BELGIAN ROYAL DECREE FOR SEA-GOING INLAND VESSELS: A REVIEW FOR CONTAINER AND BULK CARGO VESSELS

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ABSTRACT

The Belgian Royal Decree of 2007 allows inland vessels meeting certain requirements to perform a limited, non-international sea journey. After ten years of practice, the need to evaluate the performance of the Royal Decree arose, in particular with respect to inland container and bulk cargo vessels. In the present work, four reference vessels are selected as representative examples of existing container/bulk cargo vessels. For each of the four reference vessels, three significant loading conditions are selected. The Royal Decree requirements regarding stability and vertical relative motions are analyzed in detail for each vessel and loading condition. Based on the results of this analysis, a possible update of the requirements of the Royal Decree is proposed.

1 INTRODUCTION

Inland vessels are indispensable in the transportation of cargo, as an alternative to road and rail transport. The possibilities of a port to grow depend, among other things, on the availability of a stable connection with the inland waterways. In some cases, however, this connection can be unavailable for inland vessels above a certain size due to the limited dimensions of the waterways in the proximity of the port. Even when the connection is available, it could be affected by long travelling times due to the presence of locks and bridges.

When inland waterways can be reached via a limited sea-journey, it is interesting to explore the possibility of allowing inland vessels at sea, provided that strict safety conditions are met. Inland vessels are not compliant with IMO/SOLAS conventions, and as such they cannot perform an international sea-journey. Nevertheless, for a journey between two ports located in the same country, the state authority can grant permission to a specific type of inland vessel to navigate at sea. This strategy is particularly appealing in Belgium, where the connection between coastal ports and the main European inland waterway network is limited. From the coastal port of Zeebrugge, in fact, vessels larger than CEMT-IV can only travel inland as far as Brugge, since the following connection to Ghent is precluded to larger vessels. If allowed on a national sea-journey between the coastal ports and the mouth of the River Scheldt, on the other hand, large inland vessels are able to reach Antwerp and consequently the wider European network from there.

Currently, the possibility for an inland vessel to sail at sea is regulated by the Belgian Royal Decree of 8 March 2007, which stipulates an extensive list of requirements the vessel needs to comply with. Concerning the behaviour of the vessel in waves, the Royal Decree prescribes a full risk analysis aimed to evaluate, among other things, the probability that the ship faces excessive relative vertical motions which can lead to shipping of water. According to the Belgian Royal Decree, tankers and closed hatch vessels wanting to sail the estuary trajectory up to a maximum significant wave height of 1.2 m can be exempted from the need to perform a full risk analysis, provided that certain deterministic requirements on the minimum freeboard are met. Such an exemption is not present for container and open hatch bulk cargo vessels. However, a simpler way to allow these vessels on the estuary trajectory in controlled wave conditions could attract more traffic.

This study is focused on an assessment of the performance of open hatch inland dry cargo vessels along the estuary trajectory between the port of Zeebrugge and the mouth of the Scheldt estuary, with respect to the requirements of the Belgian Royal Decree. The aim of the study is to verify whether it is feasible to introduce new deterministic exemptions from the risk analysis, valid also for container and open hatch dry cargo inland vessels. Moreover, a review of the current stability regulations enforced

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by the Royal Decree is proposed. The study is based on four design vessels, which represent the entire European fleet of inland vessels with open hatches (container/bulk cargo) of CEMT class Va and larger. The study is part of a larger project entitled "Nautical-hydrodynamic investigation of the possibilities of an inland navigation connection over sea for the port of Zeebrugge" performed by the Maritime Technology Division of Ghent University and commissioned by the Flemish Government (Department of Mobility and Public Works, Maritime Access).

2 ESTUARY TRAFFIC IN FLANDERS/BELGIUM

2.1 History

Estuary traffic originated even before the seaward expansion of Zeebrugge (1972-1985). Bunker companies located in Antwerp needed to reach Zeebrugge in order to fuel sea-going vessels. For these vessels, a service rule was developed in 1962 by the Belgian Shipping Inspectorate. The vessels were only allowed to perform the journey in favourable conditions, up to 1.2 m significant wave height (average of the 33% highest waves, denoted as H_s); in practice, these trips were allowed in wind conditions up to 5 Beaufort. Freeboard requirements were given as deterministic rules, as a function of the length of the vessel. These tankers, with length of around 70 m, could easily fulfil strength requirements.

