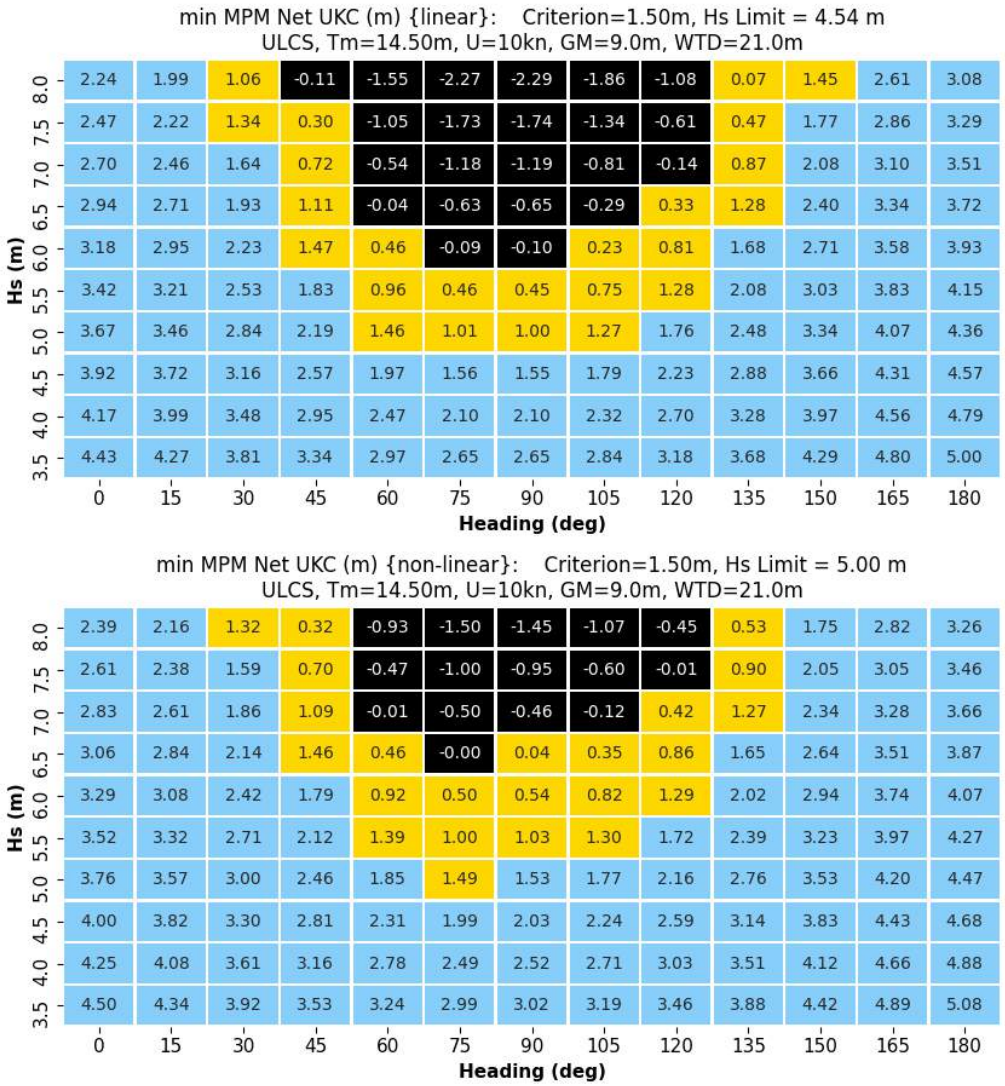

Figure 4-5: Dynamic UKC calculations for the ULCS without (top) and with (bottom) a correction for the shallow water kinematics in heave motion response.

4.3 Points of interest for seakeeping criteria evaluation

4.3.1 Summary

This section summarises the calculation matrix used for each container ship. The background and motivation is provided in following sub-sections.

The transverse acceleration on the containers was calculated at 12 reference points:

- First and last bay on the ship, and a mid-ship bay location,
- Most extreme row numbers on port and starboard[13],
- Highest tier position on deck and first (lowest) tier position on deck.

The dynamic under keel clearance (UKC) is calculated at 18 reference points:

- At ship centreline at APP (rudder stock) and FPP (bow),
- At 4 points on hull stations at PS and 4 points on SB, station 8/9 and 11/12 near ship bilge and keel plane.

[13] The exact location for the transverse location, at vessel side or half a container width inboard, has no noticeable effect.

4.3.2 Container point accelerations

The container location on board is given in a bay-row-tier reference system. See Figure 4-6.

The bay location is the longitudinal x-location, bays are numbered from the forward end of the ship to the aft. Even numbers refer to 40' containers, odd numbers to 20' containers.

The row location is the transverse y-location in the bay, the numbering is 02, 04, etc… from centreline to port side and 01, 03 etc… from centreline to starboard side. When the number of rows is odd, the middle container is given row 00 label.

The tier location is the vertical z-location of the container in the bay and row. The first container tier on cargo hold deck is usual given number 82, the second tier is 84, and so on. Tier 80 is usually the first tier above deck in the transom stern area where there are no containers below deck. The cargo hold coaming is usually 1 container high. The 6th tier above the hold is thus tier 92. Given the container height of 2.60 m the 6th tier has a location 6 x 2.60 m = 15.6 above the first container tier.

The centre of gravity of the container depends on the cargo inside. A (class-defined) default value of 0.45 times the height is used; thus 1.17 m above base.

For example, for the Panamax container ship the z bottom of stack height above keel is defined at 23.90 m (above keel). This implies that the CoG of Tier 82 is at 25.07 m above keel, and the CoG of Tier 92 (container 6 above deck) is at 40.67 m above keel.

The container locations used in this report, that is reference points for acceleration calculations, is translated into (X,Y,Z) coordinates w.r.t. the ACK reference. The calculated transverse accelerations are evaluated against the allowable transverse accelerations (acy).

The transverse accelerations are in the class rules the most critical around the mid-ship location. Near the ship stern and bow class allows slightly higher accelerations by about 3% to 6%. This is demonstrated in Section 4.4.3. In the seakeeping analysis 12 acceleration positions will be used:

- First and last bay on the ship, and mid-ship bay location
- Most extreme row numbers on port and starboard side (largest y-values)
- Highest tier position on deck and first (lowest) tier position on deck

The points are taken in the assumed CoG of the containers at 0.45H (1.17 m) from container bottom.

Further background information on the location for accelerations is provided in Section 4.4.3.

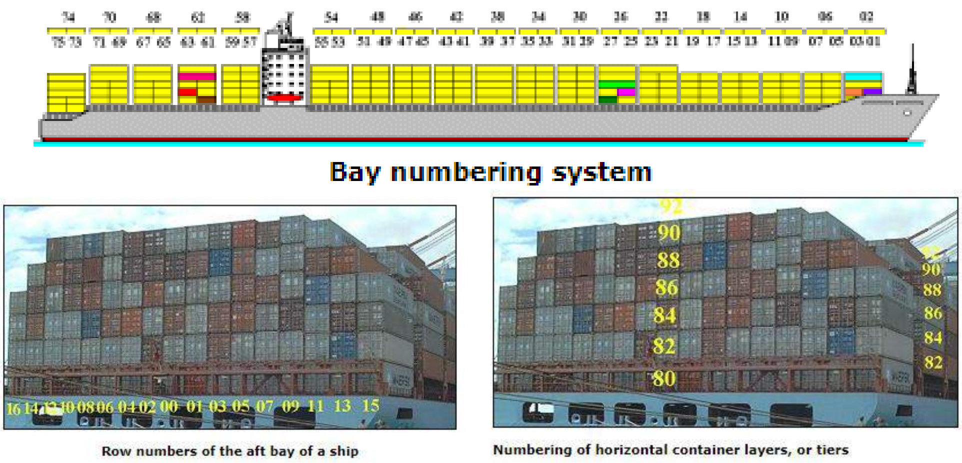

Figure 4-6: Container stowage reference system, bay-row-tier, from https://www.containerhandbuch.de/

4.3.3 Dynamic under keel clearance

The net under keel clearance or dynamic UKC is the lowest distance between the sea bottom and any part of the hull. The dynamic UKC is a time-varying quantity. The minimum value occurs when the combined effect of roll and heave is the largest.

The static UKC or gross UKC is the under keel clearance in calm water sailing conditions. This value needs to be corrected for the possible squat of the ship. Squat is the combined effect of hull sinkage and trim due to forward speed, and it changes the draught at the ship ends. Around mid-ship location the squat is very small, and the dynamic under keel clearance is often the lowest in beam seas sailing conditions around the bilge of the ship at mid-ship location. Hence the effect of squat is neglected in the present (and past) study.

Knowledge about dynamic effects in waves and the consequences for the UKC are generally not known on the bridge. The actual heave and roll motions are not known, and the inclinometer on the bridge is not a good indication for dynamic roll since it acts on the affective gravity angle, which is always larger than the real ship roll amplitude.

Figure 4-7 shows the rotated hull lines (aft and forward part are rotated mirrored). It shows that the 'touch down' point is somewhere in the bilge area and that the virtual point at 0.5B in the keel plane is significantly closer to the seabed.

Using a hydrostatic program the lowest hull point can be calculated for any heel and draught condition, under the condition of equal displacement. In Table 4-7 and overview is given for realistic heel angles. These results are independent of the real vessel draught (displacement). At realistic heel angles the bilge keel of 40 cm is not touching the ground; that will only occur for unrealistic large heel angles above 30 deg. Earlier research pointed to about 16 degrees maximum roll angles for the ULCS in very severe storm conditions (Hs of 6.5 m). The location of the lowest point changes with the heel angle, but it is typically a few meters inboard from half beam. Table 4-7 shows the location of touch-down points on the hull section.

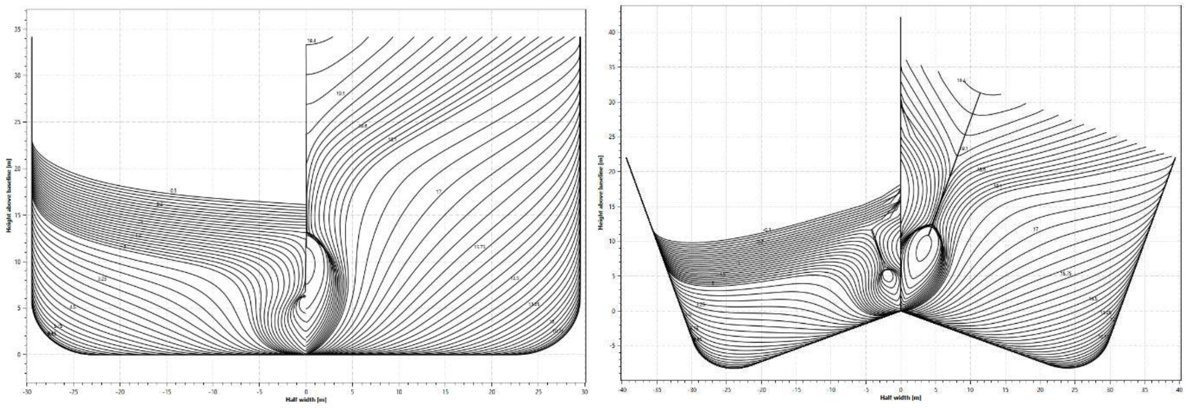

Figure 4-7: Hull lines of the ULCS, with zero heel and 20 deg heel (model split in aft and fwd part)

Table 4-7: Lowest hull point as function of heel.

ULCS, B = 59.0 m				
Heel (deg)	Hydrostatics max draft (m)	y=0.5B=29.5 m max Draft (m)	y at max draft (m)	z from keel (m) contact point
5	14.42	14.97	23.05	0.00
10	16.47	17.52	23.92	0.09
15	18.56	20.04	24.35	0.16
20	20.65	22.49	25.01	0.34

At larger heel angles, the difference between the UKC at real lowest hull point – the contact points are shown in Figure 4-8 - and the UKC calculated at half beam increases from 1 to 2 m. This difference cannot be neglected. Hence, four points on the hull around the keel plane (for the ULCS at 23, 24, 25 and 26 m transverse position) are utilised in the dynamic UKC calculations. Given the hull keel plane as shown in Figure 4-9, the points are taken slightly aft and forward of mid-ship station 10, that is at station 8 and 12, to account for a possible effect of pitch. In the previous study the conservative approach was followed and the UKC evaluation points were positioned in the virtual crossing point of keel plane and vessel beam.

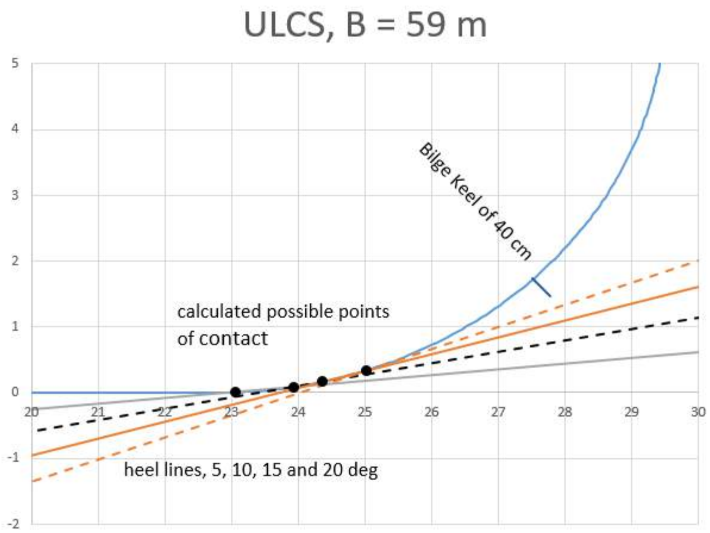

Figure 4-8: Calculated possible points of contact at heel angles from Table 4-7.

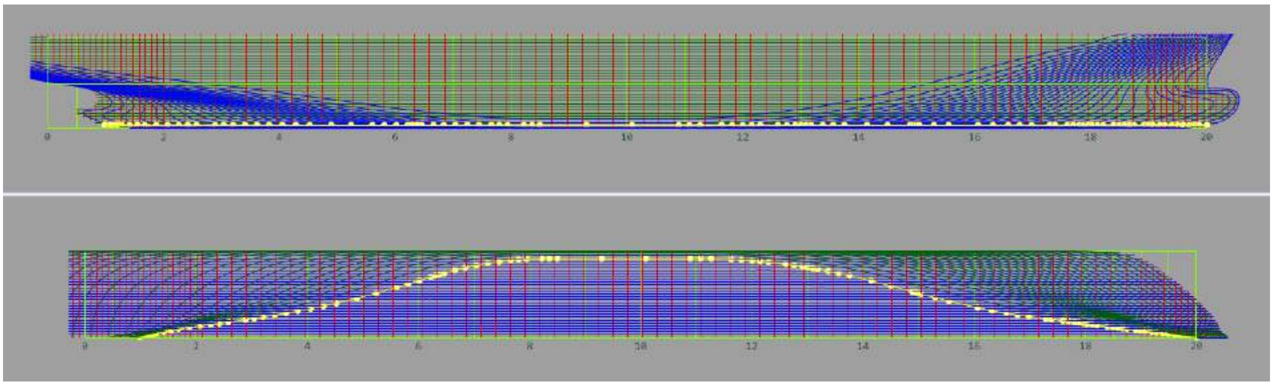

Figure 4-9: ULCS linesplan with in yellow the keel plane contour (WL = 0 m). Stations 8 and 12 are used for dynamic under keel clearance, next to the FPP and APP point at keel plane.

4.4 Seakeeping criteria

4.4.1 Summary

This section presents the summary of seakeeping criteria. Background information and motivation is presented in the following sub-sections.

The most-probable-maximum (MPM) of the motion parameters (acceleration, under keel clearance) are calculated based on a 3 hour exposure time. The same approach was used when deriving the preliminary limiting wave heights.

The maximum allowable accelerations on the containers is calculated by the StowLash program from DNV. The obtained acceleration level compare well to the data provided by class earlier. Using StowLash limiting values for any ship (loading) condition can be derived on any point of the container stacks. The acceleration levels at the most aft, mid-ship and most-forward bay will be evaluated, both at deck and the highest tier location.

4.4.2 Short term statistics

The ship motions in an irregular sea state, specified by significant wave height (Hs), peak period (Tp) and spectral shape (JONSWAP, gamma=1.5, short-crested), vary over time. This is called stochastic behaviour. The ship motion statistics follow the same 'rules' as the wave statistics (linear ship motion theory through linear response operators).

The sea states are known to be Gaussian-distributed and narrow banded, meaning that the energy of the waves is contained within a given frequency range. This energy range is prescribed by the JONSWAP wave spectral shape. For a Gaussian-distributed process, the probability of the maxima is be obtained from a Rayleigh distribution. A statistical analysis per sea state is usually denoted as a short-term approach, compared to the long-term statistics which account for all possible sea states the ship will encounter during its life time or during a specific period.

In the present study short-term statistics are used to determine the limiting sea state w.r.t. the seakeeping criteria that are expressed in a short-term statistical limiting value.

The ship motion extremes, and thus acceleration maxima or under keel clearance minima follow from the Rayleigh distribution in relation to the exposure time. The most probable maxima (MPM) is the extreme value with probability 1/N in the time duration, where N is the number of oscillations; that is the number of waves that pass by in the exposure time. If the exposure time is shortened the probability of the extreme increases, thus, in that case, there is a 'significant' probability that the MPM will be exceeded.

The maximum expected amplitude (E) of a signal is given by:

$$E(x_a) = \sqrt{m_0}\left[\sqrt{2\ln N} + \frac{0.5772}{\sqrt{2\ln N}}\right] = R_N\sqrt{m_0} \approx A_{m0}\sqrt{\ln N/2}$$

where *N* is the number of oscillations and $\sqrt{m_0} = \sigma_x$ equals the standard deviation (or rms) of the signal x, which is the square root of the area under the response spectrum. A_{m0} is the significant amplitude. The number of oscillations *N* can be approximated by dividing the exposure time by the zero crossing period of the response. The longer the exposure time, the higher the most probable maximum (the expected maximum).

Given an exposure time of e.g. 3 hours, the most probable maximum is expected to occur within this 3 hour time period, but *when* it occurs is unknown. In seakeeping analysis it is common to use a 3 hour exposure time because wave spectra are typically stationary for 3 hours.

When the exposure time is shorter, e.g. 20 min, the statistical RMS value has typically converged, but the extremes have not. The measured extreme in 20 min exposure time is most likely higher than the expected maximum based on *N* associated with 20 minutes. This is explained further in the reference paper of Ochi (1973)[14]. The reason is that expected maxima follow a distribution itself, and the probability that the maximum exceeds the expected maximum is rather high, 63%.

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[14] Ochi, M. K., 1973, On prediction of extreme values, Journal of Ship Research, Vol. 17, No. 1

An example of the Rayleigh factors of MPM over RMS for various exposure times is given in Table 4-8. The values do depend slightly on the zero crossing period, thus for other periods than 10 s, the values change. It is observed that the expected maximum in 1 hour exposure is about 8% lower compared to the 3 hour exposure time.

Table 4-8: Rayleigh factors w.r.t 3 hours exposure for different exposure times.

Exposure time (hrs)	1	2	3	6	10	30	100	300
N, Tz = 10 s	360	720	1080	2160	3600	10800	36000	108000
MPM/RMS, Tz= 10 s	3.60	3.79	3.89	4.07	4.19	4.44	4.71	4.93
factor w.r.t. 3 hrs	0.92	0.97	1.00	1.04	1.08	1.14	1.21	1.27

4.4.3 Class rules defined limiting accelerations

The DNV programs StowLash was used to calculate cargo limiting accelerations. Version 3.1.0.39360 was used. StowLash is available free of charge. Based on output files from StowLash it uses the (DnV) acceleration rules from 2013 (Pt. 5, Ch. 2, Sec. 8).

The input to StowLash are the ship dimensions, the ship stability GM value, the container stack location and the area of operation. For the latter the North Sea – Baltic Sea route is selected.

In project 32558 MARIN consulted four class societies to obtain the limiting accelerations. The obtained results from the four class societies – labelled Ref. A to Ref. D - for the Panamax ship in two loading conditions are shown in Table 4-9. The calculated StowLash value for a bay location near the bow of the ship is shown and found to be in good agreement with the by class provided values. The results show a small increase of the allowable acceleration with increasing speed. The minimum speed for which calculations could be done was 8 knots. The lowest speed gives the limiting criteria (worst case).

The stowage plan of the ship is such that all containers comply to the loads derived from the class limiting accelerations. This is an assumed maximum allowable acceleration. If the actual acceleration (during the ship voyage) is above the by class assumed allowable acceleration the structural loads will be higher and the construction *might* fail. Imbedded structural safety factors are not discussed here; hence the wording *might* fail in the previous sentence. The obtained acceleration level from class rules is thus an allowable acceleration criterion which should not be exceeded and this level is used in the derivation of the limiting wave height in the present (and previous 32558 project) study.

Given the acceleration level for the tier, the container weight and position on board, the structural loads acting on each container are calculated following the class rules under which the ship operates. A number of load components are calculated: racking forces, loads at bottom, corner post loads, lifting loads, forces as lashing element and forces at connecting elements. The stowage plan must be such that all containers on board comply to the rules and thus that the loads acting on the containers are below the allowable values. All containers on board are evaluated.

Using StowLash the acceleration limits are calculated for a number of container bay locations (x-location). The results for the Panamax vessel are shown in Table 4-10. The accelerations around mid-ship are found the lowest and these will be used for all ships when deriving limiting sea states. Near the ship bow and transom the allowable values are about 3% to 6% higher compared to the values calculated at mid-ship location. The acceleration level does not depend on the row location of the container (container y-location).

The effect of the loading condition on the accelerations at mid-ship is shown in Table 4-11. The GM value for the Panamax values is varied between 1.0 m and 4.5 m. This is the ‘possible’ GM range that was established for the Panamax vessel in project 32558 based on the spread of loading conditions in MARIN model tests / calculation studies. The stability of GM = 2.50 m in that project classed as ‘high limit’ value, the GM = 4.50 m is an extreme case. The GM = 1.0 m is a low stability value. The ship stowage plan requires GM as input value, but actual GM values for the fleet of container ships are not known, nor broadcasted with AIS. The limiting sea state height will depend on the GM, but the factor cannot be part of the advice itself. The acceleration levels shown in Table 4-11 are the most stringent for the lowest GM (GM = 1.0 m) and are almost a factor 2 higher (= less stringent) for the extreme GM case (GM = 4.5 m). The effect on the limiting wave height will be discussed in each ship type chapter since the ship response (and thus the acceleration) depends on the GM as well. For each GM condition the ship motions will be calculated for a various wave periods, and this needs to be combined with the allowable acceleration limits to obtain a limiting sea state. The result shown here is just illustrative.

The limiting accelerations are provided in each ship type section.

Table 4-9: Comparison of limiting accelerations from class and StowLash calculations by MARIN.

PANAMAX, GM = 2.50 m	Allowable acceleration (g)						
Location of container tier @ Hold 1, x=255 m from APP	Ref A	Ref B	Ref C	Ref D	StowLash, Vs = 8 kn	StowLash, Vs = 10 kn	StowLash, Vs = 15 kn
acy top-tier (Tier 94)	0.865	0.568	0.660	0.605	0.625	0.630	0.637
acy deck location (Tier 82)	0.723	0.451	0.510	0.481	0.520	0.524	0.533

PANAMAX, GM = 1.00 m	Allowable acceleration (g)						
Location of container tier @ Hold 1, x=255 m from APP	Ref A	Ref B	Ref C	Ref D	StowLash, Vs = 8 kn	StowLash, Vs = 10 kn	StowLash, Vs = 15 kn
acy top-tier (Tier 94)	0.646	0.391	0.459	0.494	0.445	0.448	0.457
acy deck location (Tier 82)	0.599	0.354	0.402	0.444	0.405	0.409	0.418

Table 4-10: Acceleration limits calculated as function of ship length.

PANAMAX, GM = 2.50 m	Allowable acceleration (g) @ Bay location (m) from APP						
StowLash, Vs = 8 kn	stern x = 15 m	x = 52	x = 96	mid-ship x = 139	x= 168	x = 197	bow x = 255
acy top-tier (Tier 94)	0.615	0.606	0.600	0.600	0.603	0.608	0.625
acy deck location (Tier 82)	0.508	0.498	0.491	0.491	0.494	0.500	0.520
acy top-tier (Tier 94)	103%	101%	100%	100%	101%	101%	104%
acy deck location (Tier 82)	103%	101%	100%	100%	101%	102%	106%

Table 4-11: Acceleration limits calculated as function of ship stability GM.

PANAMAX, L = 278 m, B = 32.30 m, Tm = 12.20 m, Vs = 8 kn								
Location of container tier @ mid-ship location	Allowable acceleration (g) for GM (m)							
	1.00	1.50	2.00	2.50	3.00	3.50	4.00	4.50
acy top-tier (Tier 94)	0.419	0.485	0.545	0.600	0.651	0.700	0.747	0.793
acy deck location (Tier 82)	0.377	0.422	0.459	0.491	0.519	0.545	0.570	0.594

4.4.4 Dynamic under keel clearance

The terminology from PIANC publication 121[15] (2014) is used. The TSS is not a harbour approach channel but the southern route has a water depth very similar to e.g. the Rotterdam port approach.

The under keel clearance in calm water is denoted as the gross under keel clearance (gross UKC). The minimum remaining under keel during sailing in waves is called the net UKC. In the present seakeeping calculation the term dynamic UKC is used to express the net UKC of the ship sailing in waves. The ship related factors mentioned in the PIANC that reduced the gross UKC to the net UKC are:

- Allowance for static draught uncertainties
- Change is water density (when entering “fresh water” harbour)
- Dynamic heel due to wind and turning
- Squat, including dynamic trim
- Wave response allowance.

Wave allowance

In vertical motions at a point of the ship are calculated from the global ship motions in waves. In PIANC this is called the wave response allowance.

Squat

In PIANC seven empirical formulations are presented to calculate the squat when sailing in shallow water conditions. Squat will increase the draught at the bow or stern, but the squat effect around mid-ship will be negligible; see Figure 4-10. The larges rolling occurs in beam seas and the dynamic under keel clearance is governed by the vertical motions of the ship around mid-ship, and not by severe pitching in head seas. Hence, squat will have a very limited effect, if at all, on the limiting significant wave height sailing in beam seas. Hence it is not included in the calculations.

Furthermore, as a general note, the PIANC guidelines mention that squat in open water is not so important and can be neglected when h/T > 1.5, where h is the water depth and T the ship draught. For the Post-Panamax with draught 13.80 m sailing at 21 m the ratio h/T is 1.52, for the ULCS with draught 14.50 m the ratio h/T is 1.45. At 19 m water depth the ratios are slightly lower.

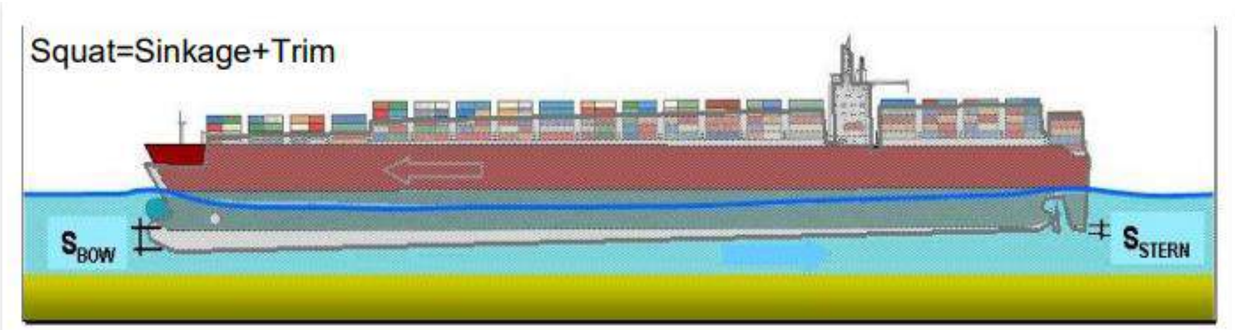


Figure 4-10: Squat effect on the local ship draught, picture taken from PIANC (2014).

Dynamic heel due to wind and turning

The dynamic heel due to wind is small. Even though the wind area of a containership is large, the wind loading will be relative small compared to the wave loads. In the PIANC guidelines an example calculation is made for a Post-Panamax ship with a low GM of 2.1 m leading to 0.5 deg list angle. For a higher GM’s, the list angle will be smaller. The ‘critical’ roll amplitudes for possible bottom contact of the ULCS are in the order of 16 degrees, so that the dynamic heel due to wind is neglected. Furthermore,

[15] PIANC 121, 2014, Design Guidelines for Harbour Approach Channels

the wind loading will be effected by the ship motions and the static approach in PIANC is questionable is a severe dynamic environment. Clearly, high waves come together with high winds.

Dynamic under keel clearance

The dynamic under keel clearance equals the water depth minus the ship draught minus the vertical ship motion amplitude (trough). Zero dynamic UKC means bottom impact. The dynamic UKC can become negative in the calculations since the seabed is a virtual boundary in the seakeeping analysis. When the ship approaches the seabed the water column below the ship get pushed away and water needs to be accelerated ‘outwards’. This stiffness the ship response and it referred to as a cushioning effect. This is a highly non-linear effect and it cannot be quantified.

Probability for bottom contact

When the preliminary limiting wave heights were derived (MARIN report 32558), the minimum dynamic under keel clearance was set to +2 m, based on (experienced captain) expert judging. The +2 m is the safety margin on bottom contact. If this approach is used for all ships at any draught and water depth (e.g. 21 m LAT and 19 m LAT) an unbalanced risk level is obtained. The probability of reaching 2 m from the seabed is much lower for a low draught vessel than for a deep draught vessel.

To obtain the probability of bottom contact, a Rayleigh curve is drawn through this +2 m reference plane, under the condition of 12.4 m draught and 21.3 m (21.0 m) water depth. The result is shown in Figure 4-11 and shows that the probability of bottom contact is 1 in 300 hours. This can be seen as a safety factor of 100 on bottom contact, or a probability of 1% that the sea bottom is reached within a 3 hour exposure time. This risk is in line with e.g. probabilistic criteria for harbour entrance (see PIANC).

The most critical eastbound TSS has a minimum LAT water depth of 19 m which extends for 4 nm. The lane water depth is below 21 m for 9 miles, and deeper for the remaining part. Sailing at 10 knots forward speed, the 19 m LAT part is sailed in about 0.5 hours. A 1% risk factor leads to a (probable) single bottom contact at 50 hours exposure time.

Note that the predictions of the ship motions are based on statistical assumed Rayleigh distributions. In reality a so-called ‘cushion’ effect can occur when the ship is very near the bottom due to fluid accelerations as the ship pushes the water away underneath the ship hull, but the importance of the effect cannot be quantified.

Based on the Rayleigh distributions, the dynamic UKC criteria are calculated and summarised in Table 4-12. Accompanying figures are shown in Figure 4-12 and Figure 4-13.

Table 4-12: Dynamic UKC criteria, all ships.

Dynamic UKC criteria Based on 1% probability bottom contact	Draught 14.5 m ULCS, 95%	Draught 13.8 m Panamax, 95%	Draught 12.4 m ULCS, avg.	Draught 12.2 m Panamax, avg.
19 m LAT area	+ 0.75 m	+ 0.80 m	+1.00 m	+1.05 m
>21 m LAT area	+ 1.50 m	+ 1.60 m	+2.00 m	+2.00 m

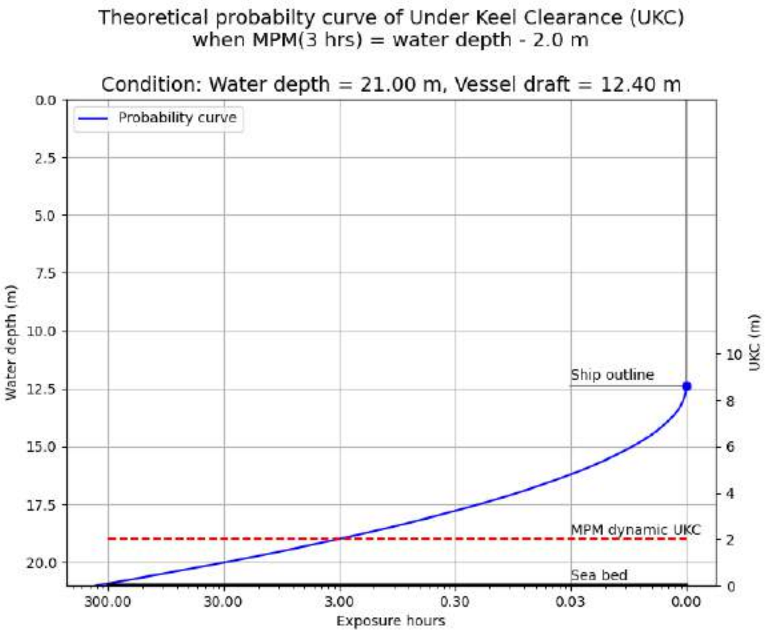


Figure 4-11: Rayleigh probability curve trough +2 m MPM keel clearance line, for given ship draught and water depth.

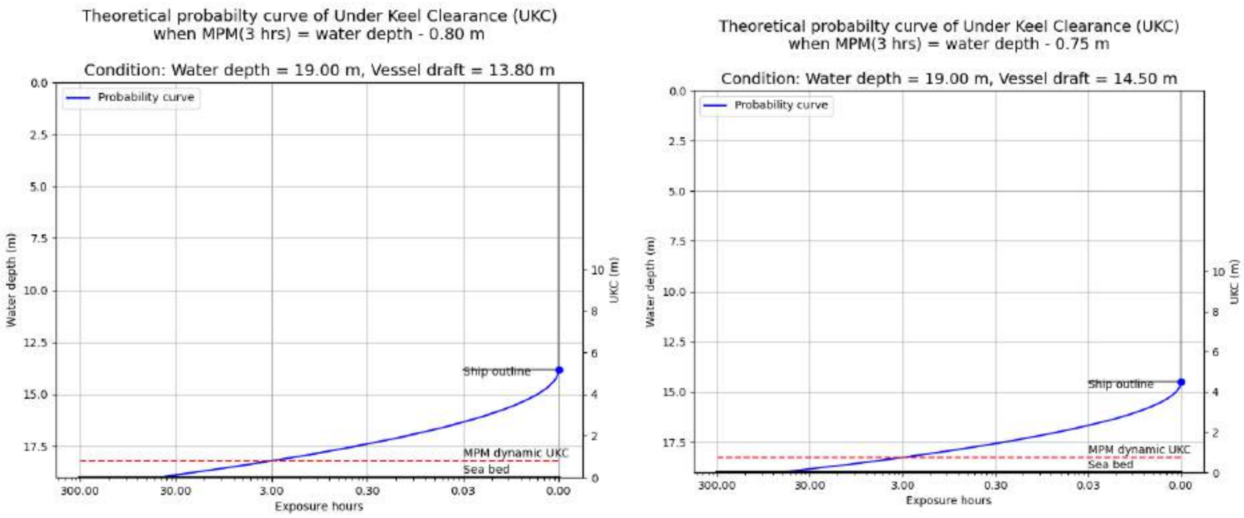


Figure 4-12: 3-hrs MPM level (red dashed line) for a ship sailing at a draught of 13.8 m (left) and 14.5 m (right) at 19 m water depth. 1% probability for bottom contact in 0.5 hours sailing time.

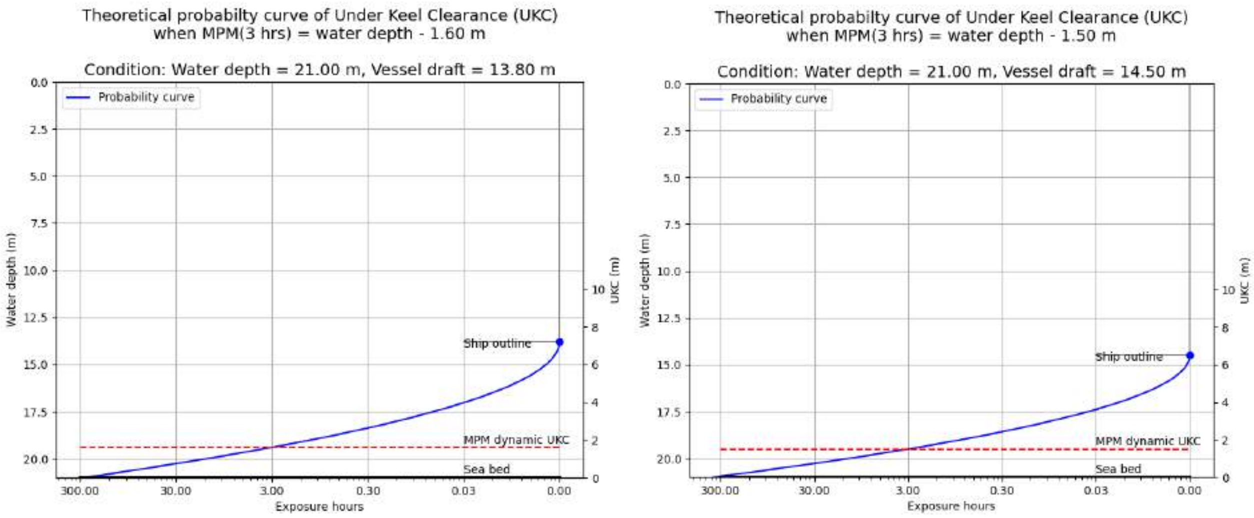


Figure 4-13: 3-hrs MPM level (red dashed line) for a ship sailing at a draught of 13.8 m (left) and 14.5 m (right) at 19 m water depth. 1% probability for bottom contact in 3 hours sailing time.

5 RESULTS FOR THE ULTRA LARGE CONTAINERSHIPS

5.1 Introduction

The Ultra Large Container Ships (ULCS) have overall dimensions exceeding the Panama Canal limitations; their beam exceeds the lock limitation of 49 m. The first locks had a length limitation of 300 m. The recent lock extensions allow ships to pass with length beyond 300 m.

The present report, the term ULCS is used for ships in length over 300 m. The typical beam of these ships is either 49 m (New-Panamax ships, carrying 19 containers across deck) or 59 m (carrying 23 containers across deck). The larger beam of 59 m will be governing for possible bottom contact in case of sever rolling, hence this one was used.

The AIS database shows that 95% of the ULCS vessels sail with a depth of 14.5 m or less, which was used in the present study. In the previous study an average draught of 12.4 m was used.

New seakeeping analysis were performed with the ULCS sailing at 12.4 m draught for the shallow water part of 19 m LAT to verify the dynamic UKC and acceleration levels.

About 1% of the ULCS sailing on the southern lane have a beam of 62 m carrying 24 containers across deck. The largest depth of those ships in the AIS database was 13.5 m. Given the above deeper draught of 14.5 m, there is no need to add this wider but lower draught containership configuration.

In Figure 5-1 two typical ULCS vessels are shown.

Figure 5-1: Examples of ULCS containerships. To the left a modern bow shaped 62 m width ULCS. To the right a more typical bow shaped ULCS (59 m beam).

5.2 Conclusions from previous investigations

The investigations performed in the previous study (32558, ULCS sailing at 12.4 m draught) give directions for the investigations in the present study:

- The overall limiting criterion on the southern route is the required dynamic under keel clearance of +2 m, which is reached at 21.3 m water depth when the Hs is about 4.5 m. There are no under keel restrictions on the northern route.
- The overall limiting criterion on the northern route is the allowable class acceleration which is reached when Hs is about 6 m. The same criterion applies to the southern route, but dynamic UKC was more restrictive here.
- The forward speed of 0, 5 and 10 knots had no effect on the limiting sea states.

- All limiting conditions were found in beam seas conditions.
- In bow-quartering to head seas wave conditions safe passage is possible under storms with Hs up to 8 m (higher waves are not recorded in the area).

5.3 Case definition

The ULCS hull shape from the previous study (32558) was used in the present study. The ship main dimensions are summarised in Table 5-1 for both sailing draughts. The deeper draught of 14.5 m covers 95% of the ULCS sailing on the southern route.

The draught increase is +1.90 m compared to the previous investigations, while the minimum water depth is decreased by 2.3 m. This significantly reduces the gross UKC from 8.9 m to only 4.5 m. Given the same hull depth, the freeboard reduces from 17.9 m to 15.8 m.

Seakeeping calculations have been performed for a GM range of 4 m to 10 m. The GM of 10 m is most likely not very likely to occur in combination with 14.5 m draught, but there is no track record available of actual GM values against sailing draught. Shipping companies will have such track records from the log-books, but these are not disclosed. The CSS code[16] includes a correction table for B/GM from 7 to 13, which implies a GM range of 4.5 m to 8.5 m. The 10 m GM was included based on the findings in the MSC ZOE accident investigations. The range of loading condition parameters is summarised in Table 5-2.

The reference points for the accelerations are presented in Table 5-3; based on the analysis discussed before. The highest tier considered was the 8th (tier 96).

The reference point for the dynamic under keel clearance are presented in Table 5-3; based on the analysis discussed before, the points were taken at the ship hull contour. In the previous study (32558) the evaluation point was the virtual crossing of the keel plane with the vessel side (0.5 B). This has been corrected and the dynamic UKC values for the ULCS sailing 12.4 m draught were re-calculated.

The green water aspects for the ULCS are discussed in Chapter 8.

The seakeeping analysis have been performed for a water depth of 19 m, 21 m and 37 m.

Table 5-1: Main particulars and properties of the ULCS at two sailing draughts.

Description	Magnitude	Magnitude
LPP (m)	379.40	379.40
B (m)	59.00	59.00
T (m) (TA=TF)	*12.40*	*14.50*
CB (-)	0.619	0.641
LCB (m) from AP	185.81	184.51
DISPLACEMENT (ton)	185771	224869
KM (m)	31.75	30.26
Bilge keel height (m)	0.40	0.40
Bilge keel length (m)	102.8 (27% LPP)	102.8 (27% LPP)

16 CSS-Code of safe practise for cargo stowage and securing, (see Annex 13), Res. A.714(17), MSC/Circ. 1026, IMO,

Table 5-2: Loading condition details of the ULCS

Description	**Loading Lowest GM**	**Loading Highest GM**
Transverse metacentre; GM (m)	4.0	10.0
Roll radius of gyration; k_{xx}	0.365 B	0.365 B
Pitch radius of gyration; k_{yy}	0.260 Lpp	0.260 Lpp
Yaw radius of gyration; k_{zz}	0.261 Lpp	0.261 Lpp

Table 5-3: Points of interest on the ULCS

Point description	**X (m) w.r.t. APP**	**Y (m) w.r.t. CL**	**Z (m) w.r.t. BL**
Container bay fwd (tier 82, tier 96)	323.0	+/- 28.10	31.4 and 51.7
Container bay mid-ship	194.6	+/- 28.10	31.4 and 51.7
Container bay aft	11.7	+/- 28.10	31.4 and 51.7
UKC forward	364.0	0.0	0.0
UKC at side, station 12	230.0	4 points on hull contour	
UKC at side, station 8	150.0	4 points on hull contour	
UKC aft	0.0	0.0	0.0

5.4 Sea keeping limiting criteria

The dynamic under keel clearance criteria are discussed in Section 0. The MPM is set such that the probability for bottom contact is 1% at the most, given the exposure time for the water depth. The criteria are presented in Table 5-4.

The allowable class accelerations were obtained from StowLash and they are summarised in Table 5-5 for both sailing draughts and all GM conditions. The values are nearly identical for both sailing draughts.

Table 5-4: Dynamic UKC criteria.

Dynamic UKC (m), MPM in 3 hrs	Water depth 19 m	Water depth 21 m
ULCS draught 12.4 m	+1.00	+2.00
ULCS draught 14.5 m	+0.75	+1.50

Table 5-5: Class allowable accelerations.

ULCS, L = 394 m, B = 59 m, Tm = 14.50 m, Vs = 15 kn							
Location of container tier @ bow location	Allowable acceleration (g) for GM (m)						
	4.0	5.0	6.0	7.0	8.0	9.0	10.0
acy top-tier, Tier 96	0.338	0.361	0.381	0.399	0.418	0.437	0.455
acy deck location, Tier 82	0.297	0.309	0.319	0.317	0.336	0.344	0.353

ULCS, L = 394 m, B = 59 m, Tm = 12.40 m, Vs = 15 kn							
Location of container tier @ bow location	Allowable acceleration (g) for GM (m)						
	4.0	5.0	6.0	7.0	8.0	9.0	10.0
acy top-tier, Tier 96	0.341	0.361	0.379	0.396	0.413	0.431	0.449
acy deck location, Tier 82	0.300	0.310	0.319	0.327	0.335	0.343	0.351

ULCS, L = 394 m, B = 59 m, Tm = 14.50 m, Vs = 15 kn							
Location of container tier @ midship location	Allowable acceleration (g) for GM (m)						
	4.0	5.0	6.0	7.0	8.0	9.0	10.0
acy top-tier, Tier 96	0.336	0.359	0.379	0.398	0.416	0.435	0.453
acy deck location, Tier 82	0.294	0.306	0.316	0.325	0.333	0.342	0.351

ULCS, L = 394 m, B = 59 m, Tm = 12.40 m, Vs = 15 kn							
Location of container tier @ midship location	Allowable acceleration (g) for GM (m)						
	4.0	5.0	6.0	7.0	8.0	9.0	10.0
acy top-tier, Tier 96	0.335	0.355	0.373	0.391	0.408	0.426	0.445
acy deck location, Tier 82	0.294	0.304	0.312	0.32	0.328	0.336	0.345

ULCS, L = 394 m, B = 59 m, Tm = 14.50 m, Vs = 15 kn							
Location of container tier @ stern location	Allowable acceleration (g) for GM (m)						
	4.0	5.0	6.0	7.0	8.0	9.0	10.0
acy top-tier, Tier 96	0.345	0.367	0.387	0.405	0.424	0.442	0.460
acy deck location, Tier 82	0.304	0.316	0.326	0.334	0.342	0.351	0.360

ULCS, L = 394 m, B = 59 m, Tm = 12.40 m, Vs = 15 kn							
Location of container tier @ stern location	Allowable acceleration (g) for GM (m)						
	4.0	5.0	6.0	7.0	8.0	9.0	10.0
acy top-tier, Tier 96	0.344	0.364	0.382	0.399	0.417	0.434	0.452
acy deck location, Tier 82	0.304	0.314	0.323	0.330	0.339	0.346	0.355

5.5 Results

5.5.1 Global ship motions

In Table 5-6 an overview is given of the SEACAL calculated natural roll periods for various GM conditions at 21 m water depth. The natural roll periods vary from 25 s for GM 4 m, to about 17 s for GM 10 m. The values are representative for all water depths on the TSS's. The range of wave periods in the area varies between 8 and 14 seconds so that in particular the vessels with higher GM condition will be prone to roll.

In Figure 5-2 the heave, roll and pitch motion RMS values in short-crested sea states of Hs 4.5 m are shown for various wave periods of the JONSWAP wave spectrum (with gamma = 1.5). As observed, the ship motions on the southern route (19 m and 21 m water depth) are different from the motions in deeper northern route (37 m) by a small amount. As observed, the heave, roll and pitch motions are the lowest at 19 m water depth and increase slightly with increasing water depth.

Although the ship motion amplitudes at 19 m draught are lower than at 21 m, the gross under keel clearance is as well 2 m less. It is expected that the motion difference is too small to compensate for this lost UKC margin.

The effect of the water depth on the accelerations is seen in Figure 5-3. For the lower wave periods the results are comparable at all three water depths. Noticeable differences are found for wave periods above 11 seconds: the acceleration level increases with increasing water depth, which is mainly the effect of slightly increased roll motion amplitudes. Based on these findings it can be expected that the local accelerations on the northern route will be slightly higher than on the southern route in the same storm condition.

Table 5-6: Roll period of the ULCS (in water) as function of GM.

Draught = 14.5 m, water depth = 21.0 m				
GM (m)	4.0	6.0	8.0	10.0
Roll period (s)	25.1	20.9	17.9	16.9

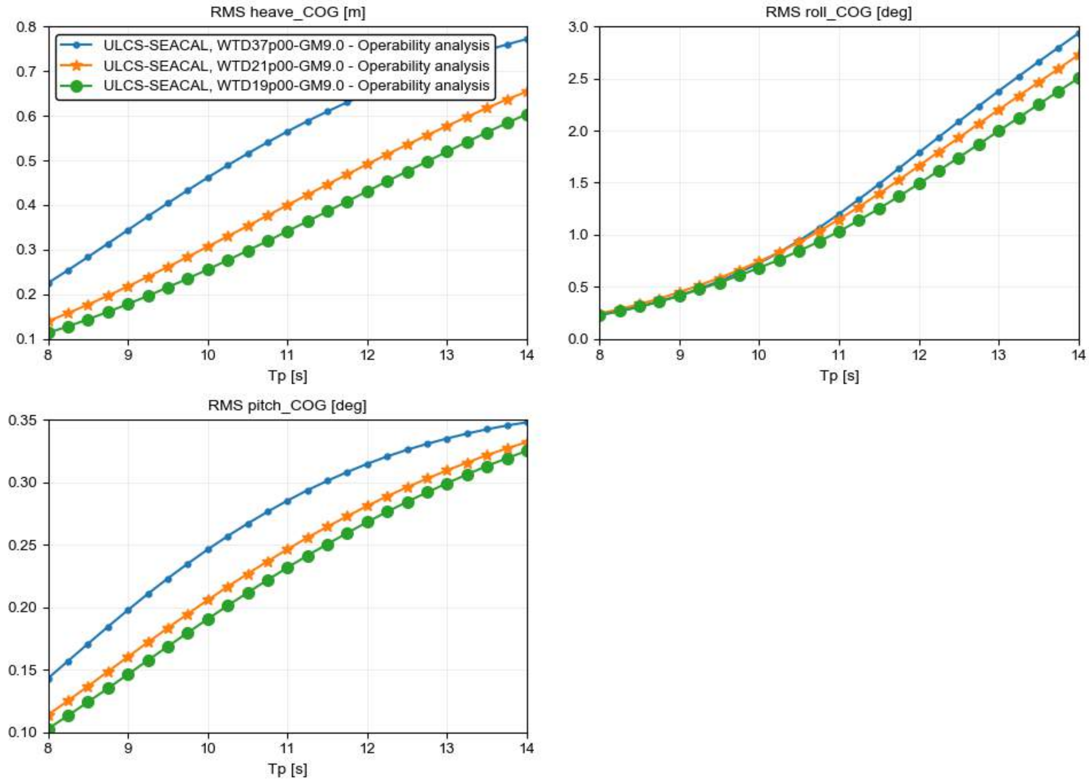


Figure 5-2: Global ship motions as function of water depth, Beam seas, Hs = 4.5 m, Tm = 14.5 m, GM = 9 m.

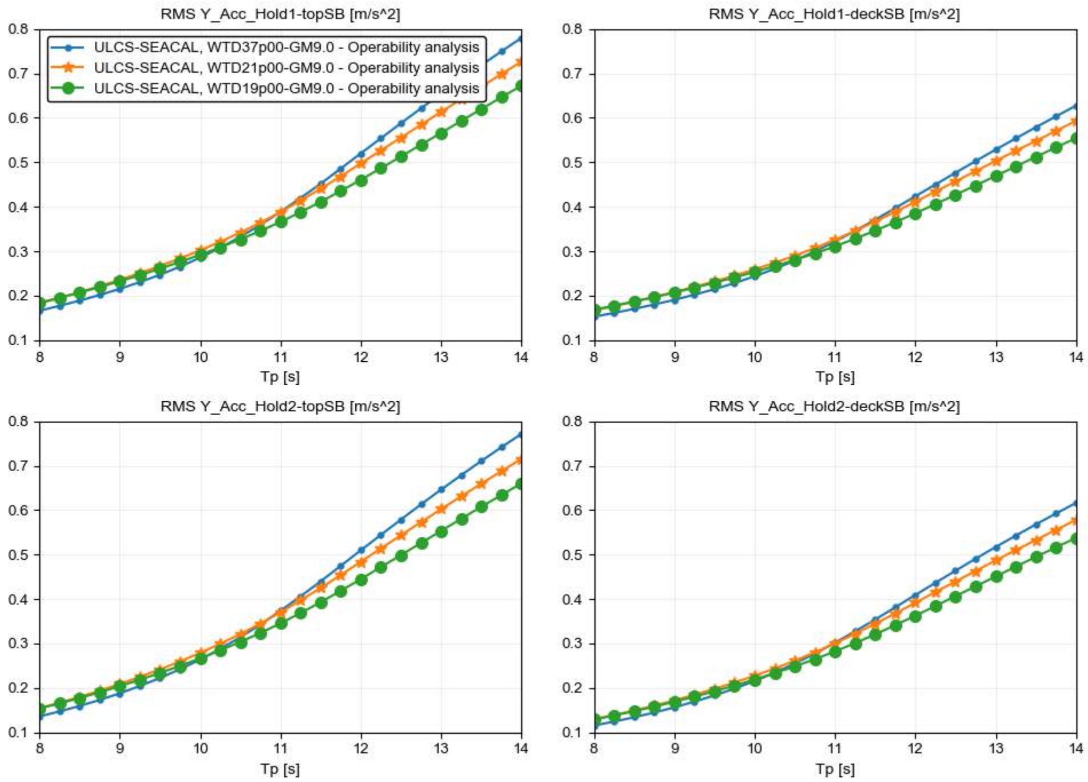


Figure 5-3: Local acceleration RMS as function of water depth. Position at the bow (hold 1) and mid-ship (hold 2) at top-tier and deck. Beam seas, Hs = 4.5m, Tm = 14.5 m, GM = 9 m.

5.5.2 Dynamic under keel clearance

The calculated dynamic under keel clearance was evaluated against the criteria listed in Table 5-4 (and include the shallow water second-order heave correction).

The following is concluded:

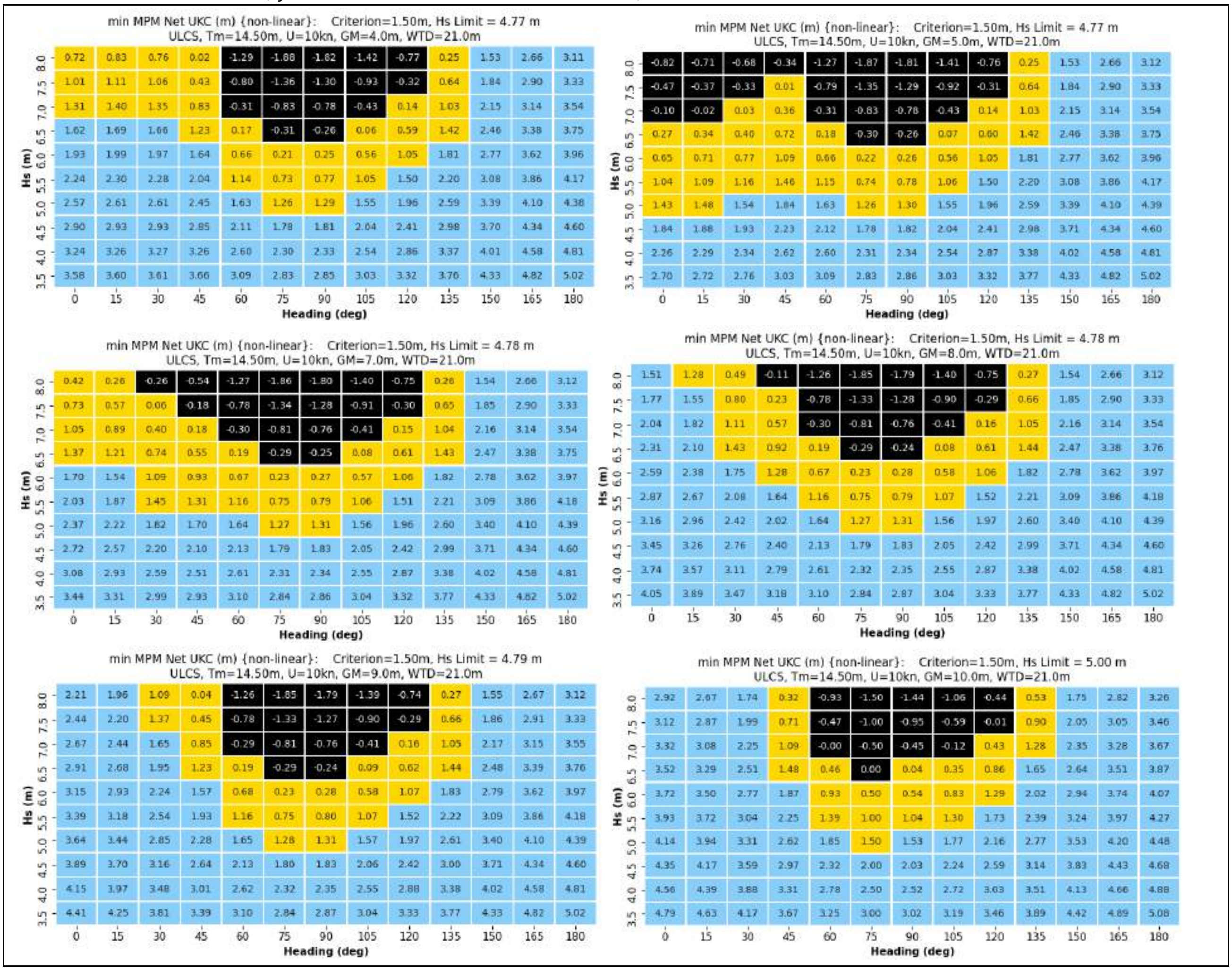
- Northern route:
  - No limitations
- Southern route, 21 m water depth, results are in Table 5-7:
  - limiting significant wave height Hs of 4.8 m at a sailing draught of 14.5 m
  - limiting significant wave height Hs of 5.6 m at a sailing draught of 12.4 m

Southern route, 19 m water depth, results are in

- Table 5-8:
  - limiting significant wave height Hs of 3.5 m at a sailing draught of 14.5 m
  - limiting significant wave height Hs of 4.1 m at a sailing draught of 12.4 m
- The limiting significant wave height is (almost) the same for all GM conditions at a given water depth.
- The limiting conditions occur in sea states with long wave periods above 11 s.
- In Table 5-9 the dynamic UKC is shown for two sea states above the limiting wave height of 3.5 m., that is in Hs 4.0 m and 4.5 m. The results show that the limiting dynamic UKC criterion is only exceed in sea states with a wave period above 11 seconds. The metocean data in Figure 2-8 shows that 98% of the sea states between Hs 3.5 and 4.0 m have a wave period below 11 seconds. A limiting wave height of 4.0 m is recommended; this is still a very safe boundary.
- With reference to the present preliminary limiting significant wave height of Hs 4.5 m, it can be read from Table 5-9 that the dynamic UKC falls just below 2 m at 21 m water depth when the ULCS draught is 14.5 m.
- The limiting conditions occur in beam seas (+/- 45 deg). But, when the GM is 6 m or less, the limiting conditions are as well found in following to stern-quartering seas.
- Around head seas conditions (+/- 30 deg), dynamic under keel clearance values remain high and sufficient for operation in any sea state up to Hs of 8 m, even at 19 m water depth; see the result tables. This gives a ULCS vessel a safe sailing heading w.r.t. the storm condition and dynamic under keel clearance.

Table 5-7: MPM of dynamic under keel clearance, 21 m water depth, sailing draught 14.5 m and 12.4 m.

black = contact with seabed, yellow = UKC between 0 m and criterion, blue = UKC > criterion.



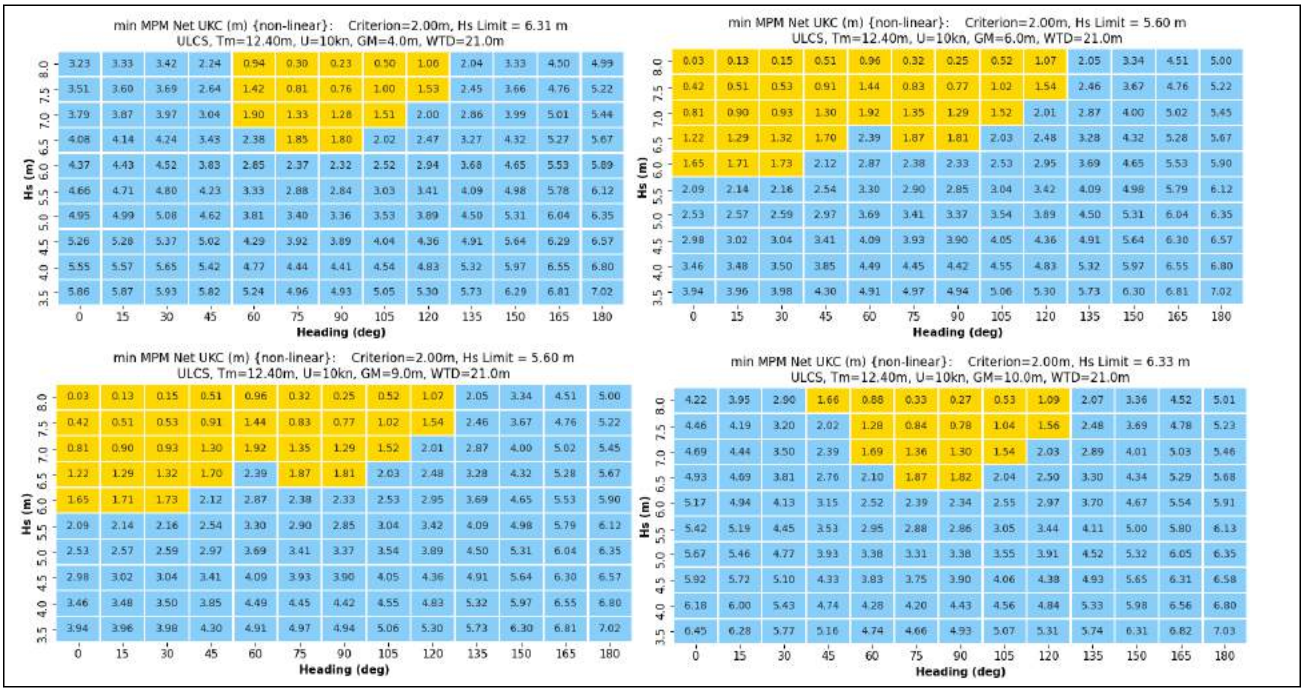
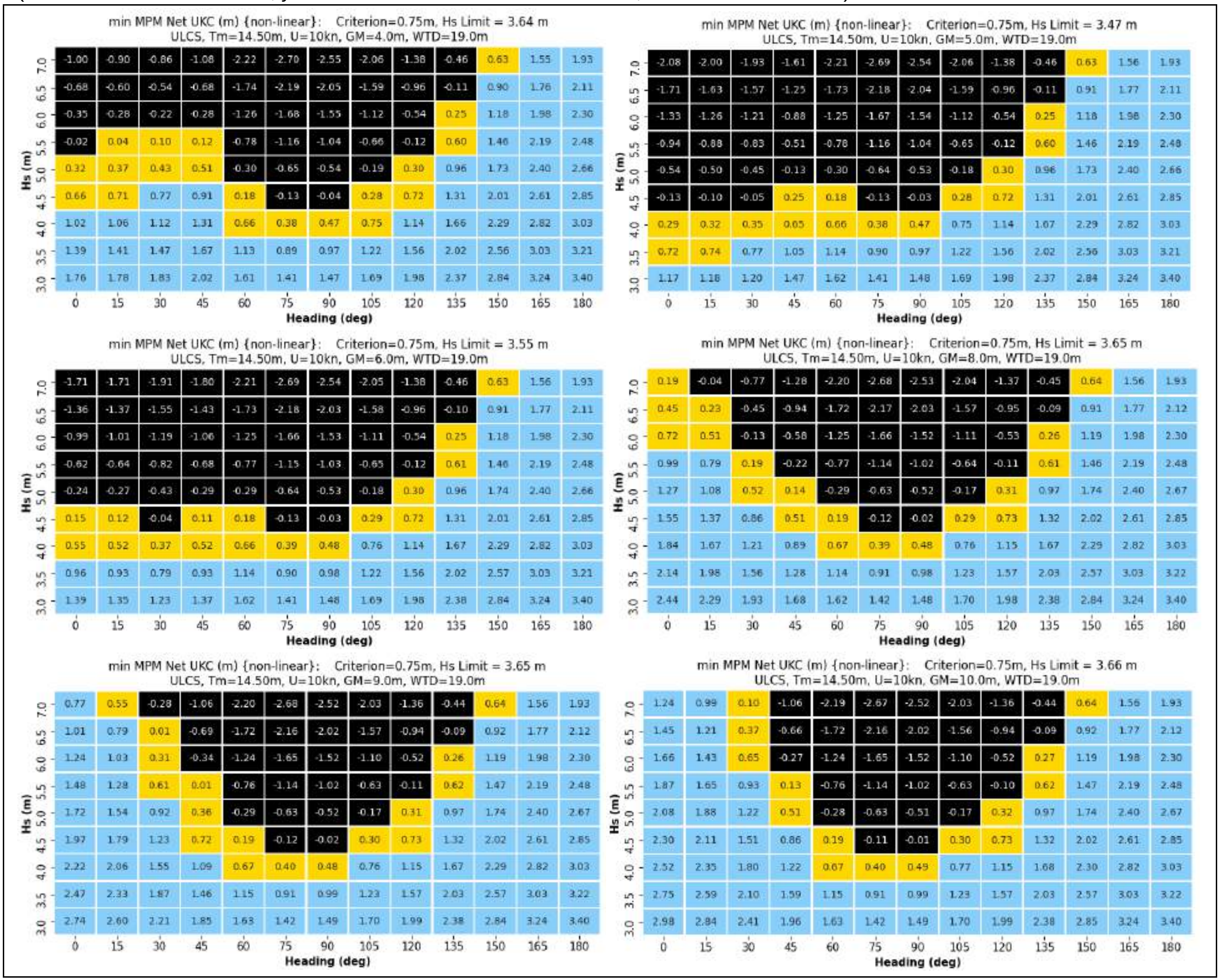


Table 5-8: MPM of dynamic under keel clearance, 19 m water depth, sailing draught 14.5 m and 12.4 m.

(black = contact with seabed, yellow = UKC between 0 m and criterion, blue = UKC > criterion).



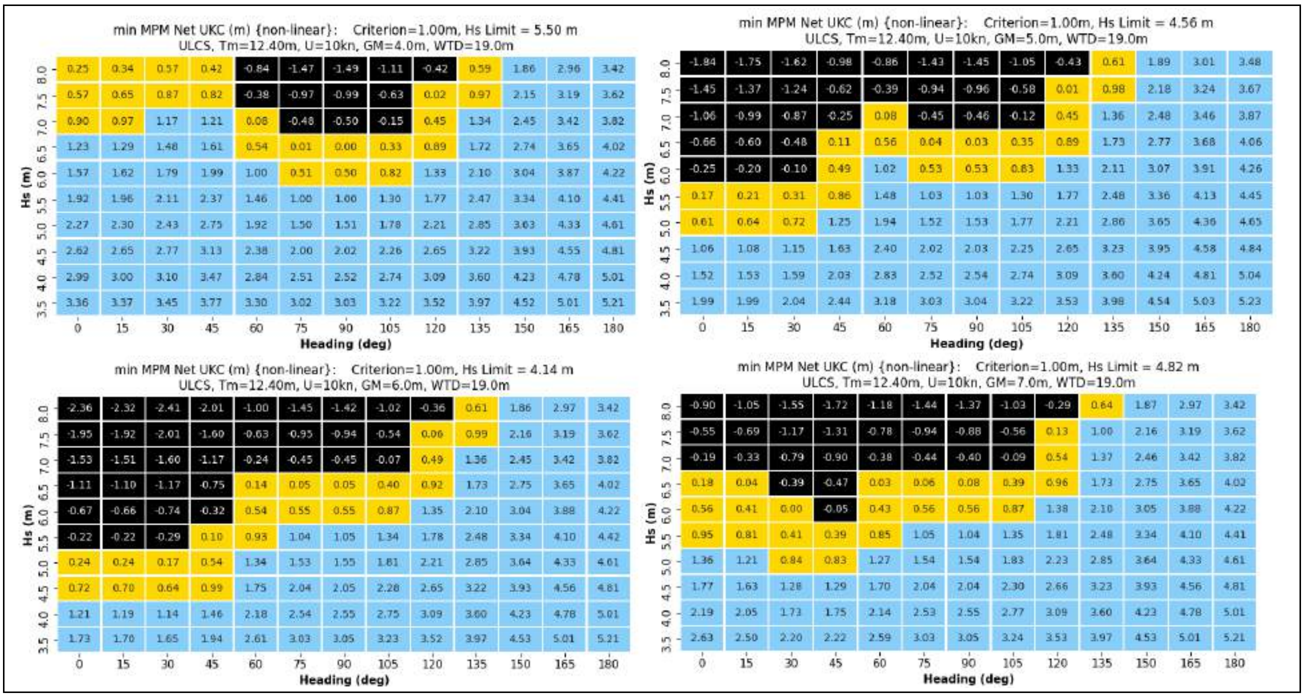


Table 5-9: Example of effect of wave period on the dynamic under keel clearance at sailing draught 14.5 m at 19 m in sea states above the limiting Hs.

min MPM Net UKC (m) for Hs=4.0 (m) {non-linear}: Criterion=0.75m, Hs Limit = 3.65 m
ULCS, Tm=14.50m, U=10kn, GM=8.0m, WTD=19.0m

Heading (deg) \ Tp (s)	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	4.23	4.16	4.07	3.97	3.87	3.76	3.64	3.52	3.41	3.28	3.16	3.03
165	4.18	4.09	3.99	3.88	3.77	3.64	3.51	3.38	3.24	3.10	2.96	2.82
150	4.01	3.90	3.77	3.63	3.47	3.32	3.15	2.98	2.81	2.64	2.46	2.29
135	3.76	3.60	3.43	3.24	3.05	2.85	2.65	2.45	2.25	2.05	1.86	1.67
120	3.47	3.26	3.04	2.82	2.59	2.36	2.14	1.92	1.71	1.51	1.32	1.15
105	3.19	2.94	2.68	2.43	2.18	1.93	1.70	1.48	1.28	1.09	0.92	0.76
90	3.00	2.73	2.44	2.16	1.90	1.64	1.40	1.18	0.98	0.80	0.63	0.48
75	2.97	2.69	2.40	2.12	1.85	1.59	1.34	1.12	0.91	0.72	0.55	0.39
60	3.10	2.85	2.59	2.33	2.08	1.84	1.61	1.40	1.19	1.01	0.83	0.67
45	3.32	3.13	2.93	2.73	2.53	2.23	1.93	1.64	1.40	1.18	1.01	0.89
30	3.47	3.35	3.17	2.86	2.56	2.27	2.00	1.75	1.55	1.39	1.27	1.21
15	3.55	3.46	3.19	2.92	2.65	2.41	2.20	2.01	1.87	1.76	1.69	1.67
0	3.57	3.43	3.17	2.91	2.67	2.44	2.25	2.09	1.97	1.89	1.85	1.84

min MPM Net UKC (m) for Hs=4.5 (m) {non-linear}: Criterion=0.75m, Hs Limit = 3.65 m
ULCS, Tm=14.50m, U=10kn, GM=9.0m, WTD=19.0m

Heading (deg) \ Tp (s)	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	4.20	4.11	4.02	3.91	3.79	3.67	3.54	3.40	3.27	3.13	2.99	2.85
165	4.14	4.04	3.93	3.81	3.68	3.54	3.39	3.24	3.09	2.93	2.77	2.61
150	3.95	3.82	3.68	3.52	3.35	3.17	2.98	2.79	2.60	2.41	2.21	2.02
135	3.67	3.49	3.29	3.09	2.87	2.65	2.42	2.19	1.97	1.75	1.53	1.32
120	3.34	3.10	2.86	2.61	2.35	2.10	1.85	1.60	1.37	1.14	0.93	0.73
105	3.02	2.74	2.46	2.17	1.89	1.61	1.36	1.11	0.88	0.67	0.47	0.30
90	2.82	2.50	2.19	1.88	1.57	1.29	1.02	0.77	0.54	0.34	0.15	-0.02
75	2.78	2.46	2.14	1.83	1.52	1.23	0.95	0.70	0.47	0.25	0.06	-0.12
60	2.93	2.64	2.35	2.07	1.78	1.51	1.26	1.01	0.78	0.57	0.37	0.19
45	3.18	2.96	2.73	2.51	2.19	1.88	1.58	1.30	1.06	0.91	0.80	0.72
30	3.34	3.17	2.85	2.52	2.24	1.99	1.76	1.53	1.36	1.27	1.23	1.23
15	3.42	3.15	2.88	2.61	2.38	2.21	2.07	1.94	1.84	1.80	1.79	1.82
0	3.37	3.11	2.85	2.59	2.39	2.26	2.15	2.06	1.99	1.97	1.99	2.02

5.5.3 Container accelerations

The limiting significant wave heights based on the allowable transverse accelerations from class are summarised for the various GM's and sailing draughts in Table 5-10. Example plots of the acceleration levels for various GM conditions as function of heading and Hs are shown in Table 5-11.

The following is concluded:

- Northern route (37 m):
  - limiting significant wave height Hs of 6.1 m at a sailing draught of 14.5 m
  - limiting significant wave height Hs of 6.1 m at a sailing draught of 12.4 m
- Southern route (19m and 21 m):
  - limiting significant wave height Hs of 6.6 m at a sailing draught of 14.5 m
  - limiting significant wave height Hs of 6.1 m at a sailing draught of 12.4 m
- The limiting significant wave heights occur for the highest GM condition of 10 m. For a GM condition of 8 m or lower, the limiting significant wave heights are 7.5 m or higher; the highest storm condition measured in the area is 8 m Hs.
- In beam seas conditions are the transverse accelerations the same on port- and starboard side containers. The vertical accelerations are the largest on the weather side. An example plot is given in Figure 5-4. It demonstrates the narrow banded heading range for critical accelerations.

- The limiting significant wave height is nearly the same for deck- and top-tier containers as well as for containers at the stern, mid-ship or bow location. It does not imply that all containers are at risk when the limiting sea state is reached because it is the mass*acceleration that determines the load. When the mass of the container is lower than the allowable mass, the securing system is less critically loaded. It is not known if the rule allowable mass is the maximum container mass at each tier height. The more heavier containers are usually stowed low in the stack.
- The limiting conditions occur in beam seas +/- 45 deg wave heading. In the head seas (+/- 30 deg) or following seas (+/- 30 deg) the accelerations stay below the class allowable values up to Hs of 8 m.

Table 5-10: Limiting significant wave heights on southern and northern route w.r.t. transverse acceleration.

Southern route, 21 m water depth						
Limiting significant wave height Hs (m), ULCS, Tm=14.5 m						
	Deck tier			Top tier		
GM (m)	aft	mid	bow	aft	mid	bow
10.0	6.7	6.8	6.6	6.9	7.0	6.9
9.0	7.0	7.4	7.2	7.3	7.6	7.5
8.0	7.5	7.9	7.9	7.8	8.0	8.0
7.0	7.9	8.0	7.5	7.9	8.0	8.0
6.0	7.9	7.6	7.5	8.0	7.8	7.7
5.0	7.8	7.8	7.7	7.9	8.0	7.8
4.0	> 8 m	> 8 m	> 8 m	> 8 m	> 8 m	> 8 m
Limiting significant wave height Hs (m), ULCS, Tm=12.4 m						
	Deck tier			Top tier		
GM (m)	aft	mid	bow	aft	mid	bow
10.0	6.1	6.2	6.2	6.2	6.4	6.2
9.0	7.2	7.0	7.2	7.8	7.7	7.8
6.0	6.5	6.3	6.5	6.6	6.5	6.6
4.0	> 8 m	> 8 m	> 8 m	> 8 m	> 8 m	> 8 m

Northern route, 37 m water depth						
Limiting significant wave height Hs (m), ULCS, Tm=14.5 m						
	Deck tier			Top tier		
GM (m)	aft	mid	bow	aft	mid	bow
10.0	6.3	6.2	6.1	6.3	6.3	6.3
9.0	6.8	6.9	6.8	6.9	7.0	7.0
7.0	7.6	> 8 m	> 8 m	> 8 m	> 8 m	> 8 m
Limiting significant wave height Hs (m), ULCS, Tm=12.4 m						
	Deck tier			Top tier		
GM (m)	aft	mid	bow	aft	mid	bow
10.0	6.1	6.1	6.1	6.1	6.1	6.2
9.0	6.4	6.5	6.7	6.4	6.6	6.7
6.0	> 8 m	> 8 m	> 8 m	> 8 m	> 8 m	> 8 m

Table 5-11: Example plots of accelerations at top-tier and deck containers versus class allowable values, water depth 21 m, sailing draught 14.5 m, GM 5 m and GM 10 m.

Red = above class limit, yellow = above 90% of class limit

max MPM transverse acc (g) @ low-tier, mid-ship, Criterion = 0.306 g, Hs Limit = 7.8 m
ULCS, Tm=14.50m, U=10kn, GM=5.00m, WTD=21.0m

Hs (m) \ Heading (deg)	0	15	30	45	60	75	90	105	120	135	150	165	180
8.0	0.297	0.305	0.312	0.296	0.258	0.217	0.185	0.154	0.117	0.079	0.049	0.031	0.025
7.5	0.282	0.290	0.297	0.281	0.244	0.205	0.174	0.145	0.110	0.074	0.046	0.029	0.024
7.0	0.268	0.275	0.281	0.266	0.231	0.193	0.163	0.136	0.103	0.069	0.043	0.027	0.022
6.5	0.253	0.260	0.265	0.251	0.217	0.181	0.153	0.126	0.095	0.064	0.040	0.025	0.021
6.0	0.237	0.244	0.249	0.235	0.203	0.169	0.142	0.117	0.088	0.059	0.037	0.023	0.019
5.5	0.221	0.227	0.232	0.219	0.189	0.156	0.131	0.108	0.081	0.054	0.034	0.021	0.018
5.0	0.205	0.211	0.215	0.203	0.174	0.144	0.120	0.098	0.074	0.049	0.030	0.020	0.016
4.5	0.189	0.194	0.198	0.186	0.160	0.131	0.109	0.089	0.066	0.044	0.027	0.018	0.014
4.0	0.172	0.176	0.180	0.169	0.144	0.118	0.097	0.079	0.059	0.039	0.024	0.016	0.013
3.5	0.154	0.158	0.161	0.151	0.129	0.105	0.086	0.069	0.052	0.034	0.021	0.014	0.011

max MPM transverse acc (g) @ high-tier, mid-ship, Criterion = 0.359 g, Hs Limit = 8.0 m
ULCS, Tm=14.50m, U=10kn, GM=5.00m, WTD=21.0m

Hs (m) \ Heading (deg)	0	15	30	45	60	75	90	105	120	135	150	165	180
8.0	0.341	0.351	0.360	0.342	0.298	0.248	0.208	0.173	0.133	0.093	0.062	0.044	0.038
7.5	0.324	0.334	0.342	0.325	0.282	0.234	0.197	0.163	0.124	0.087	0.058	0.042	0.036
7.0	0.307	0.316	0.324	0.307	0.267	0.221	0.185	0.152	0.116	0.081	0.054	0.039	0.033
6.5	0.290	0.299	0.306	0.290	0.251	0.207	0.173	0.142	0.108	0.075	0.051	0.036	0.031
6.0	0.272	0.280	0.287	0.271	0.235	0.193	0.161	0.132	0.100	0.069	0.047	0.033	0.029
5.5	0.254	0.261	0.268	0.253	0.218	0.179	0.148	0.121	0.092	0.064	0.043	0.030	0.026
5.0	0.236	0.242	0.248	0.234	0.201	0.165	0.136	0.111	0.084	0.058	0.039	0.028	0.024
4.5	0.217	0.223	0.228	0.215	0.184	0.150	0.123	0.100	0.075	0.052	0.035	0.025	0.021
4.0	0.197	0.203	0.207	0.195	0.167	0.135	0.110	0.089	0.067	0.046	0.031	0.022	0.019
3.5	0.177	0.182	0.186	0.174	0.149	0.120	0.097	0.078	0.059	0.041	0.027	0.019	0.017

max MPM transverse acc (g) @ low-tier, mid-ship, Criterion = 0.351 g, Hs Limit = 6.84 m
ULCS, Tm=14.50m, U=10kn, GM=10.00m, WTD=21.0m

Hs (m) \ Heading (deg)	0	15	30	45	60	75	90	105	120	135	150	165	180
8.0	0.160	0.185	0.235	0.291	0.350	0.392	0.400	0.364	0.290	0.200	0.120	0.067	0.047
7.5	0.152	0.175	0.223	0.276	0.332	0.372	0.379	0.344	0.274	0.189	0.113	0.063	0.044
7.0	0.143	0.165	0.210	0.260	0.313	0.351	0.358	0.325	0.258	0.177	0.106	0.059	0.041
6.5	0.134	0.155	0.197	0.245	0.294	0.330	0.336	0.305	0.241	0.166	0.099	0.055	0.038
6.0	0.125	0.144	0.184	0.228	0.275	0.308	0.314	0.284	0.225	0.154	0.092	0.051	0.035
5.5	0.116	0.134	0.171	0.212	0.255	0.286	0.291	0.263	0.208	0.142	0.085	0.047	0.032
5.0	0.106	0.123	0.157	0.195	0.235	0.264	0.268	0.242	0.191	0.130	0.078	0.043	0.029
4.5	0.097	0.112	0.143	0.178	0.215	0.241	0.245	0.221	0.174	0.118	0.070	0.038	0.026
4.0	0.087	0.101	0.129	0.161	0.194	0.217	0.221	0.199	0.156	0.106	0.063	0.034	0.023
3.5	0.077	0.090	0.115	0.143	0.172	0.193	0.196	0.176	0.138	0.094	0.056	0.030	0.021

max MPM transverse acc (g) @ high-tier, mid-ship, Criterion = 0.453 g, Hs Limit = 7.05 m
ULCS, Tm=14.50m, U=10kn, GM=10.00m, WTD=21.0m

Hs (m) \ Heading (deg)	0	15	30	45	60	75	90	105	120	135	150	165	180
8.0	0.201	0.233	0.296	0.368	0.442	0.495	0.504	0.457	0.364	0.253	0.154	0.089	0.065
7.5	0.190	0.220	0.280	0.348	0.419	0.469	0.477	0.432	0.344	0.238	0.145	0.084	0.061
7.0	0.179	0.208	0.264	0.329	0.395	0.443	0.450	0.408	0.324	0.224	0.136	0.079	0.057
6.5	0.168	0.195	0.248	0.309	0.371	0.416	0.423	0.382	0.303	0.209	0.127	0.073	0.053
6.0	0.157	0.182	0.232	0.288	0.347	0.389	0.395	0.357	0.282	0.195	0.118	0.068	0.049
5.5	0.145	0.168	0.215	0.268	0.322	0.361	0.367	0.331	0.261	0.180	0.109	0.062	0.045
5.0	0.133	0.155	0.198	0.246	0.297	0.333	0.338	0.304	0.240	0.165	0.100	0.057	0.041
4.5	0.121	0.141	0.180	0.225	0.271	0.304	0.308	0.277	0.218	0.149	0.090	0.051	0.037
4.0	0.109	0.127	0.163	0.203	0.245	0.274	0.278	0.250	0.196	0.134	0.081	0.045	0.033
3.5	0.097	0.113	0.145	0.180	0.218	0.244	0.247	0.222	0.174	0.118	0.071	0.040	0.029

max MPM transverse acc (g) @ deck-tier, bow, Criterion = 0.453 g, Hs Limit = 6.6 m
ULCS, Tm=14.50m, U=10kn, GM=10.00m, WTD=21.0m

Hs (m) \ Heading (deg)	0	15	30	45	60	75	90	105	120	135	150	165	180
8.0	0.164	0.189	0.239	0.294	0.352	0.397	0.414	0.387	0.317	0.224	0.137	0.076	0.052
7.5	0.155	0.179	0.227	0.279	0.333	0.376	0.392	0.366	0.299	0.211	0.129	0.071	0.048
7.0	0.146	0.169	0.214	0.263	0.314	0.355	0.370	0.345	0.281	0.198	0.121	0.067	0.045
6.5	0.137	0.158	0.201	0.247	0.295	0.334	0.347	0.323	0.263	0.185	0.113	0.062	0.042
6.0	0.127	0.147	0.187	0.231	0.276	0.312	0.324	0.301	0.244	0.172	0.104	0.057	0.039
5.5	0.118	0.137	0.174	0.214	0.256	0.289	0.300	0.278	0.226	0.158	0.096	0.053	0.035
5.0	0.108	0.126	0.160	0.197	0.236	0.267	0.276	0.256	0.207	0.145	0.088	0.048	0.032
4.5	0.099	0.115	0.146	0.180	0.216	0.243	0.252	0.233	0.188	0.131	0.079	0.043	0.029
4.0	0.089	0.103	0.132	0.162	0.195	0.220	0.227	0.209	0.168	0.117	0.071	0.038	0.026
3.5	0.079	0.092	0.117	0.144	0.173	0.195	0.202	0.185	0.149	0.103	0.062	0.034	0.023

max MPM transverse acc (g) @ high-tier, bow, Criterion = 0.453 g, Hs Limit = 6.9 m
ULCS, Tm=14.50m, U=10kn, GM=10.00m, WTD=21.0m

Hs (m) \ Heading (deg)	0	15	30	45	60	75	90	105	120	135	150	165	180
8.0	0.204	0.236	0.300	0.369	0.441	0.497	0.514	0.477	0.389	0.275	0.169	0.096	0.068
7.5	0.193	0.224	0.284	0.350	0.418	0.471	0.487	0.451	0.367	0.259	0.159	0.090	0.063
7.0	0.182	0.211	0.268	0.330	0.395	0.445	0.460	0.425	0.345	0.242	0.149	0.084	0.059
6.5	0.171	0.198	0.251	0.310	0.371	0.418	0.431	0.398	0.323	0.226	0.139	0.078	0.055
6.0	0.159	0.184	0.235	0.289	0.347	0.390	0.403	0.371	0.300	0.210	0.128	0.072	0.051
5.5	0.147	0.171	0.218	0.269	0.322	0.362	0.374	0.344	0.277	0.194	0.118	0.066	0.046
5.0	0.135	0.157	0.200	0.247	0.297	0.334	0.344	0.316	0.254	0.177	0.108	0.060	0.042
4.5	0.123	0.143	0.183	0.226	0.271	0.305	0.314	0.288	0.231	0.161	0.098	0.054	0.038
4.0	0.111	0.129	0.165	0.204	0.245	0.275	0.283	0.259	0.207	0.144	0.087	0.048	0.034
3.5	0.098	0.115	0.147	0.181	0.218	0.245	0.251	0.229	0.183	0.127	0.077	0.042	0.030

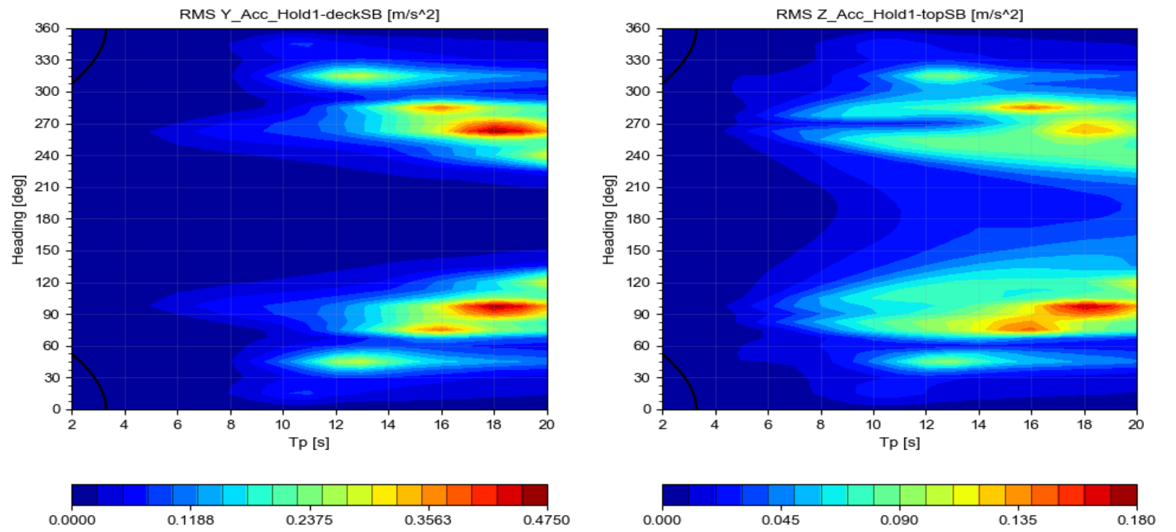


Figure 5-4: Example of transverse acceleration level (left) and vertical acceleration level (right) on starboard side containers in waves of Hs of 1.0m. Weather side = SB side in beam waves 90 deg.

5.5.4 Green water

The green water discussion is presented Chapter 8. The results shown in the summary table, Table 5-12, are valid for the given freeboard height.

5.6 Final limiting wave heights for the ULCS

Table 5-12 lists the final derived limiting significant wave heights for the ULCS containerships on the northern and southern route.

The limiting conditions occur in beam seas +/- 45 deg.

There are no limitations when sailing in head seas condition +/- 30 deg.

The only limiting criterion on the northern route is exceedance of the by class rules assumed acceleration in storms of Hs 6.1 m or higher. Note that this is an acceleration limit and not a securing load limit. The loading computer will verify if the securing load is exceeded given the actual mass of the container.

The acceleration limits are consistent between deck and top-tier containers. The limiting sea state does not depend on the considered tier height.

The limiting criterion on the southern route is the dynamic UKC, leading to Hs of 4.8 m westbound, and Hs 3.5 m eastbound. Since the limiting dynamic UKC criterion at Hs of 4.0 m is only exceeded in 2% of the occurring wave periods, this Hs provides a sufficient safety level.

Based on 40 years of metocean data, the significant wave height is 3.5 m or higher for about 208 hours/year (9 days).

The determined seakeeping calculation accuracy is conservative, while the accuracy of the metocean condition is biased low. Both errors cancel out. Further reduction on Hs due to the metocean inaccuracy is not deemed necessary.

Table 5-12: Final proposed limiting sea state conditions, ULCS.

Relevant for beam seas sailing +/- 45 deg	**ULCS** sailing draught 14.5 m freeboard 15.8 m	**ULCS** sailing draught 12.4 m freeboard 17.9 m
Northern route (37 m)	**Hs ≈ 6.1 m (accelerations)** no risk on bottom contact Hs ≈ 7.4 m (green water)	Hs ≈ 6.1 m (accelerations) no risk on bottom contact Hs ≈ 7.4 m (green water)
Southern route westbound, min LAT = 21 m	Hs ≈ 6.6 m (accelerations) **Hs ≈ 4.8 m** (bottom contact) Hs ≈ 5.5 m (green water)	Hs ≈ 6.1 m (accelerations) Hs ≈ 5.6 m (bottom contact) Hs ≈ 5.9 m (green water)
Southern route eastbound, min LAT = 19 m	Hs ≈ 6.6 m (accelerations) **Hs ≈ 4.0 m** (bottom contact) Hs ≈ 5.5 m (green water)	Hs ≈ 6.1 m (accelerations) Hs ≈ 4.1 m (bottom contact) Hs ≈ 5.5 m (green water)

6 RESULTS FOR THE PANAMAX CONTAINERSHIPS

6.1 Introduction

Panamax and New-Panamax refer to containerships that are designed to travel through the Panama Canal. The Panamax vessel have a beam up to 33 m (32.2 m) and a length up to 297 m; these ships could travel through the first Panama Canal locks (1914). With the extension of the locks (in operation since 2016), the maximum beam the ships that can travel through the Panama Canal is 54 m. The length can exceed 300 m (< 426 m). The New-Panamax ships are covered by the ULCS class.

Ships that could not travel through the Panama Canal before the lock extension in 2016 are called Post-Panamax ships.

In this Chapter 6, the ships with a length <300 m (297 m) are called Panamax ships when the beam is less then 32.3 m and Post-Panamax ships when the beam exceeds 33 m. The same wording is used in the network study (report 33883-2-MO). This study showed that the Post-Panamax ships up to 300 m have a maximum beam of 40 m.

The name of the current chapter remains “Panamax”, for consistency with the previous investigations and report in 32558, and for consistency with the vessel naming in the present route advice.

However, it is recommended to change the length limitation from 300 m to 297 m. Ships in length over 297 m sometimes have a beam of 43 m.

In Figure 6-1 two typical Post-Panamax containerships are seen. There is often a container bay aft of the bridge.

Figure 6-1: Typical Post-Panamax containerships with length < 297 m.

6.2 Conclusions from the previous investigations

The investigations performed in the previous study (32558, Panamax sailing at 12.2 m draught) give directions for the investigations in the present study:

- The overall limiting criterion on the southern route is the required under keel clearance of +2 m, which is reached at 21.3 m water depth when the Hs is about 4.5m. There are no under keel restrictions on the northern route.
- The overall limiting criterion on the northern route is the green water threat. The limiting sea significant wave height was found in model tests at 5.7 m Hs, under the given freeboard height of 9.2 m.
- The forward speed of 0, 5 and 10 knots had no effect on the limiting sea states.

- All limiting conditions were found in beam seas conditions.
- In bow-quartering to head seas wave conditions safe passage is possible under storms with Hs up to 8 m (higher waves are not recorded in the area).

6.3 Case definition

The beam, depth and length distributions of the Post-Panamax containerships are given in Figure 6-2.

The data shows that about 70% of the Post-Panamax vessels have a beam of 40 m. The Panamax hull shape from project 32558 was modified to this value. The length was kept the same at 278 m. The draught was set to 13.8 m to cover 95% of all containerships between 200 and 297 m.

The 95% draught for the classical Panamax vessels (beam 32.3 m) was derived at 13.2 m, but this this below 13.8 m, so the Panamax ship is not revisited.

The characteristics of the Post-Panamax vessel are summarised in Table 6-1. The GM condition was varied between 2 m and 6 m and the loading condition details are summarised in Table 6-2. The typically GM of a Post-Panamax is expected to be higher than for a classical Panamax ship due to its increased breadth. The CSS code provides an acceleration correction table for B/GM between 7 and 13. This covers a GM range of 3.0 m to 5.7 m.

It is noted that the higher GM values might be exceptional for deep draught conditions. However, the AIS data does not broadcast GM, so there is no information to correlate draught and GM.

The reference points for the accelerations are presented in Table 6-3; and as discussed by the ULCS ships, the reference points are taken at bay locations at the bow, mid-ship and stern. The container stacks on deck are assumed to be maximum seven tier high (tier 94). The most occurring hull depth of 24.3 has been used to define the position of tier 82 on the cargo hold.

The reference point for the dynamic under keel clearance are presented in Table 6-3; they are taken on the hull contour of station 9 and 11, plus the forward and aft extremes at centreline.

Table 6-1: Main particulars and properties of the Post-Panamax and Panamax vessel.

	Post-Panamax	**Panamax**
Description	**Magnitude**	**Magnitude**
LPP (m)	278.0	278.0
B (m)	40.0	32.2
T (m) (TA=TF)	13.80	12.20
CB (-)	0.646	0.63
LCB (m) from AP	132.6	134.8
DISPLACEMENT (ton)	101548	70324
KM (m)	19.538	15.04
Bilge keel height (m)	0.40	0.40
Bilge keel length (m)	77.5 (27.9% LPP)	77.5 (27.9% LPP)

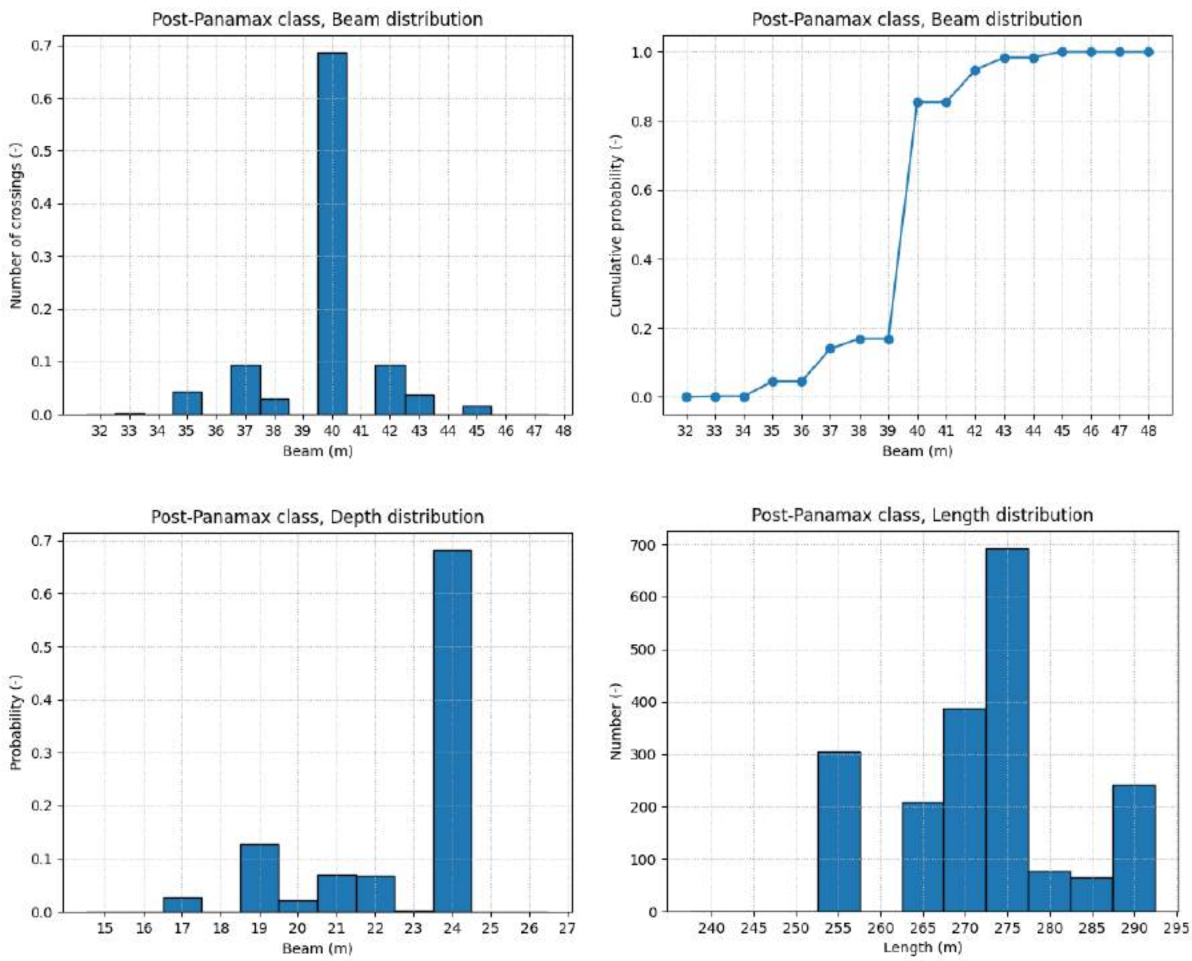


Figure 6-2: Beam, depth and length distributions of the Post-Panamax containerships.

Table 6-2: Loading condition details of the Post-Panamax.

Description	**LC Lowest GM**	**LC2 Highest GM**
Transverse metacentre; GM (m)	2.0	6.0
Roll radius of gyration; k_{xx} base value	0.370 B	0.370 B
Pitch radius of gyration; k_{yy}	0.26 Lpp	0.26 Lpp
Yaw radius of gyration; k_{zz}	0.26 Lpp	0.26 Lpp

Table 6-3: Points of interest on the Post-Panamax.

Point description	**X (m) w.r.t. APP**	**Y (m) w.r.t. CL**	**Z (m) w.r.t. BL**
Container bay fwd (tier 82, tier 94)	255.0	+/- 18.85	28.07 and 43.97
Container bay mid-ship	139.0	+/- 18.85	28.07 and 43.97
Container bay aft	20.0	+/- 18.85	28.07 and 43.97
UKC forward	278.0	0.0	0.0
UKC at side, station 11	152.9	4 points on hull contour	
UKC at side, station 9	125.1	4 points on hull contour	
UKC aft	0.0	0.0	0.0

6.4 Sea keeping limiting criteria

The dynamic under keel clearance criteria are discussed in Section 0. The MPM is set such that the probability for bottom contact is 1% at the most, given the exposure time for the water depth. The criteria are presented in Table 6-4.

The allowable class accelerations were obtained from StowLash and they are summarised in Table 6-5 for the 13.8 m sailing draughts and all GM conditions. The limiting values for the Panamax ship in the previous report (32558) sailing with GM 2.5 m were 0.57 g top-tier and 0.45 g deck-tier. For the Post-Panamax sailing at such very low GM the class values are slightly lower.

Table 6-4: Dynamic UKC criteria.

Dynamic UKC (m), MPM in 3 hrs	Water depth 19 m	Water depth 21 m
Panamax draught 12.2 m	+1.05	+2.00
Post-Panamax draught 13.8 m	+0.80	+1.60

Table 6-5: Maximum allowable accelerations.

POST-PANAMAX, L = 278 m, B = 40 m, Tm = 13.80 m, Vs = 10 kn							
Location of container tier @ forward location	Allowable acceleration (g) for GM (m)						
	2.0	3.0	4.0	4.5	5.0	5.5	6.0
acy top-tier, Tier 94	0.439	0.510	0.569	0.597	0.624	0.651	0.677
acy deck location, Tier 82	0.393	0.438	0.473	0.488	0.503	0.517	0.531

POST-PANAMAX, L = 278 m, B = 40 m, Tm = 13.80 m, Vs = 10 kn							
Location of container tier @ mid ship location	Allowable acceleration (g) for GM (m)						
	2.0	3.0	4.0	4.5	5.0	5.5	6.0
acy top-tier, Tier 94	0.410	0.477	0.534	0.560	0.586	0.611	0.636
acy deck location, Tier 82	0.370	0.416	0.451	0.466	0.481	0.496	0.510

POST-PANAMAX, L = 278 m, B = 40 m, Tm = 13.80 m, Vs = 10 kn							
Location of container tier @ stern location	Allowable acceleration (g) for GM (m)						
	2.0	3.0	4.0	4.5	5.0	5.5	6.0
acy top-tier, Tier 94	0.421	0.488	0.544	0.570	0.595	0.619	0.644
acy deck location, Tier 82	0.382	0.427	0.462	0.477	0.492	0.506	0.521

6.5 Results

6.5.1 Global ship motions

The bilge keel roll damping of the Post-Panamax vessel was calculated by SEACAL and corrected with the same tuning factor as derived from for the Panamax vessel. The tuning factor for the Panamax vessel was derived on the basis of the roll motion RMS as obtained in the model tests (project 32558).

In Table 6-6 an overview is given of the SEACAL calculated natural periods at various GM conditions at 21 m water depth. The natural roll periods vary from 23 s for GM 2 m, to about 13 s for GM 6 m. The values are representative for all water depths on the TSS. The range of wave periods in the area varies between 8 and 14 seconds so that in particular the vessels with higher GM condition will be prone to roll.

In Figure 6-3 the heave, roll and pitch motions RMS values in short-crested sea states of Hs 4.5 m are shown for various wave periods of the JONSWAP wave spectrum (with gamma = 1.5). The ship roll motions in shallow water conditions (19 and 21 m) are slightly larger than the roll motions in deep water of the northern route. The difference in ship motions at a water depth of 19 m and 21 m are insignificant.

The roll motions of the Post-Panamax ship are, in the same sea state of Hs 4.5 m, almost 40% larger than the roll motions of the ULCS. This is a very significant difference and the main cause is most likely the lower B/T ratio of 2.9 the Post-Panamax comparted to the B/T of 4.1 for the ULCS. This lower B/T value leads to a low hull wave damping, while a relatively high draught of the Post-Panamax leads to a submerged transom stern and large wave excitation.

Table 6-6: Roll period of the Post-Panamax (in water) as function of GM

Draught = 13.80 m, water depth = 21.0 m, Post-Panamax					
GM (m)	2.0	3.0	4.0	5.0	6.0
Roll period (s)	23	18.5	15.8	14.5	13.2

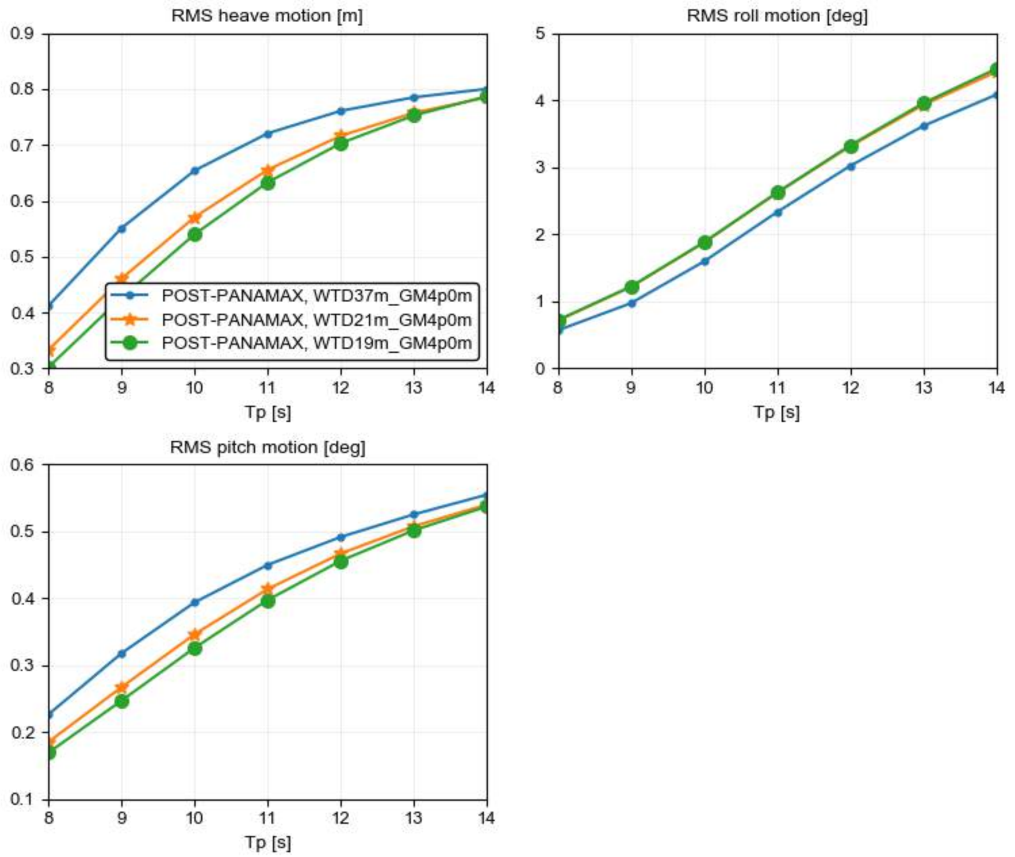


Figure 6-3: Global ship motions as function of water depth, Beam seas, Hs = 4.5 m, Tm = 13.8 m, GM = 4 m.

6.5.2 Dynamic under keel clearance

The calculated dynamic under keel clearance was evaluated against the criteria listed in Table 6-4 (and include the shallow water second-order heave correction).

The following is concluded:

- Northern route:
  - No limitations (both Panamax and Post-Panamax vessel).
- Southern route, 21 m water depth, results are in Table 6-7:
  - limiting significant wave height Hs of 3.5 m at a sailing draught of 13.8 m (Post-Panamax)
  - limiting significant wave height Hs of 4.5 m at a sailing draught of 12.2 m (Panamax)
- Southern route, 19 m water depth, results are in Table 6-7:
  - limiting significant wave height Hs of 2.7 m at a sailing draught of 13.8 m (Post-Panamax)
  - limiting significant wave height Hs of 4.5 m at a sailing draught of 12.2 m (Panamax)
- The limiting significant wave height is (almost) the same for all GM conditions at a given water depth.
- The limiting conditions occur in beam seas condition (+/- 30 deg). In head seas condition (+/- 15 deg) there is no risk on bottom contact up to Hs of 8 m.
- The metocean data statistics, see Table 2-1, shows that the Hs of 2.5 m is exceed 10% of the time.

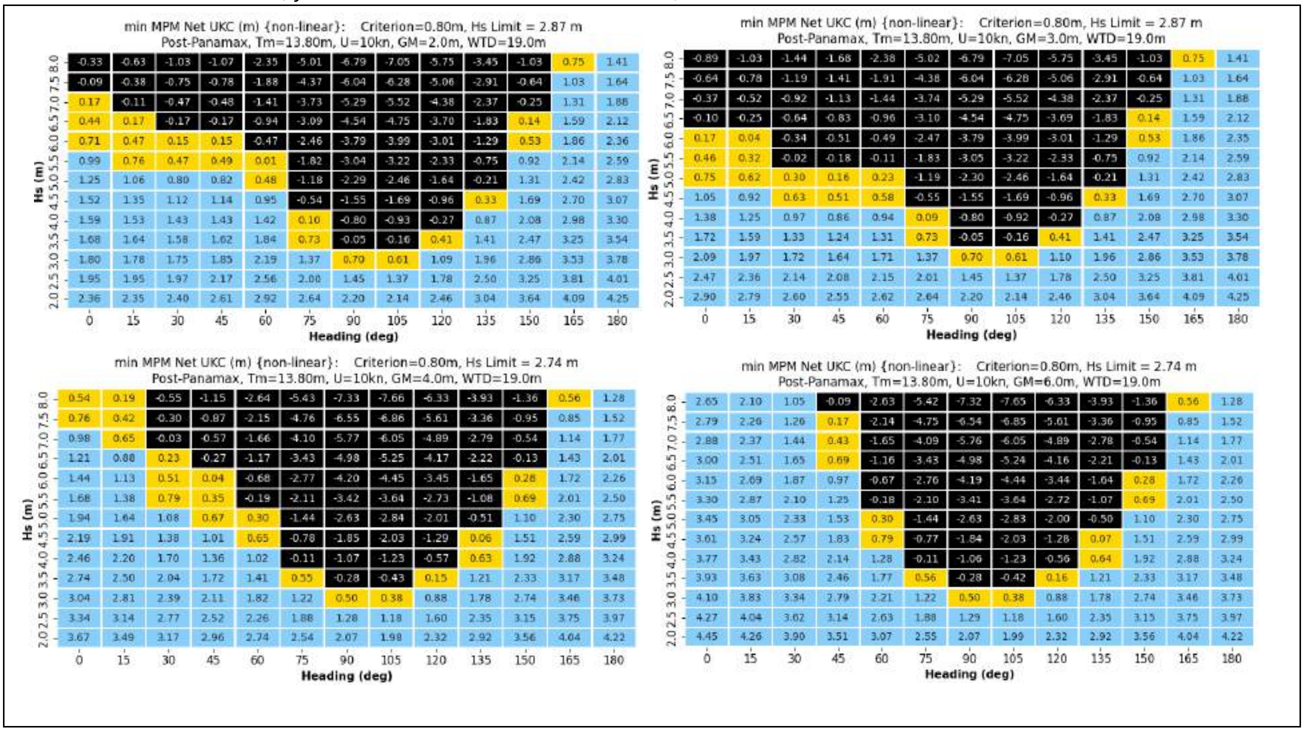
The effect of the wave period on the dynamic UKC is shown in Table 6-8 for the water depth of 19 m and for Hs **above** the limiting wave height, that is for Hs = 3.5 m, 4.0 m and 4.5 m. The following is observed:

- Up to Hs of 4.5 m, the dynamic UKC is above the limiting criteria when the wave period is lower than 10 seconds.
- At Hs = 4.0 m (which is almost twice the limiting Hs of 2.7 m) the dynamic UKC is above the limiting criteria when the wave period is 10.5 seconds or lower.
- From Figure 2-8 (the wave scatter diagram) it can be read that 87% of the sea states with a height between 3.5 and 4.0 m Hs have a wave period less than 10 seconds, and 98% of the sea states have a wave period less than 11 seconds.
- The metocean data statistics, see Table 2-1, shows that the Hs of 4.0 m is exceed 1.1% of the time, or about 4 days a year.

Based on the above observations, the limiting sea state of Hs = 4.0 m is a more realistic warning level for risk on bottom contact. In about 13% of the sea states with this Hs there is 1% risk on bottom contact given if the water depth is 19 m LAT. This water depth occurs at the most once per year. At 21 m LAT, a limiting wave height of 4.0 m Hs leads to sufficient dynamic UKC when the wave periods is 11.5 seconds or lower. Hence, in 98% of all occurring sea states the risk is less than 1% for bottom contact.

Table 6-7: MPM of dynamic under keel clearance, as function of GM at 13.8 m draught, 19 m and 21 m water depth. Post-Panamax vessel.

black = contact with seabed, yellow = UKC between 0 m and criterion, blue = UKC > criterion.



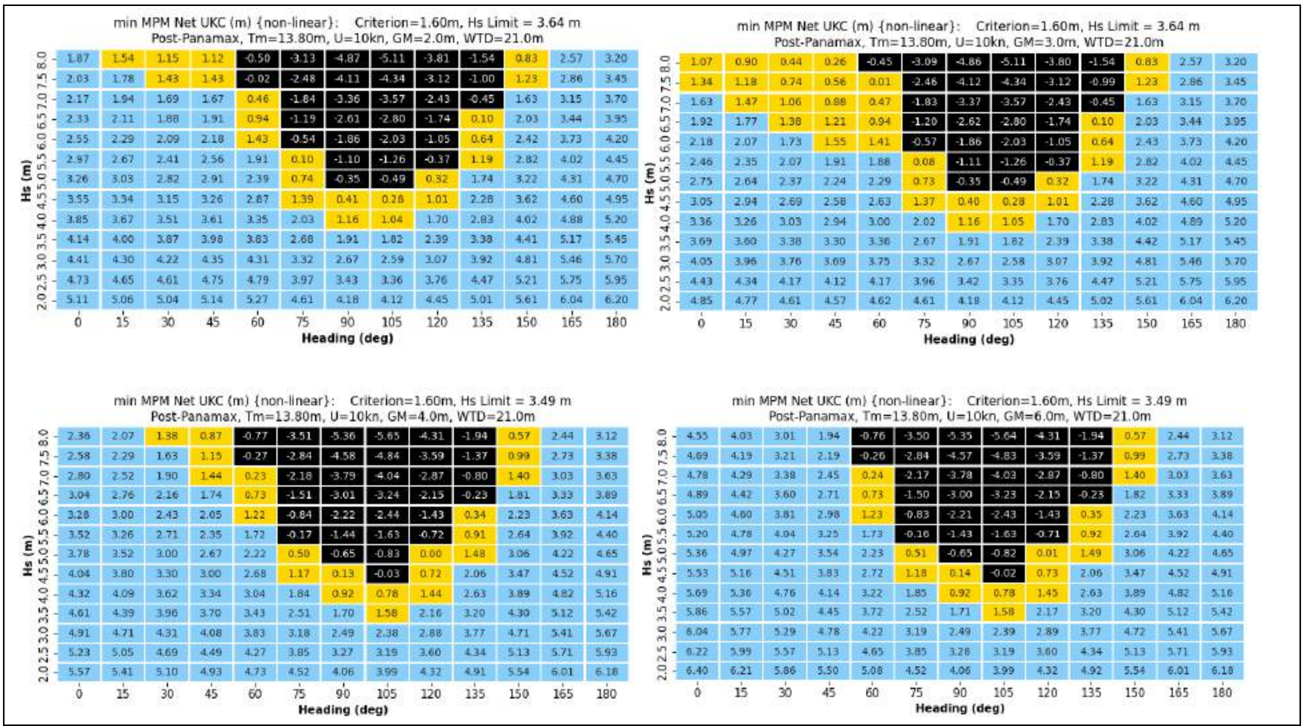
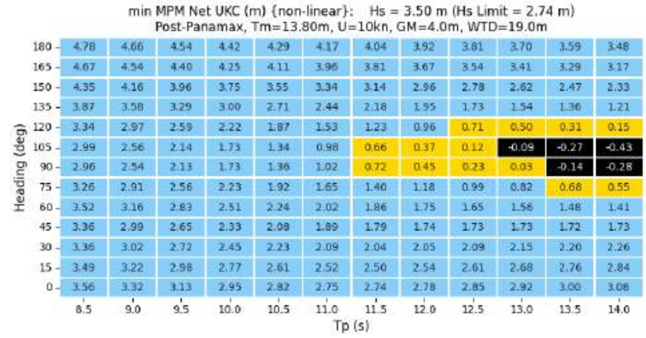
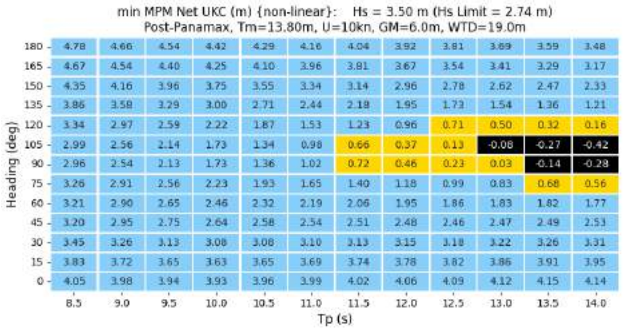
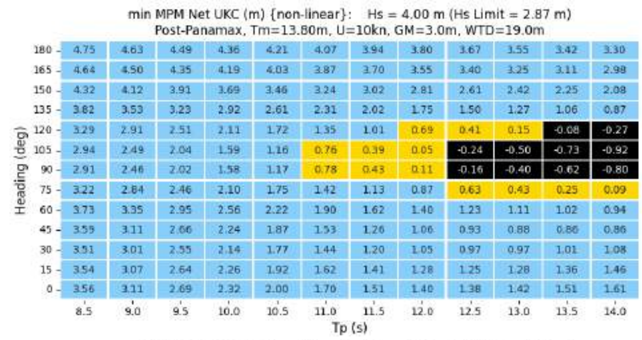


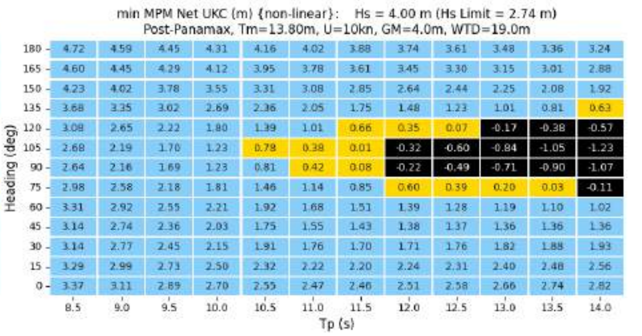
Table 6-8: MPM of dynamic under keel clearance, as function of heading and wave period for Hs = 3.5 m, Hs = 4.0 m and Hs = 4.5 m, 19 m water depth. Post-Panamax vessel.

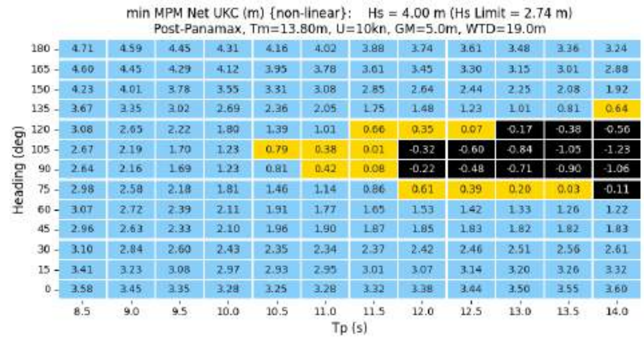
black = contact with seabed, yellow = UKC between 0 m and criterion, blue = UKC > criterion.

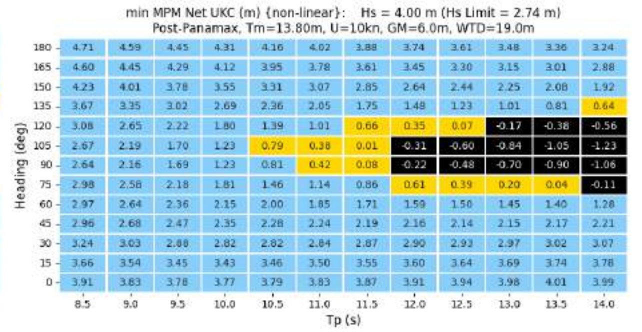


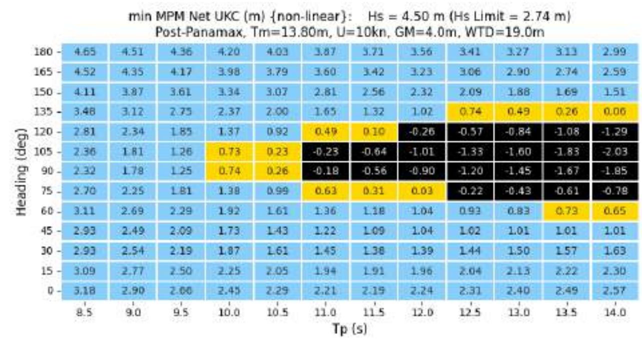


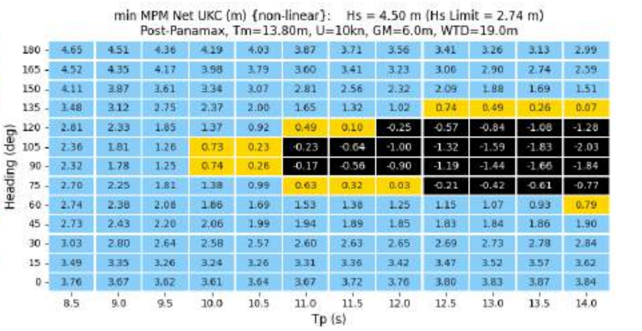












6.5.3 Container accelerations

The limiting significant wave heights based on the allowable transverse accelerations from class are summarised for the various GM's and sailing draughts in Table 5-10. Example plots of the acceleration levels for various GM conditions as function of heading and Hs are shown in Table 5-11.

The following is concluded:

- Northern route (37 m):
  - limiting significant wave height Hs of 6.0 m at a sailing draught of 13.8 m (Post-Panamax)
  - limiting significant wave height Hs of 6.5 m at a sailing draught of 12.2 m (Panamax)
- Southern route (19m and 21 m):
  - limiting significant wave height Hs of 5.3 m at a sailing draught of 13.8 m (Post-Panamax)
  - limiting significant wave height Hs of 5.5 m at a sailing draught of 12.2 m (Panamax)
- There is a significant effect of the GM on the limiting sea state. In general, a higher GM leads to a lower limiting significant wave height. At the lowest GM there are no sailing limitations w.r.t. the acceleration criterion.
- The limiting significant wave height is nearly the same for deck- and top-tier containers as well as for containers at the stern, mid-ship or bow location. It does not imply that all containers are at risk when the limiting sea state is reached because it is the mass*acceleration that determines the load. When the mass of the container is lower than the allowable mass, the securing system is less critically loaded. It is not known if the rule allowable mass is the maximum container mass at each tier height. The more heavier containers are usually stowed low in the stack.
- The limiting conditions occur in beam seas +/- 45 deg wave heading.
- In the head seas (+/- 30 deg) the accelerations stay below the class allowable values up to Hs of 8 m (on both routes). In following seas (+/ 30 deg) and in combination with a low GM the limiting significant wave height is about 6 m on the southern route, and none on the northern route.
- The northern route is more safe than the southern route w.r.t. the acceleration limits.

Table 6-9: Limiting significant wave heights on southern and northern route w.r.t. transverse acceleration

Southern route, 21 m water depth and 19 m water depth (acc limiting Hs is within 0.1 m)						
Limiting significant wave height Hs (m), Post-Panamax, Tm=13.8 m						
	Deck tier			Top tier		
GM (m)	aft	mid	bow	aft	mid	bow
6.0	5.6	5.4	5.6	5.9	5.6	5.5
5.0	5.7	5.5	5.6	5.5	5.3	5.6
4.0	5.9	5.9	6.1	5.7	5.7	6.1
3.0	6.3	6.2	6.4	6.1	6.0	6.4
2.0	7.8	7.5	7.7	7.4	7.1	7.5

Northern route, 37 m water depth						
Limiting significant wave height Hs (m), Post-Panamax, Tm=13.8 m						
	Deck tier			Top tier		
GM (m)	aft	mid	bow	aft	mid	bow
6.0	6.5	6.3	6.2	6.2	6.0	6.3
5.0	6.5	6.2	6.3	6.1	6.0	6.3
4.0	6.7	6.7	7.0	6.5	6.5	7.0
3.0	> 8.0	> 8.0	> 8.0	> 8.0	> 8.0	> 8.0
2.0	> 8.0	> 8.0	> 8.0	> 8.0	> 8.0	> 8.0
Limiting significant wave height Hs (m), Panamax, Tm=12.2 m (32558)						
GM (m)	Deck Tier			Top Tier		
4.0				3.5		
2.5				5.5		
1.0				> 8 m		

Table 6-10: Accelerations at top-tier and deck containers versus class allowable values, water depth 21 m, sailing draught 13.8 m, GM 2 to 6 m.

Red = above class limit. Yellow = above 90% of limit.

max MPM transverse acc (g) @ low-tier, mid-ship, Criterion = 0.370 g, Hs Limit = 7.5 m
Post-Panamax, Tm=13.80m, U=10kn, GM=2.00m, WTD=21.0m

Hs (m) \ Heading (deg)	0	15	30	45	60	75	90	105	120	135	150	165	180
8.0	0.362	0.373	0.388	0.386	0.366	0.337	0.300	0.254	0.200	0.136	0.088	0.056	0.045
7.5	0.351	0.357	0.371	0.368	0.351	0.319	0.282	0.240	0.189	0.127	0.082	0.053	0.042
7.0	0.341	0.347	0.355	0.353	0.334	0.300	0.266	0.226	0.177	0.118	0.076	0.049	0.039
6.5	0.330	0.335	0.343	0.338	0.314	0.282	0.249	0.212	0.166	0.109	0.071	0.046	0.037
6.0	0.315	0.323	0.329	0.322	0.293	0.263	0.232	0.198	0.153	0.101	0.065	0.042	0.034
5.5	0.286	0.298	0.308	0.297	0.273	0.244	0.215	0.185	0.137	0.092	0.060	0.039	0.031
5.0	0.267	0.274	0.282	0.275	0.253	0.225	0.199	0.171	0.122	0.084	0.054	0.035	0.028
4.5	0.247	0.254	0.261	0.254	0.232	0.206	0.182	0.157	0.108	0.075	0.049	0.032	0.025
4.0	0.226	0.232	0.239	0.231	0.211	0.186	0.167	0.142	0.096	0.067	0.044	0.028	0.022
3.5	0.207	0.211	0.215	0.208	0.189	0.167	0.152	0.117	0.084	0.059	0.038	0.025	0.020
3.0	0.188	0.191	0.193	0.185	0.166	0.150	0.136	0.096	0.072	0.050	0.033	0.021	0.017
2.5	0.166	0.168	0.168	0.159	0.144	0.133	0.111	0.080	0.060	0.042	0.027	0.018	0.014
2.0	0.140	0.142	0.141	0.135	0.125	0.115	0.081	0.064	0.048	0.033	0.022	0.014	0.011

max MPM transverse acc (g) @ high-tier, mid-ship, Criterion = 0.410 g, Hs Limit = 7.1 m
Post-Panamax, Tm=13.80m, U=10kn, GM=2.00m, WTD=21.0m

Hs (m) \ Heading (deg)	0	15	30	45	60	75	90	105	120	135	150	165	180
8.0	0.411	0.424	0.443	0.443	0.421	0.385	0.342	0.290	0.231	0.163	0.111	0.076	0.063
7.5	0.398	0.406	0.424	0.422	0.403	0.365	0.322	0.274	0.218	0.152	0.104	0.072	0.060
7.0	0.386	0.394	0.405	0.404	0.383	0.344	0.303	0.258	0.205	0.141	0.097	0.067	0.056
6.5	0.374	0.381	0.390	0.387	0.359	0.323	0.284	0.242	0.191	0.131	0.090	0.062	0.052
6.0	0.356	0.366	0.375	0.368	0.336	0.301	0.264	0.226	0.176	0.121	0.083	0.057	0.048
5.5	0.324	0.337	0.351	0.340	0.313	0.279	0.245	0.210	0.158	0.110	0.076	0.053	0.044
5.0	0.302	0.311	0.321	0.314	0.290	0.257	0.226	0.195	0.141	0.100	0.069	0.048	0.040
4.5	0.279	0.287	0.297	0.290	0.266	0.235	0.207	0.179	0.126	0.090	0.062	0.043	0.036
4.0	0.256	0.263	0.271	0.264	0.241	0.213	0.190	0.162	0.112	0.080	0.055	0.038	0.032
3.5	0.234	0.239	0.245	0.238	0.216	0.190	0.172	0.133	0.098	0.070	0.048	0.033	0.028
3.0	0.212	0.216	0.219	0.211	0.190	0.171	0.154	0.110	0.084	0.060	0.041	0.029	0.024
2.5	0.187	0.190	0.191	0.181	0.164	0.152	0.126	0.091	0.070	0.050	0.034	0.024	0.020
2.0	0.158	0.160	0.160	0.153	0.142	0.130	0.092	0.073	0.056	0.040	0.028	0.019	0.016

max MPM transverse acc (g) @ low-tier, mid-ship, Criterion = 0.416 g, Hs Limit = 6.2 m
Post-Panamax, Tm=13.80m, U=10kn, GM=3.00m, WTD=21.0m

Hs (m) \ Heading (deg)	0	15	30	45	60	75	90	105	120	135	150	165	180
8.0	0.427	0.450	0.487	0.499	0.495	0.486	0.463	0.413	0.334	0.240	0.154	0.092	0.065
7.5	0.407	0.430	0.464	0.476	0.474	0.464	0.441	0.393	0.317	0.227	0.145	0.086	0.061
7.0	0.388	0.408	0.441	0.453	0.451	0.442	0.418	0.372	0.299	0.214	0.136	0.080	0.057
6.5	0.367	0.387	0.418	0.429	0.428	0.418	0.396	0.351	0.280	0.200	0.127	0.074	0.052
6.0	0.349	0.365	0.393	0.404	0.404	0.394	0.374	0.330	0.262	0.186	0.118	0.068	0.048
5.5	0.330	0.345	0.368	0.378	0.379	0.371	0.350	0.307	0.244	0.172	0.109	0.062	0.044
5.0	0.310	0.324	0.346	0.355	0.356	0.347	0.326	0.285	0.225	0.158	0.100	0.056	0.040
4.5	0.289	0.302	0.323	0.331	0.331	0.322	0.301	0.261	0.206	0.144	0.090	0.050	0.036
4.0	0.267	0.280	0.298	0.305	0.305	0.296	0.275	0.238	0.186	0.130	0.080	0.044	0.032
3.5	0.244	0.255	0.273	0.279	0.279	0.269	0.248	0.213	0.166	0.115	0.069	0.039	0.028
3.0	0.219	0.230	0.246	0.251	0.250	0.240	0.220	0.188	0.145	0.100	0.059	0.033	0.024
2.5	0.192	0.202	0.216	0.221	0.219	0.210	0.191	0.161	0.123	0.084	0.048	0.028	0.020
2.0	0.163	0.172	0.184	0.188	0.186	0.177	0.159	0.133	0.101	0.067	0.039	0.022	0.016

max MPM transverse acc (g) @ high-tier, mid-ship, Criterion = 0.477 g, Hs Limit = 6.0 m
Post-Panamax, Tm=13.80m, U=10kn, GM=3.00m, WTD=21.0m

Hs (m) \ Heading (deg)	0	15	30	45	60	75	90	105	120	135	150	165	180
8.0	0.499	0.527	0.572	0.588	0.585	0.574	0.546	0.487	0.396	0.287	0.189	0.117	0.086
7.5	0.476	0.503	0.546	0.561	0.559	0.548	0.520	0.463	0.375	0.272	0.178	0.109	0.081
7.0	0.453	0.478	0.519	0.533	0.533	0.521	0.493	0.439	0.353	0.255	0.167	0.102	0.075
6.5	0.430	0.453	0.491	0.505	0.505	0.494	0.467	0.414	0.331	0.239	0.156	0.094	0.070
6.0	0.408	0.428	0.462	0.475	0.477	0.465	0.440	0.388	0.310	0.222	0.144	0.086	0.064
5.5	0.385	0.404	0.433	0.445	0.447	0.438	0.413	0.362	0.288	0.206	0.133	0.079	0.059
5.0	0.362	0.380	0.407	0.418	0.420	0.410	0.384	0.335	0.266	0.189	0.122	0.071	0.054
4.5	0.337	0.354	0.380	0.389	0.391	0.380	0.355	0.307	0.243	0.172	0.110	0.064	0.048
4.0	0.312	0.327	0.350	0.359	0.360	0.349	0.324	0.280	0.219	0.155	0.097	0.057	0.043
3.5	0.285	0.299	0.321	0.328	0.328	0.317	0.292	0.251	0.195	0.137	0.084	0.049	0.038
3.0	0.256	0.269	0.288	0.295	0.294	0.282	0.259	0.221	0.171	0.119	0.072	0.042	0.032
2.5	0.224	0.236	0.254	0.259	0.258	0.247	0.225	0.190	0.145	0.100	0.059	0.035	0.027
2.0	0.191	0.201	0.216	0.221	0.219	0.208	0.187	0.157	0.119	0.079	0.047	0.028	0.021

max MPM transverse acc (g) @ low-tier, mid-ship, Criterion = 0.451 g, Hs Limit = 5.9 m
Post-Panamax, Tm=13.80m, U=10kn, GM=4.00m, WTD=21.0m

Hs (m) \ Heading (deg)	0	15	30	45	60	75	90	105	120	135	150	165	180
8.0	0.349	0.382	0.439	0.477	0.514	0.549	0.559	0.528	0.450	0.346	0.238	0.150	0.111
7.5	0.334	0.366	0.419	0.456	0.492	0.526	0.535	0.503	0.429	0.328	0.225	0.141	0.105
7.0	0.318	0.348	0.399	0.435	0.470	0.502	0.509	0.478	0.406	0.311	0.212	0.133	0.098
6.5	0.301	0.330	0.379	0.413	0.447	0.477	0.483	0.451	0.384	0.293	0.199	0.124	0.092
6.0	0.284	0.312	0.359	0.390	0.422	0.450	0.455	0.425	0.361	0.274	0.186	0.115	0.085
5.5	0.266	0.293	0.337	0.367	0.397	0.423	0.427	0.398	0.337	0.255	0.172	0.107	0.079
5.0	0.247	0.273	0.315	0.343	0.372	0.395	0.398	0.371	0.313	0.236	0.159	0.098	0.072
4.5	0.228	0.252	0.292	0.318	0.345	0.367	0.369	0.342	0.288	0.216	0.145	0.089	0.065
4.0	0.208	0.231	0.268	0.292	0.317	0.337	0.338	0.313	0.262	0.196	0.130	0.079	0.058
3.5	0.187	0.208	0.243	0.265	0.288	0.306	0.306	0.282	0.235	0.175	0.116	0.070	0.051
3.0	0.166	0.184	0.216	0.236	0.257	0.273	0.272	0.250	0.207	0.153	0.101	0.061	0.044
2.5	0.142	0.159	0.187	0.205	0.224	0.237	0.236	0.216	0.178	0.130	0.085	0.051	0.037
2.0	0.118	0.132	0.157	0.172	0.188	0.199	0.198	0.180	0.147	0.107	0.069	0.041	0.029

max MPM transverse acc (g) @ high-tier, mid-ship, Criterion = 0.534 g, Hs Limit = 5.7 m
Post-Panamax, Tm=13.80m, U=10kn, GM=4.00m, WTD=21.0m

Hs (m) \ Heading (deg)	0	15	30	45	60	75	90	105	120	135	150	165	180
8.0	0.420	0.461	0.532	0.580	0.625	0.668	0.680	0.641	0.547	0.423	0.293	0.188	0.143
7.5	0.402	0.441	0.508	0.555	0.599	0.640	0.650	0.611	0.521	0.401	0.278	0.178	0.134
7.0	0.382	0.420	0.484	0.529	0.572	0.611	0.619	0.580	0.494	0.380	0.262	0.167	0.126
6.5	0.362	0.399	0.460	0.502	0.544	0.580	0.587	0.548	0.467	0.357	0.246	0.156	0.117
6.0	0.342	0.377	0.435	0.474	0.514	0.548	0.554	0.516	0.438	0.335	0.229	0.145	0.109
5.5	0.320	0.354	0.409	0.446	0.483	0.515	0.519	0.484	0.410	0.312	0.213	0.134	0.100
5.0	0.298	0.330	0.382	0.417	0.452	0.481	0.484	0.450	0.380	0.288	0.196	0.122	0.092
4.5	0.275	0.305	0.354	0.387	0.420	0.446	0.449	0.416	0.350	0.264	0.178	0.111	0.083
4.0	0.251	0.279	0.325	0.355	0.386	0.410	0.411	0.380	0.318	0.239	0.160	0.100	0.074
3.5	0.226	0.252	0.294	0.322	0.350	0.372	0.372	0.343	0.286	0.213	0.142	0.088	0.065
3.0	0.200	0.223	0.262	0.287	0.313	0.332	0.331	0.303	0.252	0.187	0.124	0.076	0.056
2.5	0.172	0.192	0.227	0.249	0.272	0.289	0.287	0.262	0.216	0.159	0.105	0.064	0.047
2.0	0.143	0.160	0.190	0.209	0.229	0.243	0.241	0.218	0.179	0.131	0.085	0.051	0.037

max MPM transverse acc (g) @ low-tier, mid-ship, Criterion = 0.481 g, Hs Limit = 5.5 m
Post-Panamax, Tm=13.80m, U=10kn, GM=5.00m, WTD=21.0m

Hs (m) \ Heading (deg)	0	15	30	45	60	75	90	105	120	135	150	165	180
8.0	0.269	0.311	0.385	0.448	0.518	0.584	0.621	0.607	0.537	0.425	0.303	0.199	0.151
7.5	0.256	0.296	0.367	0.428	0.496	0.560	0.595	0.581	0.512	0.404	0.288	0.188	0.142
7.0	0.245	0.283	0.349	0.407	0.473	0.535	0.568	0.553	0.486	0.383	0.272	0.177	0.134
6.5	0.231	0.267	0.330	0.386	0.448	0.508	0.540	0.524	0.459	0.362	0.256	0.166	0.125
6.0	0.217	0.251	0.311	0.364	0.423	0.481	0.510	0.495	0.433	0.340	0.240	0.155	0.117
5.5	0.202	0.234	0.291	0.341	0.397	0.452	0.479	0.464	0.405	0.318	0.223	0.144	0.108
5.0	0.187	0.217	0.271	0.318	0.371	0.421	0.447	0.432	0.377	0.295	0.206	0.132	0.099
4.5	0.171	0.199	0.249	0.294	0.344	0.391	0.414	0.400	0.348	0.271	0.189	0.120	0.090
4.0	0.155	0.181	0.227	0.268	0.315	0.359	0.380	0.366	0.318	0.247	0.170	0.108	0.080
3.5	0.138	0.162	0.204	0.242	0.285	0.325	0.344	0.331	0.286	0.221	0.152	0.095	0.071
3.0	0.120	0.142	0.180	0.214	0.253	0.290	0.307	0.294	0.253	0.194	0.132	0.083	0.061
2.5	0.102	0.121	0.154	0.184	0.220	0.252	0.266	0.255	0.219	0.166	0.113	0.070	0.052
2.0	0.083	0.099	0.127	0.153	0.183	0.211	0.223	0.213	0.182	0.137	0.092	0.057	0.041

max MPM transverse acc (g) @ high-tier, mid-ship, Criterion = 0.586 g, Hs Limit = 5.3 m
Post-Panamax, Tm=13.80m, U=10kn, GM=5.00m, WTD=21.0m

Hs (m) \ Heading (deg)	0	15	30	45	60	75	90	105	120	135	150	165	180
8.0	0.333	0.386	0.480	0.562	0.651	0.732	0.776	0.757	0.670	0.531	0.382	0.253	0.194
7.5	0.317	0.368	0.459	0.536	0.622	0.702	0.744	0.725	0.638	0.506	0.362	0.239	0.183
7.0	0.305	0.352	0.436	0.510	0.593	0.670	0.710	0.690	0.606	0.480	0.343	0.225	0.172
6.5	0.287	0.333	0.413	0.483	0.562	0.637	0.675	0.655	0.573	0.453	0.323	0.211	0.161
6.0	0.269	0.313	0.389	0.456	0.531	0.603	0.638	0.618	0.540	0.426	0.302	0.197	0.150
5.5	0.251	0.292	0.364	0.428	0.499	0.566	0.600	0.579	0.506	0.398	0.281	0.182	0.138
5.0	0.232	0.271	0.339	0.398	0.466	0.528	0.559	0.540	0.471	0.369	0.260	0.168	0.127
4.5	0.213	0.248	0.312	0.368	0.432	0.490	0.518	0.500	0.435	0.340	0.237	0.152	0.115
4.0	0.192	0.226	0.285	0.336	0.396	0.450	0.476	0.458	0.397	0.309	0.214	0.137	0.103
3.5	0.171	0.202	0.256	0.303	0.358	0.408	0.431	0.414	0.358	0.277	0.191	0.121	0.091
3.0	0.150	0.177	0.225	0.268	0.318	0.363	0.384	0.368	0.317	0.244	0.167	0.105	0.079
2.5	0.127	0.151	0.193	0.231	0.276	0.316	0.334	0.319	0.273	0.208	0.142	0.089	0.066
2.0	0.104	0.124	0.159	0.192	0.230	0.265	0.280	0.267	0.227	0.172	0.116	0.072	0.053

max MPM transverse acc (g) @ low-tier, mid-ship, Criterion = 0.510 g, Hs Limit = 5.6 m
Post-Panamax, Tm=13.80m, U=10kn, GM=6.00m, WTD=21.0m

Hs (m) \ Heading (deg)	0	15	30	45	60	75	90	105	120	135	150	165	180
8.0	0.206	0.253	0.342	0.431	0.527	0.608	0.653	0.645	0.580	0.465	0.334	0.218	0.163
7.5	0.195	0.240	0.326	0.411	0.503	0.583	0.626	0.618	0.554	0.443	0.317	0.206	0.154
7.0	0.190	0.233	0.312	0.391	0.479	0.555	0.597	0.589	0.526	0.420	0.300	0.194	0.144
6.5	0.182	0.222	0.296	0.370	0.453	0.527	0.567	0.559	0.498	0.397	0.282	0.182	0.135
6.0	0.170	0.208	0.278	0.348	0.427	0.498	0.536	0.527	0.468	0.373	0.264	0.169	0.125
5.5	0.158	0.194	0.259	0.326	0.401	0.467	0.503	0.494	0.439	0.349	0.246	0.157	0.116
5.0	0.145	0.179	0.240	0.302	0.374	0.435	0.469	0.460	0.408	0.323	0.227	0.144	0.106
4.5	0.133	0.163	0.220	0.278	0.345	0.402	0.433	0.425	0.377	0.297	0.207	0.131	0.096
4.0	0.120	0.148	0.200	0.253	0.315	0.368	0.397	0.389	0.344	0.270	0.187	0.117	0.086
3.5	0.106	0.131	0.179	0.227	0.284	0.333	0.359	0.352	0.310	0.242	0.167	0.104	0.076
3.0	0.092	0.115	0.157	0.200	0.251	0.295	0.318	0.312	0.274	0.213	0.145	0.090	0.065
2.5	0.078	0.097	0.134	0.172	0.217	0.255	0.276	0.270	0.236	0.182	0.123	0.076	0.055
2.0	0.063	0.079	0.110	0.141	0.180	0.213	0.230	0.224	0.195	0.150	0.101	0.061	0.044

max MPM transverse acc (g) @ high-tier, mid-ship, Criterion = 0.636 g, Hs Limit = 5.4 m
Post-Panamax, Tm=13.80m, U=10kn, GM=6.00m, WTD=21.0m

Hs (m) \ Heading (deg)	0	15	30	45	60	75	90	105	120	135	150	165	180
8.0	0.261	0.322	0.438	0.554	0.679	0.783	0.838	0.825	0.741	0.595	0.430	0.283	0.214
7.5	0.247	0.306	0.417	0.529	0.649	0.750	0.803	0.790	0.708	0.567	0.408	0.267	0.202
7.0	0.241	0.297	0.401	0.502	0.617	0.715	0.766	0.753	0.673	0.538	0.386	0.252	0.189
6.5	0.232	0.284	0.380	0.476	0.584	0.679	0.728	0.715	0.637	0.509	0.363	0.236	0.177
6.0	0.218	0.266	0.357	0.448	0.551	0.641	0.688	0.675	0.599	0.478	0.340	0.219	0.164
5.5	0.202	0.248	0.333	0.419	0.517	0.601	0.646	0.633	0.562	0.447	0.316	0.203	0.151
5.0	0.186	0.229	0.309	0.389	0.482	0.560	0.602	0.590	0.523	0.415	0.292	0.186	0.139
4.5	0.170	0.209	0.283	0.358	0.445	0.518	0.557	0.545	0.483	0.381	0.267	0.169	0.125
4.0	0.153	0.189	0.257	0.326	0.407	0.475	0.510	0.499	0.441	0.346	0.241	0.152	0.112
3.5	0.136	0.168	0.230	0.293	0.366	0.429	0.461	0.451	0.397	0.310	0.215	0.134	0.099
3.0	0.118	0.147	0.202	0.258	0.324	0.380	0.409	0.400	0.351	0.273	0.187	0.116	0.085
2.5	0.100	0.124	0.172	0.221	0.279	0.329	0.355	0.346	0.302	0.233	0.159	0.098	0.072
2.0	0.081	0.101	0.141	0.182	0.232	0.274	0.296	0.288	0.250	0.192	0.129	0.079	0.058

6.6 Green water

The green water discussion is presented Chapter 8. The results shown in the summary table, , are valid for the given freeboard height.

6.7 Final limiting wave heights for the Panamax ships

Table 6-11 lists the final derived limiting significant wave heights for the ULCS containerships on the northern and southern route.

The limiting conditions occur in beam seas +/- 45 deg.

There are no limitations when sailing in head seas condition +/- 15 deg.

The only limiting criterion on the northern route is exceedance of the by class rules assumed acceleration in storms of Hs 6.0 m or higher. Note that this is an acceleration limit and not a securing load limit. The loading computer will verify if the securing load is exceeded given the actual mass of the container. The limiting Hs concerning the acceleration is 5.3 m Hs on the southern route.

The acceleration limits are consistent between deck and top-tier containers. The limiting sea state does not depend on the considered tier height.

The limiting criterion on the southern route is the dynamic UKC. At 19 m LAT the limiting sea state of 2.7 m Hs was found from direct calculations, using a 1% risk for bottom contact in any sea state (Hs-Tp) and any heading.

Further data analysis shows that when the limit is set to Hs of 4.0 m there is only a small number of beam sea states in which the risk of bottom contact is above 1%. This limit is proposed as a more realistic criterion.

Based on 40 years of metocean data, the significant wave height is 4.0 m or higher for about 96 hours/year (4 days).

The determined seakeeping calculation accuracy is conservative, while the accuracy of the metocean condition is biased low. Both errors cancel out. Further reduction on Hs due to the metocean inaccuracy is not deemed necessary.

Table 6-11: Final proposed limiting sea state conditions, Panamax class.

Relevant for beam seas sailing +/- 45 deg	**Post-Panamax** (beam 40 m) sailing draught 13.8 m freeboard 10.2 m	**Panamax** (beam 32.3 m) sailing draught 12.2 m freeboard 9.2 m
Northern route (37 m)	**Hs ≈ 6.1 m (accelerations)** no risk on bottom contact Hs ≈ 6.5 m (green water)	Hs ≈ 6.1 m (accelerations) no risk on bottom contact Hs ≈ 5.7 m (green water)
Southern route westbound, min LAT = 21 m	Hs ≈ 5.3 m (accelerations) **Hs ≈ 4.0 m** (bottom contact) Hs ≈ 5 m (green water)	Hs ≈ 5.5 m (accelerations) Hs ≈ 4.5 m (bottom contact) Hs ≈ 4.8 m (green water)
Southern route eastbound, min LAT = 19 m	Hs ≈ 5.3 m (accelerations) **Hs ≈ 4.0 m** (bottom contact) Hs ≈ 5 m (green water)	Not derived & not expected to be governing.

7 RESULTS FOR THE FEEDER CONTAINERSHIPS

7.1 Introduction

The Feeder containerships have a length between 100 and 200 m. Some of these ships are fully cellular containership, others are general cargo ships with possible containers on deck. In Figure 7-1 two typical (fully cellular) Feeders are shown.

Figure 7-1: Typical Feeder containerships.

7.2 Conclusions from previous investigations

The investigations performed in the previous two studies (32558, 33327) give directions for the additional investigations in the present study.

In Table 1-1 (Chapter 1) the preliminary limiting significant wave heights are given based on the model test results and seakeeping calculations for a Feeder with a draught of 9.20 m and a freeboard of 3.0 m. The investigations in 32558 concluded:

- When sailing in beam waves conditions, the green water risk to the containers lead to the overall limiting significant wave height of Hs 3.3 m.
- The acceleration limit is the least constraining factor and only occurs in the most extreme seas in the area (Hs > 6.5 m). The limits only occur in beam seas heading.
- In rather high sea states (Hs > 5.5 m), bottom contact due to large pitch and heave motions is possible in head seas on the southern route. The Feeders do not touch ground at the side, even in high beam seas condition.
- In report 32558 further investigations were recommended to detail the green water risk which is considered to be function of freeboard and the wave steepness in particular. This further investigations are presented in report 33327.

Further investigations for the green water threat on Feeder class containerships was carried out in MARIN project 33327. A combination of model tests, CFD simulations and FE calculations was performed. This chain of “tools” is new in the application of green water and provides realistic insights in container safety or failure due to green water impacts. The study comes with significant effort and costs and cannot be generalised to other situations easily. A snap-shot of a wave impact in model test and CFD and of a critical FEM calculation result (not correlated) is shown in Figure 7-2. The results from project 33327 lead to a proposed final limiting significant wave height as function of wave direction and vessel freeboard. The table is presented in Table 7-1.

Table 7-1: Final proposed limiting wave heights for Feeders as function of freeboard height (project 33327).

Freeboard height	**2.3 m**	**3.8 m**	**5.3 m**
135/225 deg (bow-quartering waves)	3.4 m	4.5 m	5.6 m
90/270 deg (beam waves)	*2.4 m*	*3.0 m*	*3.4 m*
45/315 deg (stern-quartering waves)	3.5 m	4.9 m	6.0 m

The following conclusions are copied from the conclusions in project 33327:

- From the table of limiting wave heights is can be seen that the beam waves yield the lowest limit. For a range of freeboard heights investigated the limiting wave height is 2.4 to 3.4 m.
- The results obtained at various wave heights show that this advice is independent of the water depth.
- The newly found limiting sea states are lower than initially proposed. One reason is that the wave conditions were changed from a most probably wave period in the model tests to more steeper occurring sea states in the area of interest (lower Tp values at the same wave height). In general it is known that in steeper seas green water risk increases.
- In bow and stern quartering waves, the situation gets better. The overall exposure is less and the impact loads on containers from an impact are lower. Given a freeboard height of 2.3 m, the limiting significant wave height increases by +1 m, for a ship with freeboard 5.3 m the limiting wave height increases by +2.2 m.
- The results obtained (33327) at various wave heights show that the advice is independent of the water depth (configuration 2, freeboard height 3.8 m).
    - Southern route, beam seas: Hs limit = 3.0 m
    - Northern route, beam seas: Hs limit = 3.1 m
    - Deep North Sea, beam seas: Hs limit = 3.1 m
- When the wave height exceeds 3.0 m, the situation degrades in shallow water faster then in deep water.

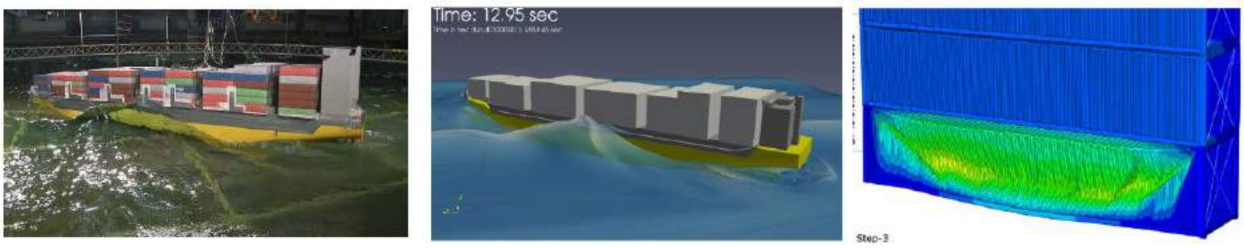


Figure 7-2: Model test (left), CFD (middle) and FEM (right) utilised to derive limiting wave heights.

7.3 Final limiting wave heights for the Feeders

Given the fact that the green water risk limits the operation of the Feeders more than the transverse accelerations or possible risk on bottom contact, no additional sea keeping calculations are performed in the present investigations.

The final limiting significant wave heights derived for the Feeders are presented in Table 7-2. Note that the freeboard heights are discrete values. For a ship with different freeboard that the three values listed in the table, the limiting significant wave height will be different.

It is noted that the final proposed limiting significant wave height is not a single value as used at present. Clearly this complicates the advice to the Feeders and it is most likely even ‘nearly impossible’ due to the many ships sailing on the TSS.

It is noted that the design freeboard is present in the AIS data, but the actual freeboard is not. This can only be re-calculated from the actual draught and known vessel depth.

Table 7-2: Final proposed limiting wave heights for Feeders as function of freeboard height (project 33327).

Freeboard height	**2.3 m**	**3.8 m**	**5.3 m**
135/225 deg (bow-quartering waves)	3.4 m	4.5 m	5.6 m
90/270 deg (beam waves)	*2.4 m*	*3.0 m*	*3.4 m*
45/315 deg (stern-quartering waves)	3.5 m	4.9 m	6.0 m

The freeboard height is an important factor and in Chapter 8 the results from the AIS network study are combined with the limiting sea states from all model tests for discrete freeboard values. The result is a “risk” matrix showing the % of ships with given freeboard height.

The present route advice warning for waves above Hs of 3.3 m was based on the first investigations (32558) in sea states with relative long wave periods and a freeboard height of 3.0 m. In Chapter 8 an analysis is made using the present data obtained in steeper sea states. The derived limiting wave height for a ship with freeboard 3.0 m is Hs of 2.8 m.

The new lower limiting Hs comes from the inclusion of steeper sea states with shorter wave period. Longer wave periods give some risk reduction, but risk remains. An overview of the steepest sea states used is given in Figure 7-3 in relationship to the wave scatter diagram.

When the overall lowest significant wave height will be used in the new final route advice, that is Hs of 2.4 m, a number of ships with higher freeboard with will be advised to take measures will they are not at risk. But, using a higher threshold could imply that some Feeders are at risk while not being warned. This is further discussed in Chapter 8.

Note that the present Netherlands Coastguard route advice does not detail the possible measures to take; it is based on knowledgeable and/or experienced driven ‘good seamanship’.

The safest measure is to sail at low speed in head waves. Until significant wave heights of 6 m the loads on the containers at the bow in head waves are limited and no critical parametric roll is observed.

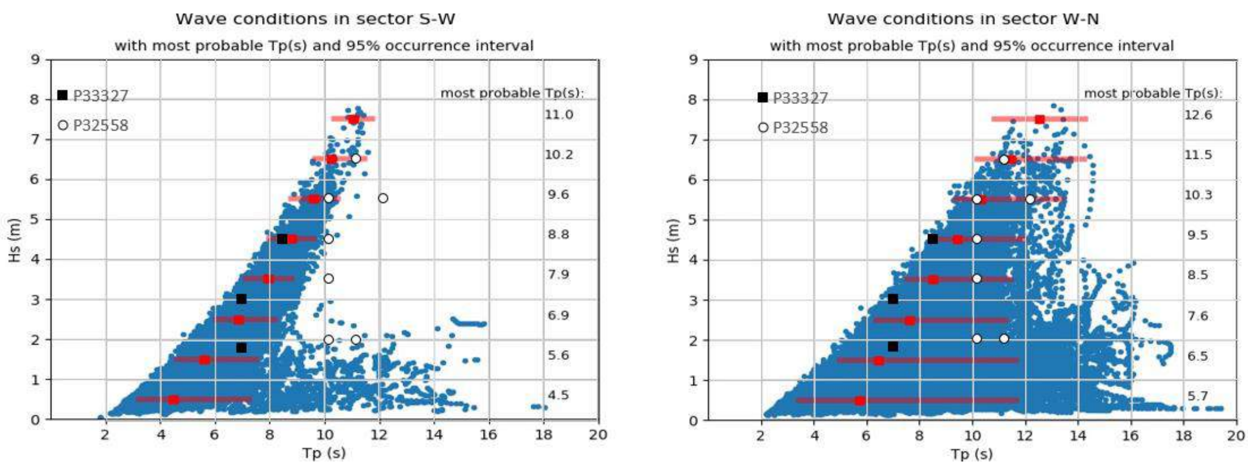


Figure 7-3: Hind-cast wave spectra from the S-W and W-N sector with marking of the wave conditions used in the green water investigations for the Feeder class containerships.

8 GREEN WATER LIMITING WAVE HEIGHT FOR CONTAINERSHIPS

8.1 Introduction

In this chapter the limiting wave height(s) for green water risk are discussed. The results from project 32558 and 33327 are used. In project 32558 the Feeder, Panamax and ULCS were model tested and the green water limiting sea states were derived. The wave conditions used were (around) most probable wave periods occurring in the area of interest. The peak spectra for these waves is longer than the shortest occurring wave period at that specific wave height. In project 33327 the steepest wave conditions were used for the model tests of the Feeder class containership for a range of freeboard levels and wave directions. This leads to a lower significant wave height in beam seas and insight in the behaviour in more quartering and head wave conditions.

Further derivations on green water in this chapter focus on the freeboard variation observed in the network analysis and to set the obtained green water limits into perspective for the possible route advice, also for the larger ship types. No additional model tests were conducted for the Panamax and ULCS with respect to green water, but the insights from the tests with the Feeder class ships in Report 33327 (related to the sensitivity for the freeboard level) can also give insight in green water on Panamax and ULCS ships with lower freeboards.

The present limiting wave height for the ULCS and the Panamax is governed by the dynamic under keel clearance in the southern route, and on the northern route it is governed by the by class imposed allowable accelerations. For the Panamax vessels the green water and allowable accelerations impose a nearly identical risk.

8.2 Additional freeboard investigations

Freeboard investigations will be carried out on the AIS data from the period January 2018 up to February 2022.

8.2.1 Freeboard investigations in project 33327 – Feeder class

The Feeder class includes all ships between 100 and 200 m in length.

In view of the model test preparations in project 33327 the freeboard rules were investigated. The minimum freeboard requirements for the Feeders as defined in the Load Line Convention depends on many parameter. The bare minimum is found to be 1 m. In Figure 8-2 (taken from project 33327) the minimum freeboard is found to increase with length.

Reviewing existing Feeders, different container on deck configurations were found. This was adopted as variations in the model tests. The final advice is independent of the container configuration.

Figure 8-1: Freeboard assessment according regulations and two distinct different container on deck configurations.

8.2.2 Freeboard distributions – Feeder class

The actual freeboard is calculated from the given ship depth and actual sailing draught. The calculation is verified against the provided minimal freeboard that is present in the AIS data.

The actual freeboard distribution of all Feeders on the northern and southern TSS is provided in Figure 8-2. From all Feeders only 7% selects the northern route (1368 crossings), and thus 93% selects the southern route (19620 crossings).

The distribution shows values below 1 m, which are considered anomalies in the input data. There are as well extreme values above 10 m freeboard which are not shown; they are based on wrong input data. A realistic freeboard should be at least 1.0 m.

The actual freeboards of the Feeder fleet is shown in Figure 8-3 as function of the ship length. Three horizontal lines are added that represent the freeboard values for the Feeders used in the model tests: 2.3 m, 3.8 m and 5.3 m. The AIS database is corrected for ships that sail at unrealistic freeboard (that is e.g. sail at a draught higher than the allowed draught from the Plimsoll mark).

All Feeders above 180 m in length always sail with a freeboard above 3.8 m. Many Feeders sail from time to time with a freeboard above 5.3 m.

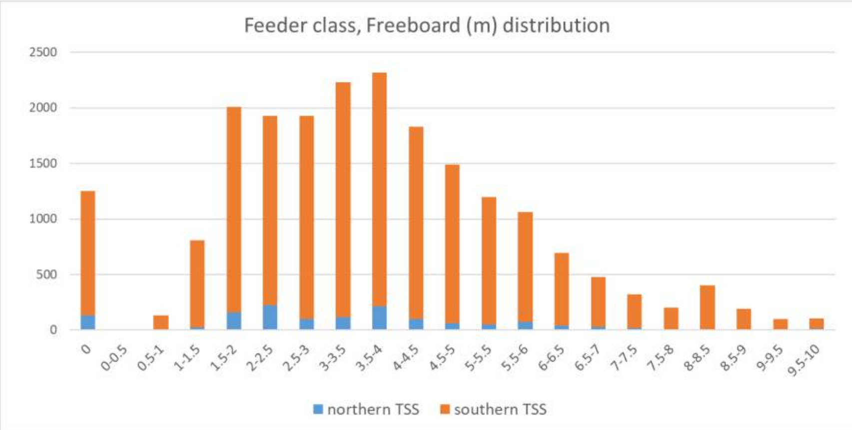


Figure 8-2: Freeboard distribution of all ships in the TSS, bin size 0.50 m. (Raw AIS data, data table limited to 10 m freeboard).

The actual freeboard versus ship length as shown confirms the data trend of calculated freeboard versus length as shown in Figure 8-1, although the real data shows many ships with lower freeboard as well. It is noted that the actual freeboard is derived from the manually input actual sailing draught and given ship depth. If the actual draught is entered wrongly the actual freeboard is wrong as well and some data is perhaps incorrect. But, that cannot be further verified. Unrealistic low draught sailing conditions are removed. Further studying of the database revealed that it includes varies ship type descriptions. Many of these ships are found regularly crossing the TSS, but upon inspection it is not likely that all these ship types carry containers on board. Using only the ships labelled with ID 70 to 74 gives a more realistic list of Feeders that could potentially carry containers on deck. The freeboard distribution plot was however hardly effected after these corrections. But that last data set is used. Note that the data used in report 33883-1-MO uses all Feeder ships in length < 200 m.

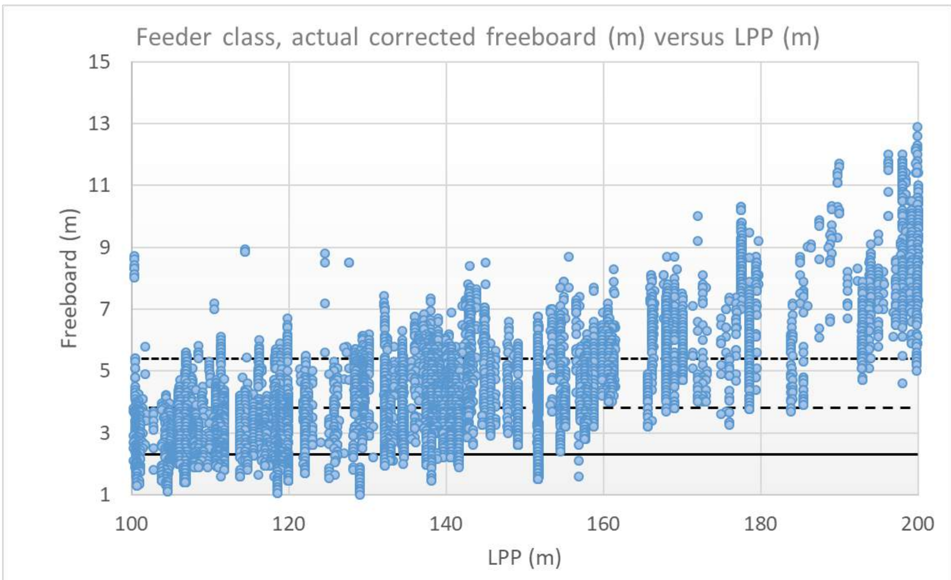


Figure 8-3: Actual freeboard of Feeders (after AIS data cleaning and correction). Horizontal lines at freeboard height from the model tests, 2.3 m, 3.8 m and 5.3 m.

From the possible container carrying Feeders, the freeboard distributions are presented in Figure 8-4 in various graphs (same data, different representation). The data plots reveal the possible impact of a limiting significant wave height as function of the freeboard. Clearly, these are averaged values while the fleet of Feeders during storm conditions, or in approaching storm conditions can be different, for example because low freeboards vessel choose to take shelter. But, the values are certainly indicative.

- 9.3% of the fleet sails with a freeboard less than 2.3 m = 90.7% sails with freeboard > 2.3 m
- 40.8% of the fleet sails with a freeboard less than 3.8 m = 59.2% sails with freeboard > 3.8 m

- 73.5% of the fleet sails with a freeboard less than 5.3 m = 26.5% sails with freeboard > 5.3 m
- 9.3% of the fleet sails with a freeboard between 1.0 and 2.3 m
- 31.5% of the fleet sails with a freeboard between 2.3 and 3.8 m
- 32.7% of the fleet sails with a freeboard between 3.8 and 5.3 m
- 6% of the fleet sails with a freeboard of 8 m or more.

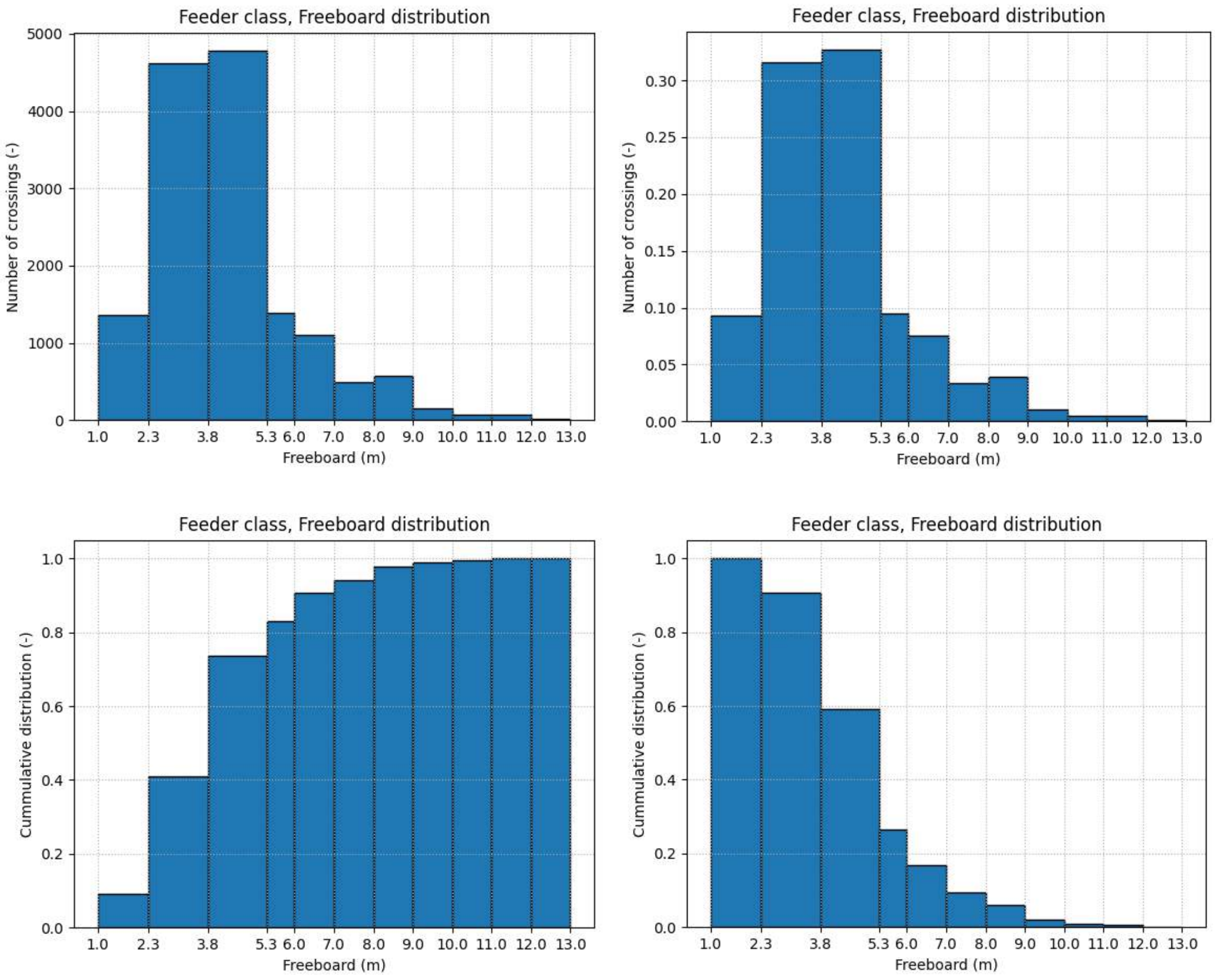


Figure 8-4: Actual freeboard height distribution of Feeder class; various presentations.

8.2.3 Freeboard distributions – Panamax class

The Panamax class includes all ships between 200 and 300 m. The classical width limitation of the Panamax classed ship is 32.3 m. The current lock length limit is 294 m, and all ships with a beam over 32.3 m are called Post-Panamax ships.

The AIS databased for the Panamax classed ships on the southern route is investigated. 86% of all Panamax vessels (classical and post) sail on the southern route.

The following numbers in this section refer to the classical Panamax ships.

The AIS database is cleaned for ships with an actual freeboard lower than the design freeboard, which should not occur as it would imply that the ships sails at deeper allowed draught.
The lowest recorded freeboard height on the southern route was 3.04 m, the highest 15.8 m.

The freeboard distributions are presented in Figure 8-5 in various forms. The following is concluded:

- 0.3% of the fleet sails with a freeboard less than 3.8 m = 99.7% sails with freeboard > 3.8 m
- 2.9% of the fleet sails with a freeboard less than 5.3 m = 97.1% sails with freeboard > 5.3 m
- 0.3% of the fleet sails with a freeboard between 3.0 and 3.8 m
- 2.6% of the fleet sails with a freeboard between 3.8 and 5.3 m
- 74.5% of the fleet sails with a freeboard of 8 m or more.
- 71.6% of the fleet sails with a freeboard between 8 and 12 m
- 2.8% of the fleet sails with a freeboard more than 12 m.

The values are related to green water risk in Section 8.3.

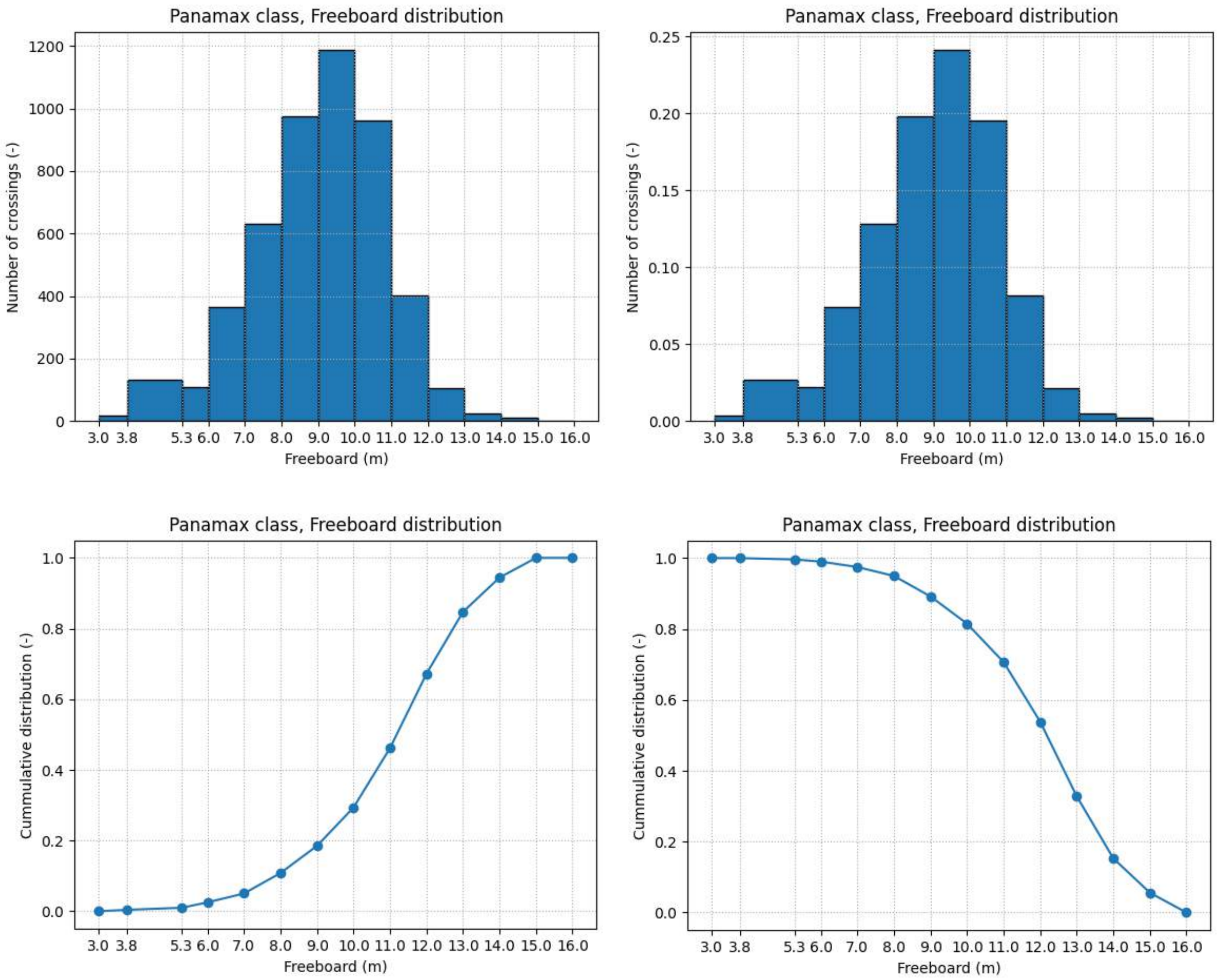


Figure 8-5: Actual freeboard height distribution of Panamax class; various presentations.

8.2.4 Freeboard distributions – Post-Panamax class

The Post-Panamax class includes all ships between 200 and 300 m in length and a beam of more than 33 m. Actual the limiting length for the Panamax locks is 294 m in length and 51 m in beam. 31% of the ships in length between 200 and 300 m are Post-Panamax ships.

The AIS database is cleaned for ships with an actual freeboard lower than the design freeboard, which should not occur as it would imply that the ships sail at deeper allowed draught.
The lowest recorded freeboard height on the southern route was 4.12 m, the highest 17.3 m.

The freeboard distributions are presented in Figure 8-6 in various forms. The following is concluded:

- 0.4% of the fleet sails with a freeboard less than 5.3 m = 99.6% sails with freeboard > 5.3 m
- 0.4% of the fleet sails with a freeboard between 4.1 and 5.3 m
- 4.6% of the fleet sails with a freeboard between 5.3 and 8 m
- 95% of the fleet sails with a freeboard of 8 m or more.
- 40.8% of the fleet sails with a freeboard between 8 and 12 m
- 54.2% of the fleet sails with a freeboard more than 12 m.

The values will be related to green water risk in Section 8.3.

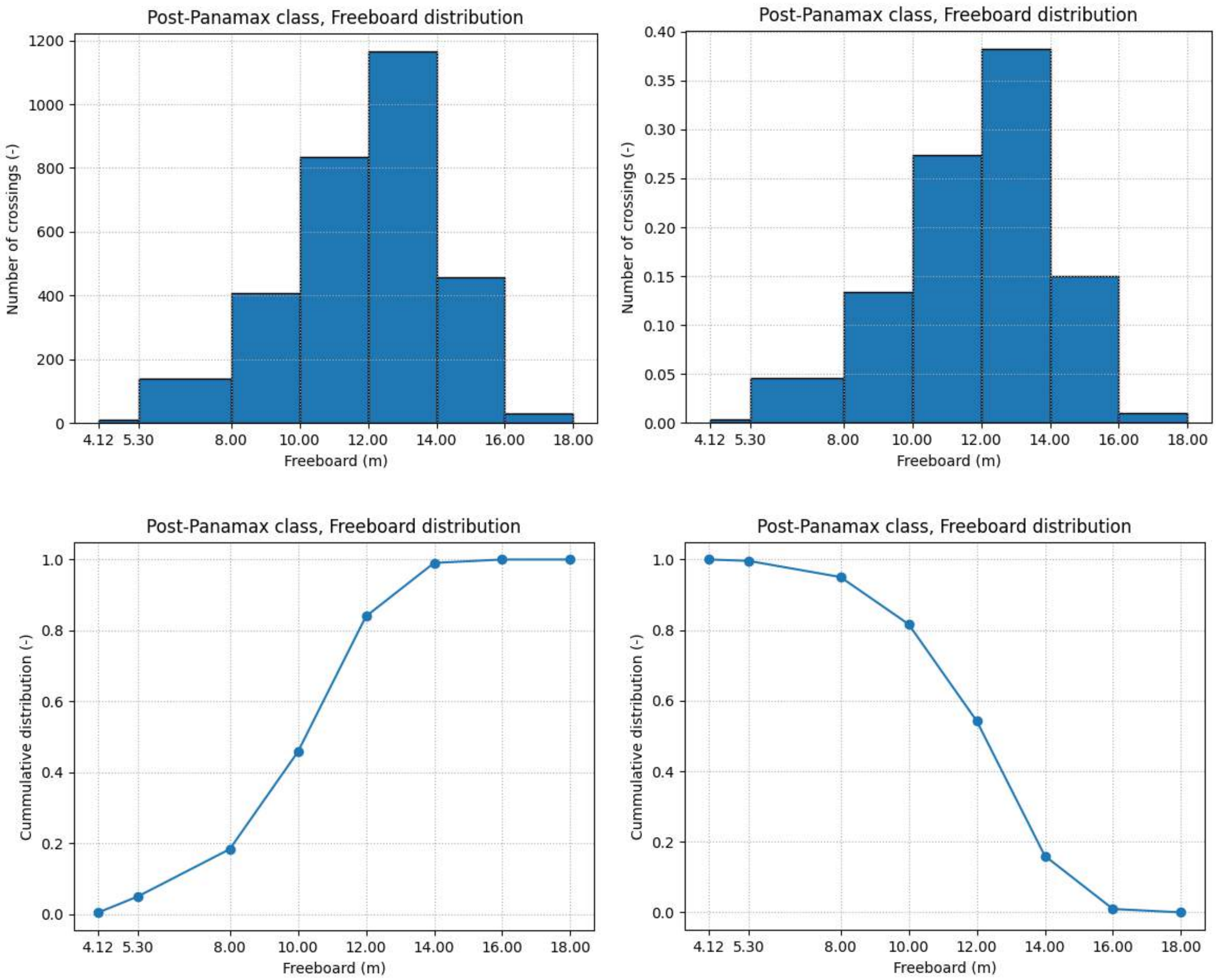


Figure 8-6: Actual freeboard height distribution of Post-Panamax class; various presentations.

8.2.5 Freeboard distributions – ULCS class

The ULCS class includes all ships with length above 300 m (295 m).

The lowest recorded freeboard height on the southern route was 5.6 m, the highest 33.3 m.

The freeboard distributions are presented in XX in various forms. The following is concluded:

- 0.0% of the fleet sails with a freeboard less than 5.3 m = 100% sails with freeboard > 5.3 m
- 0.7% of the fleet sails with a freeboard between 5.3 and 8 m
- 99.3% of the fleet sails with a freeboard of 8 m or more.

- 10.3% of the fleet sails with a freeboard between 8 and 12 m
- 60.4% of the fleet sails with a freeboard between 12 m and 18 m.
- 28.6% of the fleet sails with a freeboard of 18 m or more.

The values will be related to green water risk in Section 8.3.

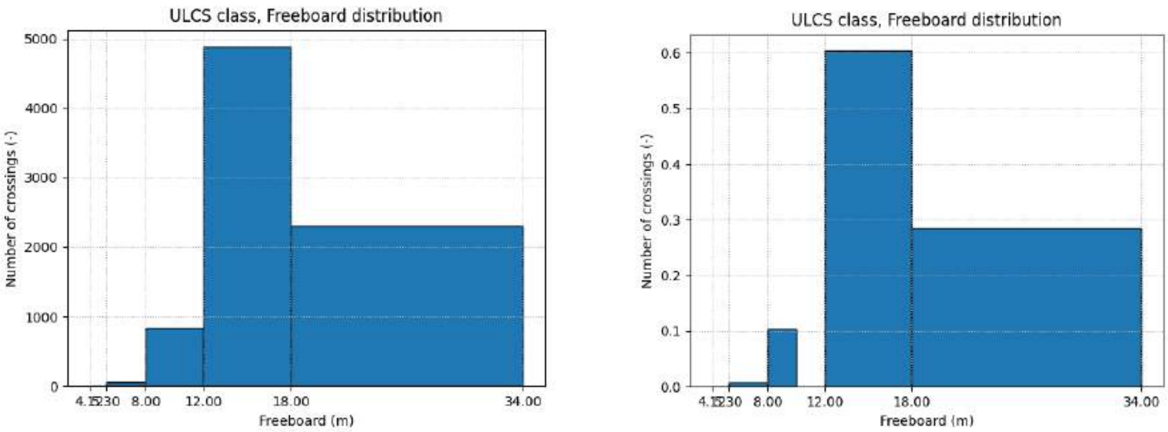


Figure 8-7: Actual freeboard height distribution of ULCS class.

8.3 Discussion final limiting wave heights for green water

The final limiting significant wave heights for the Feeder ships are derived in MARIN project 33327, and they are adopted in the present project. The advice is presented earlier in this chapter, see Table 7-1, repeated here for readability.

Table 8-1: Final limiting wave height for Feeder class container ships (project 33327).

Freeboard height	**2.3 m**	**3.8 m**	**5.3 m**
135/225 deg (bow-quartering waves)	3.4 m	4.5 m	5.6 m
90/270 deg (beam waves)	*2.4 m*	*3.0 m*	*3.4 m*
45/315 deg (stern-quartering waves)	3.5 m	4.9 m	6.0 m

Green water risk is the critical parameter in a warning system for the Feeders. The limiting wave heights are the same for the northern and southern route; one overall warning to all Feeders will be sufficient. The network analysis shows anyhow that 93% of the Feeders sail the southern route.

In project 33327 the limiting wave heights are presented as function of discrete freeboard values. In practice the freeboard of the actual ship will deviate from these discrete 2.3 m, 3.8 m or 5.3 m; being in between, higher and sometimes even less. A freeboard of 1.0 m is considered the lowest possible. The longer Feeders close to 200 m can sail with freeboards above 4 m, up to 9 m.

To obtain a green water limiting wave height as function of freeboard for all ship types, the limiting Hs values derived based on the observations and measurements in the model basin for the ULCS and Panamax vessel (project 32558) are all put in a single graph together with the Feeders. The data is shown in Figure 8-8. Note that the data comes from different wave periods.

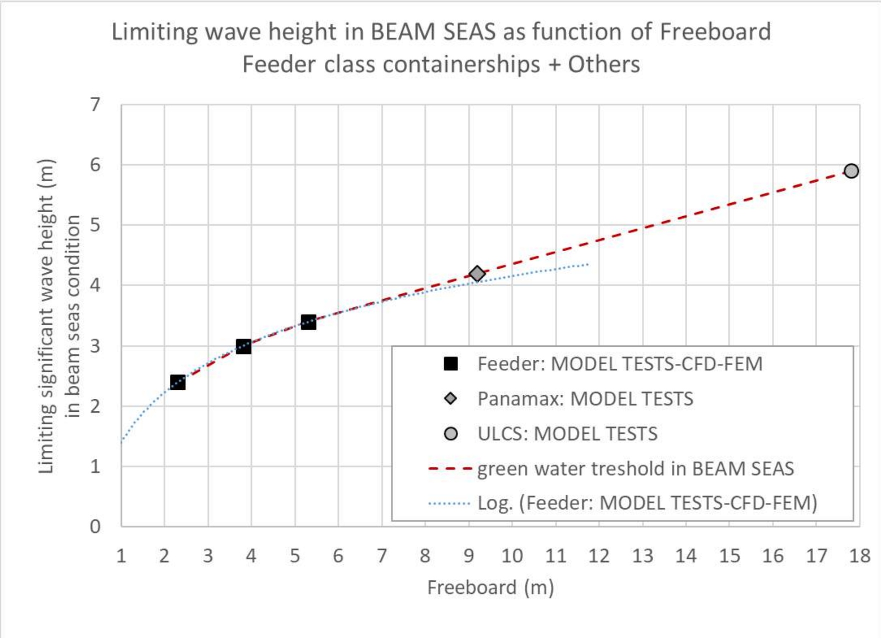


Figure 8-8: Green water limiting wave heights for the Feeders, and the trend line through the data points for the Panamax and ULCS. Data limited to beam seas condition only. Valid for southern route.

Despite the varying wave periods, the result show a consistent trend. The observed trend can be understood when we realise that green water in beam waves in shallow water, despite the variation in ship motions, is dominated by the interaction of the steep (breaking) waves with the vertical side of the ship that acts like a wall (limited by the freeboard on the upper side). This observed trend can be used to estimate the susceptibility and sensitivity for green water of the larger ships types (Panamax and ULCS) with lower freeboard levels than tested freeboard in project 32558. As example the results of Figure 8-8 suggest that a containership with freeboard height of 8 m is exposed to serious green water exposure on the deck containers from Hs of 4.0 m onwards.

Based on these observations in Table 8-2 a common used risk table format is developed to describe the risk associated as function of significant wave height and freeboard. The risk description is indicative and separates the risk for ships sailing in beam seas and non-beam seas condition. The table includes all data for the Feeders, extended with the (limited) data for the Panamax (freeboard about 9 m) and ULCS vessels (freeboard 18 m).

Table 8-2: Risk matrix for green water impact and possible damage of containers on deck as function of wave height and freeboard height.

Risk for green water impact and damages of deck containers	Freeboard between 1.0 m and 2.3 m (cumm. < 2.3 m)	Freeboard between 2.3 m and 3.8 m (cumm. < 3.8 m)	Freeboard between 3.8 m and 5.3 m (cumm. < 5.3 m)	Freeboard between 5.3 m and 8.0 m (cumm. < 8 m)	Freeboard between 8 m and 12 m (cumm. < 12 m)	Freeboard between 12 m and 18 m (cumm. < 18 m)	Freeboard above 18 m
% of FEEDER ships on route TSS	9.3% (9.3%)	31.5% (40.8%)	32.5% (73.3%)	20.7% (94.0%)	6% (100%)	none	none
% of PANAMAX ships on route TSS	none	0.3% (0.3%)	2.6% (2.9%)	22.7% (25.6%)	71.6% (97.2%)	2.8% (100%)	none
% of POST-PANAMAX ships on route TSS	none	none	0.4% (0.4%)	4.6% (5.0%)	40.8% (45.8%)	54.2% (100%)	none
% of ULCS ships on route TSS	none	none	none	0.7% (0.7%)	10.3% (11.4%)	60.4% (71.4%)	28.6%
Hs > 6.0 m	extreme risk at all headings	extreme risk at all headings	extreme risk at all headings	high to extreme risk at all headings	high to extreme risk at all headings	unsafe in beam seas, expected safe otherwise	unsafe in beam seas, expected safe otherwise
4.5 m < Hs < 6.0 m	extreme risk at all headings	high to extreme risk at all headings	high to extreme risk at all headings	unsafe in beam seas, safe at other headings	unsafe in beam seas, safe at other headings	unsafe in beam seas, expected safe otherwise	safe at all headings
3.4 m < Hs < 4.5 m	high risk at all headings	unsafe in beam seas, safe at other headings	unsafe in beam seas, safe at other headings	unsafe in beam seas, safe at other headings	safe at all headings	safe at all headings	safe at all headings
3.0 m < Hs < 3.4 m	unsafe in beam seas, safe at other headings	unsafe in beam seas, safe at other headings	safe at all headings	safe at all headings	safe at all headings	safe at all headings	safe at all headings
2.4 m < Hs < 3.0 m	unsafe in beam seas, safe at other headings	safe at all headings	safe at all headings	safe at all headings	safe at all headings	safe at all headings	safe at all headings
Hs < 2.4 m	risk in beams seas for low freeboard ships	safe at all headings	safe at all headings	safe at all headings	safe at all headings	safe at all headings	safe at all headings

9 CONCLUSIONS

The present project 33883 is the third project for the Ministry on the safety of containerships sailing on the TSS above the Dutch Wadden Islands.

The following summarises the findings of the present investigations:

- A large number of seakeeping calculations was performed and the findings are reported in this volume. The seakeeping calculations are performed with the 3D panel code SEACAL. The SEACAL calculations are validated against earlier performed model tests (MARIN project 32558). SEACAL is a linear 3D seakeeping tool with an exact forward speed formulation.
- The model tests (project 32558) show significant higher-order shallow water effects in the waves and ship motions. The downward heave motions are at least 20% reduced compared to linear predictions due to these higher order effects. The dynamic under keel (UKC) calculations are corrected for this effect.
- A network analysis was performed on all containership on the northern and southern route, and the findings are reported in 33883-2-MO. The network data was used to calculate the ship draught for the Panamax and ULCS class ships covering 95% of the ships on route. This lead to an increased draught of the ULCS and Panamax vessel compared to previous research in which average draught conditions were used.
- The southern TSS between Texel and the German border is about 60 nm long. The westbound lane has a minimum water depth of 21 m LAT. The eastbound lane has a minimum depth of 19 m LAT over 4 nm, selecting a mid-water passage. On the German side the water depth decreases even to 17 m, but this part of the route is not included in the present investigations.
- The class allowable transverse acceleration limits have been calculated with the by DNV provided StowLash software. The acceleration limits are evaluated for deck containers and high-tier (top) containers along the ship length.
- The dynamic UKC criterion is set to a 1% probability risk level. The sailing of 10 knots is used to calculate the exposure time over a given LAT water depth (but not exceeding 3 hours). The 1% probability level leads to an absolute safety margin equal for all ships and equal to a +2 m clearance for the ULCS sailing at 12.4 m draught in 21.3 m water depth (the reference case MSC ZOE).
- The limiting significant wave height is calculated for three different phenomena:
  - Dynamic under keel clearance
  - Class allowable transverse accelerations for all containers on deck
  - Green water impact risk on deck containers
- The Feeders are governed by green water risk. The findings in the previous chapter presents the limiting significant wave height as function of freeboard height. A relationship between freeboard and limiting significant wave height is derived that can be used for all ships. The limiting sea state for the Feeder with 3 m freeboard, as used in the model tests of the first study (32558), is 0.5 m lower than in the preliminary advice. This is due to the steeper sea states included in the second model test campaign (project 33327).
- The safe sailing of the ULCS and Panamax vessel are governed by dynamic under keel clearance on the southern route. With the increase draught and lower water depth, the limiting significant wave height is 0.5 m lower than in the preliminary advice.

- The limiting significant wave height for dynamic UKC is governed by the exceedance of the proposed criteria in long wave periods, with peak periods above the most probable sea states for the given Hs limit. These Hs – Tp sea states have a low probability of occurring, e.g. < 2% for a given Hs. Given all other uncertainties in the calculations (in particular the non-linear hydrodynamics in shallow water conditions) the risk-consequence for selecting a slightly less restrictive dynamic UKC has been reported.
- The calculated limiting significant wave heights are not further corrected for the bias in the metocean study. The SWAN model predicts the significant wave height too low by on average 0.37 m with standard deviation 0.32 m. Further details can be found in the DELTARES report submitted with the present study.[17]
- The seakeeping accuracy is weighted against the metocean accuracy. It is concluded that further reduction of the calculated significant wave height is not needed; the seakeeping calculations are typically biased high, the metocean prediction biased low.
- The table with the final proposed limiting significant wave heights can be found in the Management summary.

Wageningen, June 2022
MARITIME RESEARCH INSTITUTE NETHERLANDS

For Ir. G. Gaillarde
Head of Ships Department

[17] DELTARES, report 11207734-002-HYE-0001

APPENDICES

APPENDIX 1 SEAKEEPING CALCULATION COMPARISON

For the present seakeeping analysis the SEACAL program has been used, while the calculations in the previous project were done with a combination of PRECAL and FATIMA.

The following tables show a comparison of the basic ships motions of the ULCS with a GM of 9.25 m in shallow water of 21.3 m depth and significant wave height of Hs is 5.0 m. The calculations are in short-crested sea states. The following is observed:

The heave motions of the ULCS is the largest at 90 deg heading. In PRECAL/FATIMA calculations it was 3.3 m, in the present SEACAL analysis it is 2.7 m. The overall trend is the same.

The roll motions of the ULCS is the largest at 75 deg heading. In the PRECAL/FATIMA calculations the maximum MPM was 12.6 deg at 14 sec wave period, in the latest SEACAL calculations it is 13.0 deg in the same condition. This is nearly identical. The overall trend is the same.

The pitch motions of the ULCS is (nearly) the largest at 90 deg heading, and the same response of 1.4 deg MPM is observed in both calculations. In the PRECAL/FATIMA calculations a maximum is found at 120 deg heading (bow quartering) which is not found in the present SEACAL calculations.

The comparison of global motions show that the SEACAL calculations and the PRECAL/FATIMA calculations are very similar, but not identical. This was expected as the two seakeeping tools use a slightly different forward speed approach of how the flow physics are calculated. It is important to note that the roll motions in beam seas compare well.

A comparison of the obtained transverse accelerations shows very comparable values between the SEACAL and the PRECAL/FATIMA calculations. The values are not exactly similar but on average within 5%.

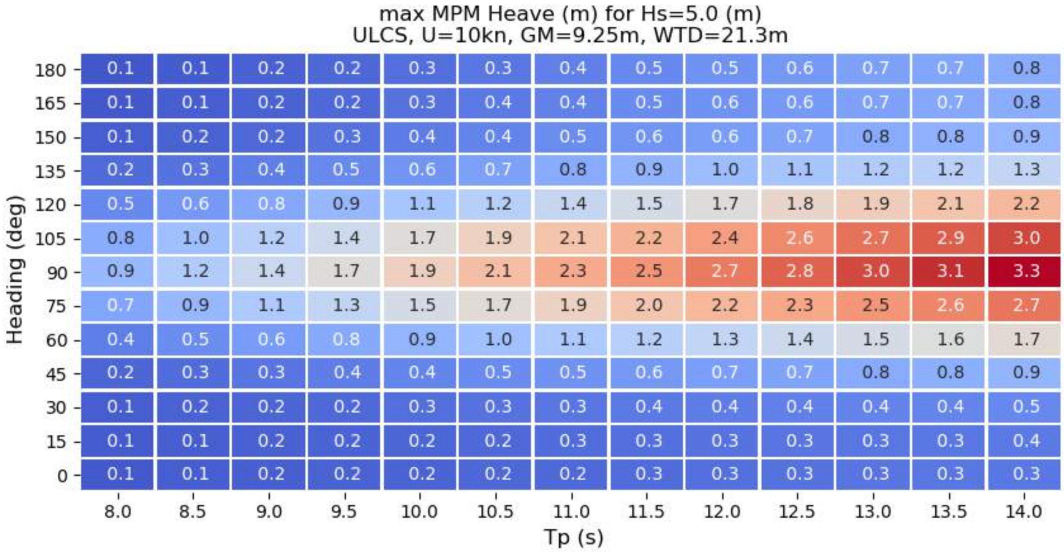
The dynamic under keel clearance shows the same trend in both calculations. Using a criterion that the dynamic UKC is not less than +2.0 m the following is found:

- Previous study: limiting Hs = 4.50 m (MPM is 1.99 m)
- Present study: limiting Hs = 4.36 m (linear interpolation)

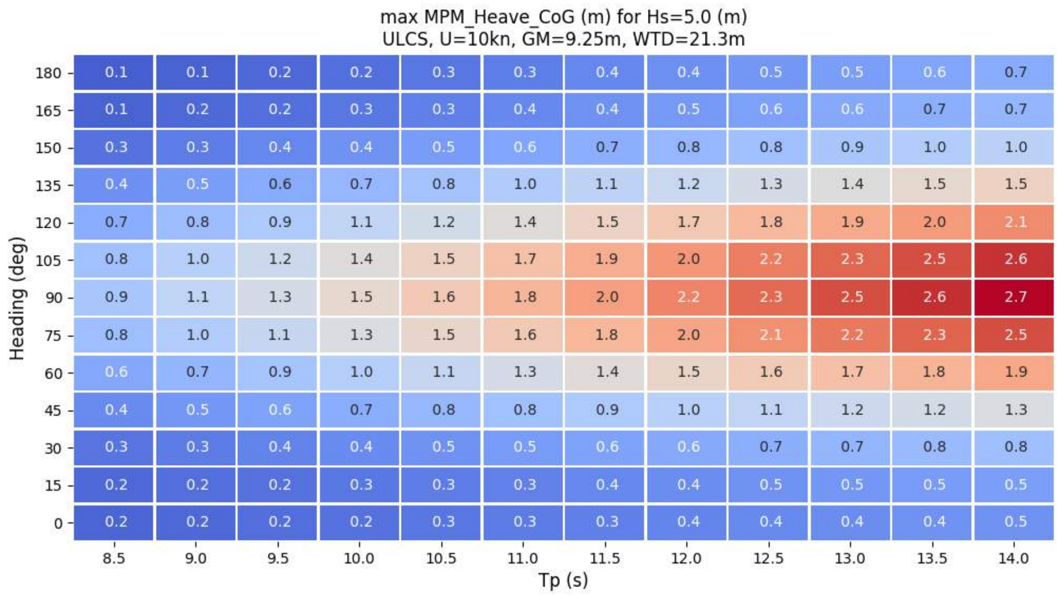
The difference of 15 cm is a difference of 3% and rather small in absolute sense.

Note that when the dynamic under keel clearance is predicted on the hull contour itself, the limiting wave height increases to 6.21 m.

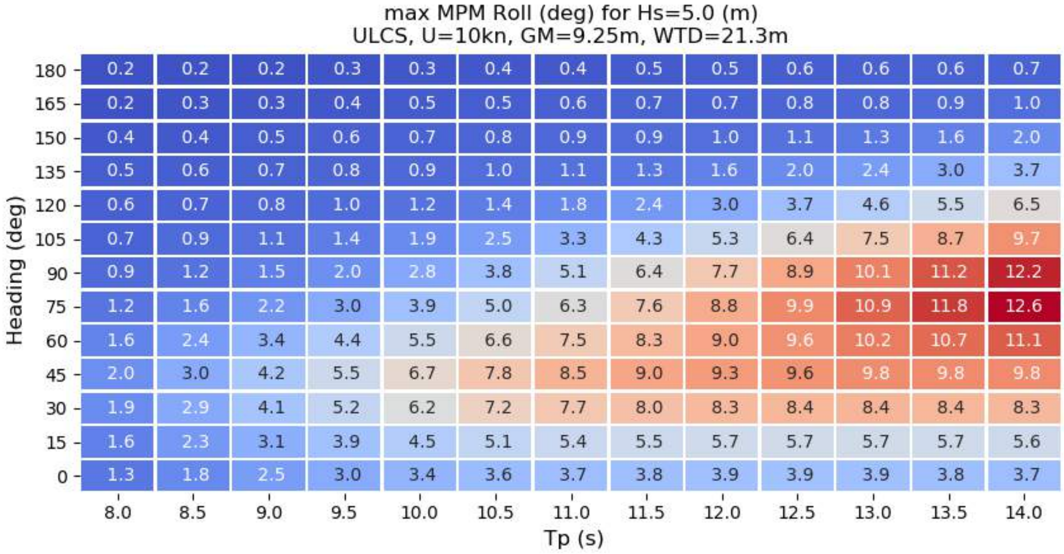
HEAVE MPM (m), ULCS, project 32558:



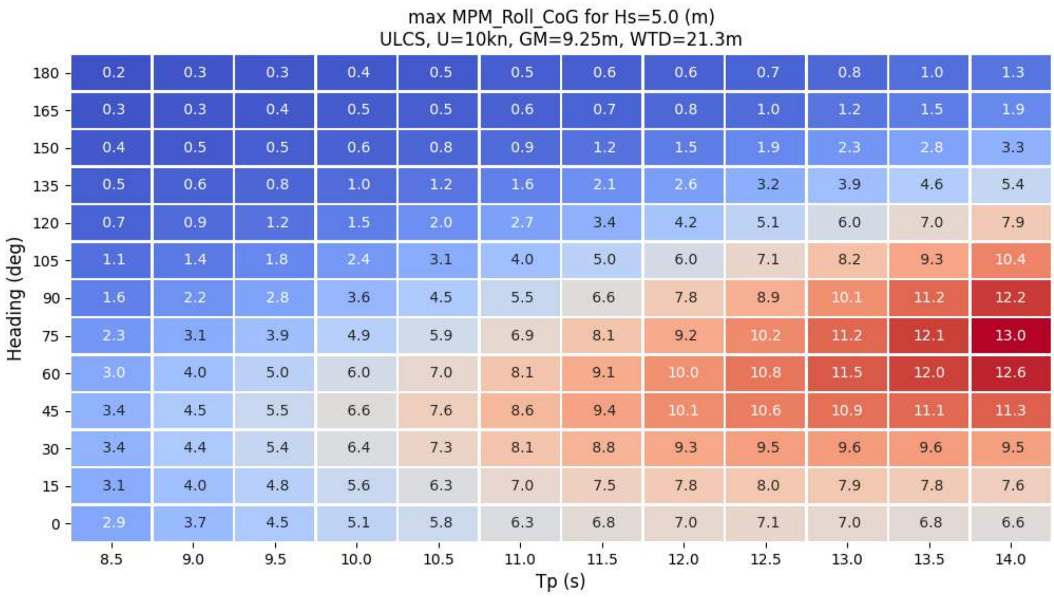
HEAVE MPM (m), ULCS, project 33883:



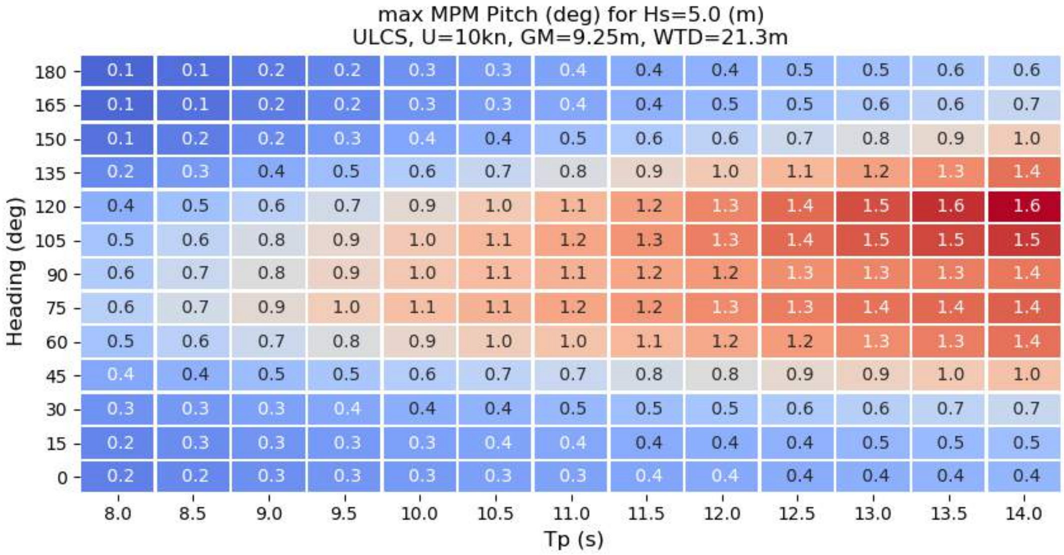
ROLL MPM (deg), ULCS, project 32558:



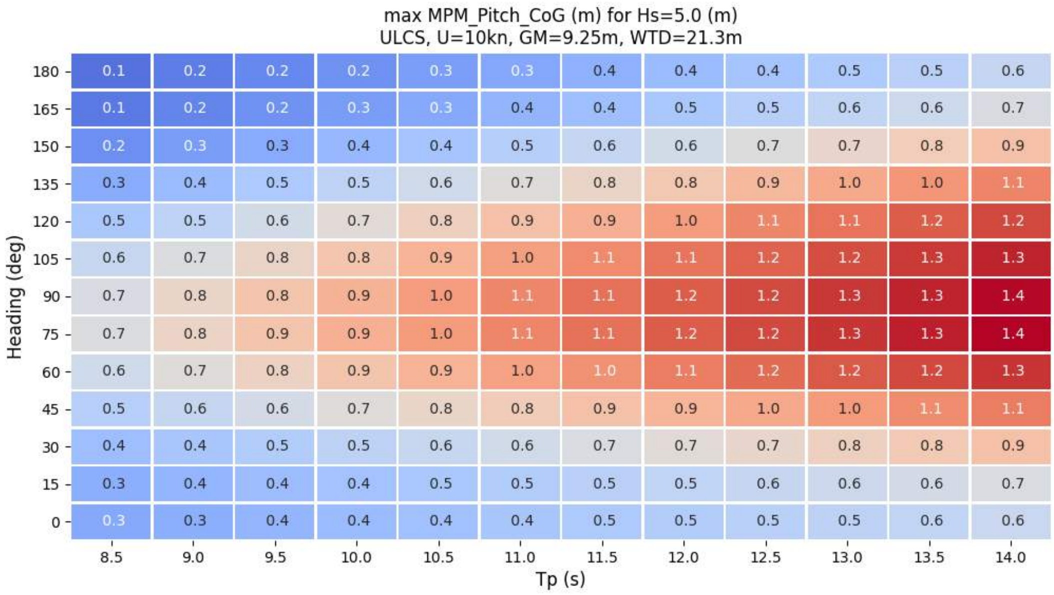
ROLL MPM (deg), ULCS, project 33883:



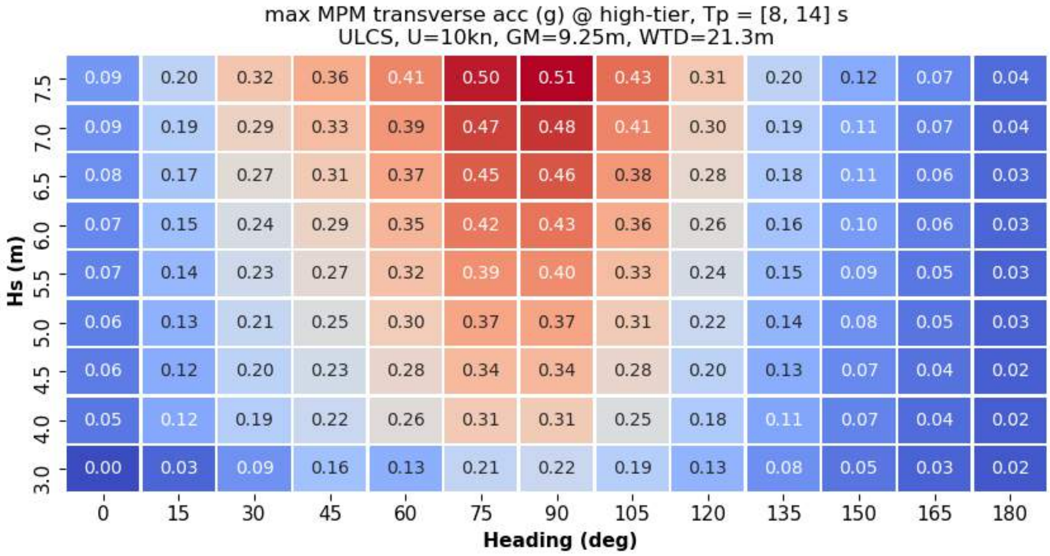
PITCH MPM (deg), ULCS, project 32558:



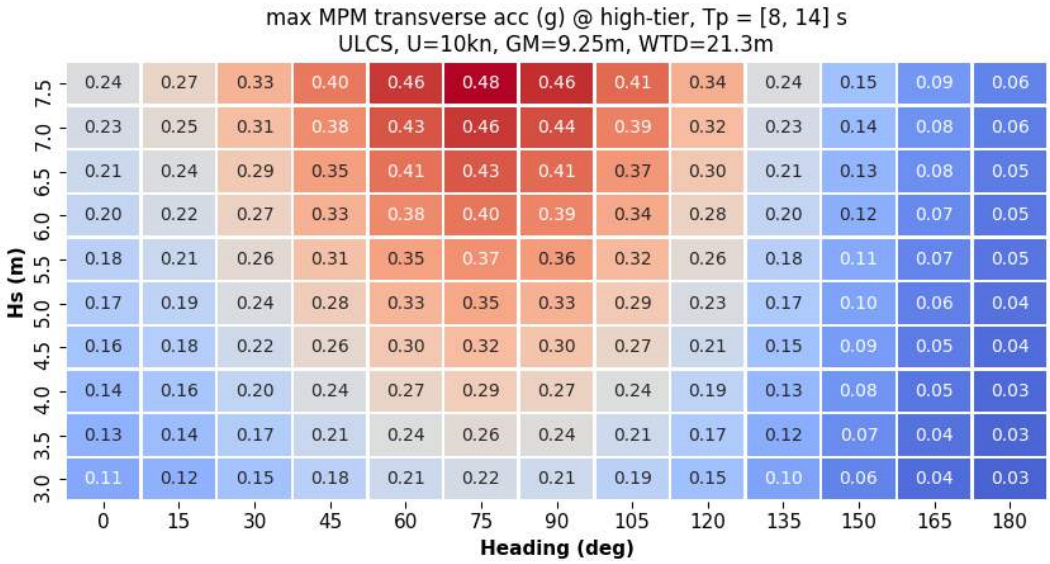
PITCH MPM (deg), ULCS, project 33883:



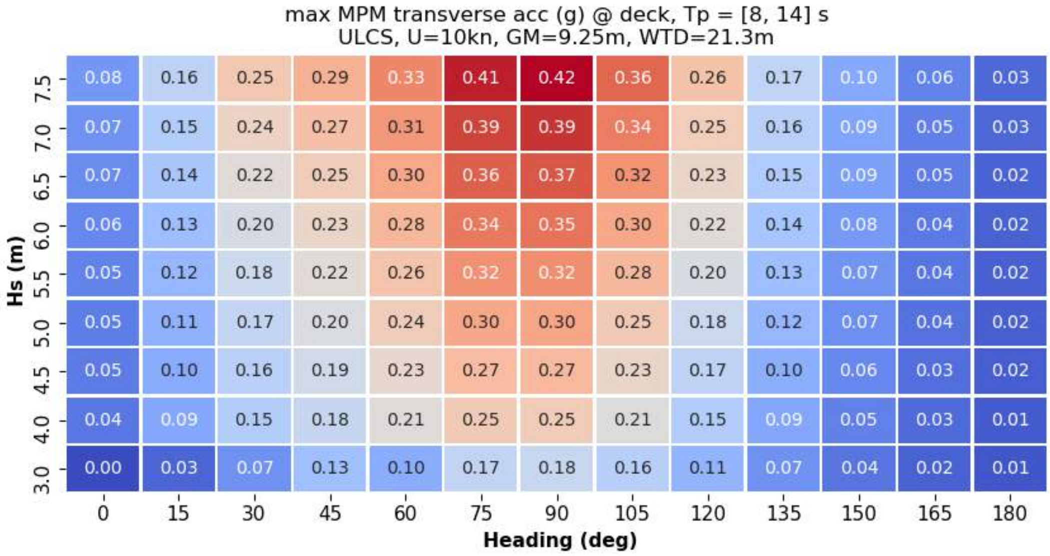
Y-ACC MPM, top-tier location, ULCS, project 32558:



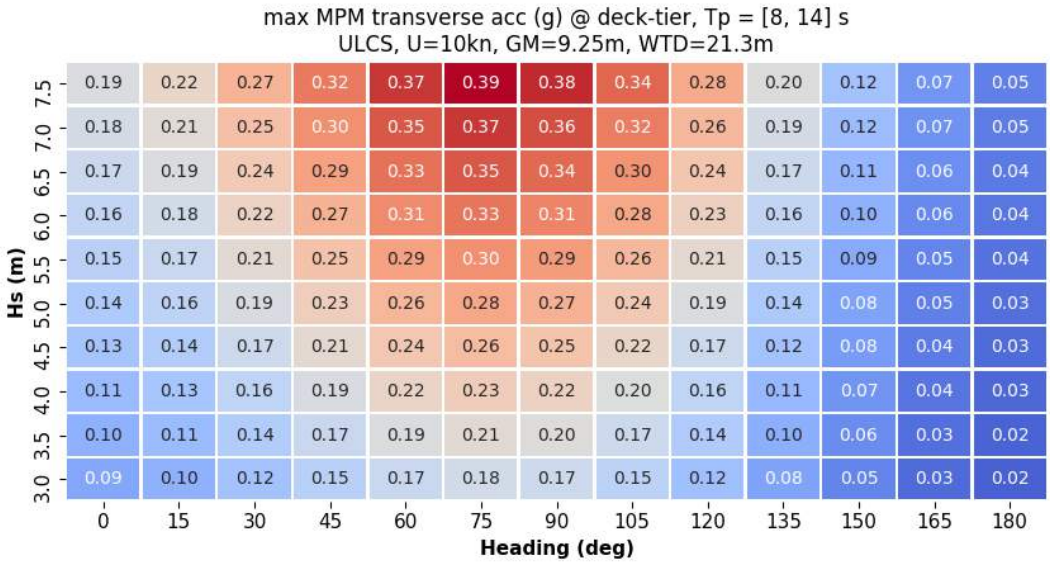
Y-ACC MPM, top-tier location, ULCS, project 33883:



Y-ACC MPM, deck-tier location (82), ULCS, project 32558:

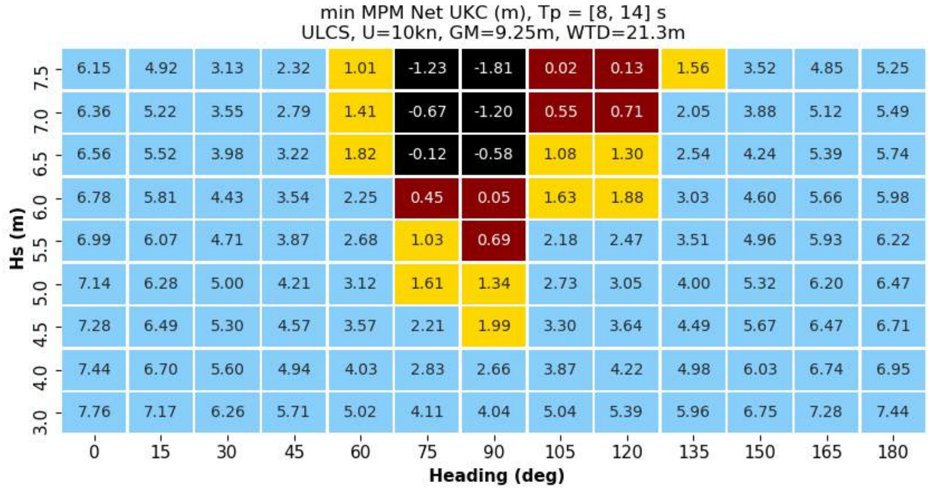


Y-ACC MPM, deck-tier location (82), ULCS, project 33883:



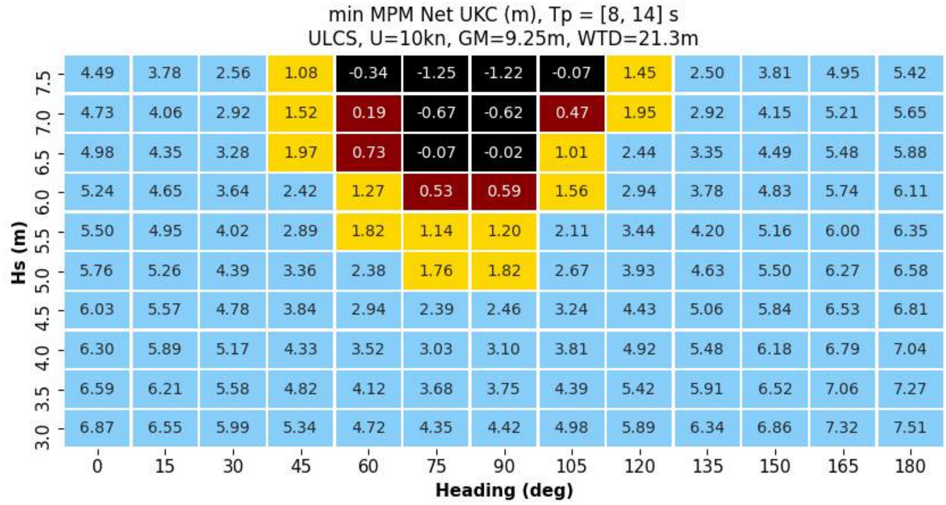
MPM minimum dynamic under keel clearance, ULCS, project 32558:

<u>Net UKC taken at the virtual hull point at half beam/keel plane (as used in that report evaluations):</u>

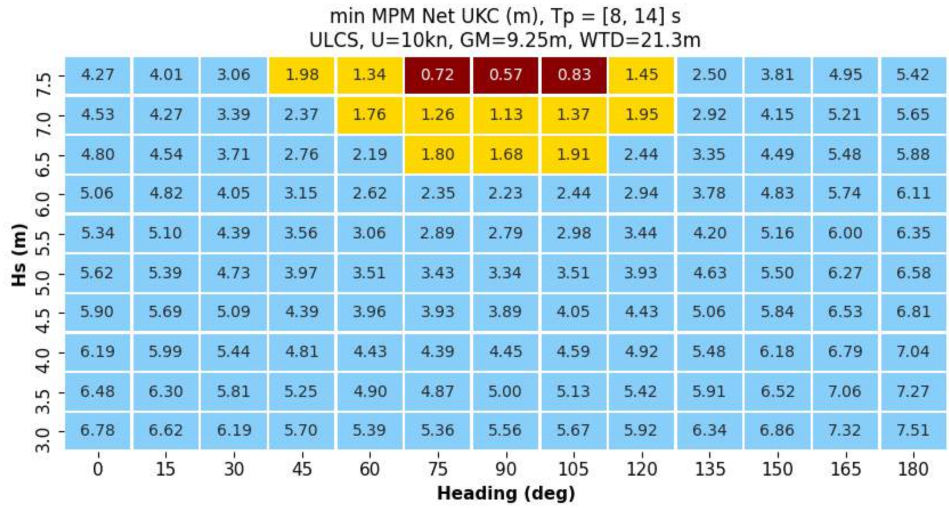


MPM minimum dynamic under keel clearance, ULCS, project 33883:

<u>Net UKC taken at the virtual hull point at half beam/keel plane (for comparison)</u>



<u>Net UKC taken at the hull sectional shape (to be used):</u>



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