Along the trajectory waves exceed 1.2 m H_s 13% of the time (Vantorre & Van Zwijnsvoorde, 2016), based on wave recordings at the Bol van Heist (BVH) measuring buoy (see paragraph 3.1). In order to establish a more reliable connection, skippers started to request an extension of the limiting conditions up to 1.6 m and even 1.9 m H_s, which would grant them almost permanent access to the sea-trajectory. Not only tankers, but also car carriers and container vessels were interested to get involved in this promising market. Initially, these requests were taken into consideration on an individual basis. Three tankers (Tanzanite, Breitling and Texas) and three RoRos (Waterways 1/2/3) were granted permission based on individual assessments in the period 2003-2007. Two of these ships are shown in Figure 2-1.

Figure 2-1 : Estuary tanker Tanzanite[6] and Roro vessel Waterways I[6].

This ad-hoc approach ended in March 2007 with the publication of the Royal Decree (RD2007) of *inland vessels performing non-international sea-journeys* (Federale Overheidsdienst Mobiliteit en Vervoer, 2007). The Royal Decree enforces a set of general regulations to allow an inland vessel at sea. Such regulations were designed based on a feasibility study executed by Ghent University and Lloyd's Register (Vantorre, et al., 2006). A more detailed description is given in paragraph 2.3.

Up to this day, inland vessels which want to navigate at sea must be certified based on this regulatory document. An example of a vessel certified according to RD2007 is the container vessel Deseo (Figure 2-2). All vessels certified according to the regulation will be called *estuary* vessels in the following text.

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[6] Rights belong to Teun De Wilt (Tanzanite), Christian Westerink (Waterways I) and Patrick Hermans (Deseo).

Figure 2-2 : Estuary container vessel Deseo[6].

2.2 Port of Zeebrugge

Europe's biggest ports are all located in Western Europe. The biggest European ports are found in the stretch between Le Havre and Hamburg: Le Havre, Antwerp, Rotterdam, Amsterdam, Bremerhaven and Hamburg (Figure 2-3). The port of Zeebrugge needs to compete with these harbours, when it comes to attracting cargo and passenger lines. A major aspect in the competitiveness of a port is the availability of a developed hinterland connection, to improve the speed and cost effectiveness at which goods reach their end destination. Since the Belgian road network is congested and rail transport always faces limitations due to influence of the passenger train schedule, there is a need of sufficient inland vessel transport capacity in the modal split. For the ports of Antwerp and Ghent (Ghent is part of '*North Sea Port*'), 38% (Port of Antwerp, 2017) and 50% (Port of Ghent, 2016) of the cargo is transported by inland vessels. For Zeebrugge, this share is negligible, at 0.3% (Port of Zeebrugge, 2016) of the total cargo.

Figure 2-3 : Location of largest European ports in the Hamburg – Le Havre range.[7]

This can be explained by looking at the inland waterways surrounding the port of Zeebrugge, shown in Figure 2-4. CEMT-VI vessels are able to reach Brugge using the Boudewijnkanaal. However, only CEMT IV vessels are able to pass Brugge and continue their journey towards Ghent, from where a connection with Antwerp is possible through the Ghent-Terneuzen canal and the River Scheldt. Therefore, large travel times (Truijens, Vantorre, & Vanderwerff, 2006) and/or limited cargo capacity explain the small share of inland transport in the port's model split. An upgrade of the present inland waterways has been explored (new canal, enlarging existing waterway), but never executed because of political, environmental and social reasons. A project for an upgrade of the nautical infrastructure near Brugge is currently going on[8], focusing on the main bottlenecks represented by bridges and locks (Steenbrugge bridge and Dampoort lock).

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[7] © OpenStreetMap-authors

[8] http://stadsvaart.be/waar/ (in Dutch)

The port of Zeebrugge thus really depends on estuary traffic to increase the amount of cargo transported by inland vessels. Nowadays, the estuary traffic forms 5.8% (Port of Zeebrugge, 2016) of the harbour's modal split. A simplification of the requirements in RD2007 to allow inland vessels at sea could attract more parties to invest in sea-going inland vessels. Naturally, a review of the current regulations must be preceded by a thorough study of the impact on safety of any planned simplification to the rules.

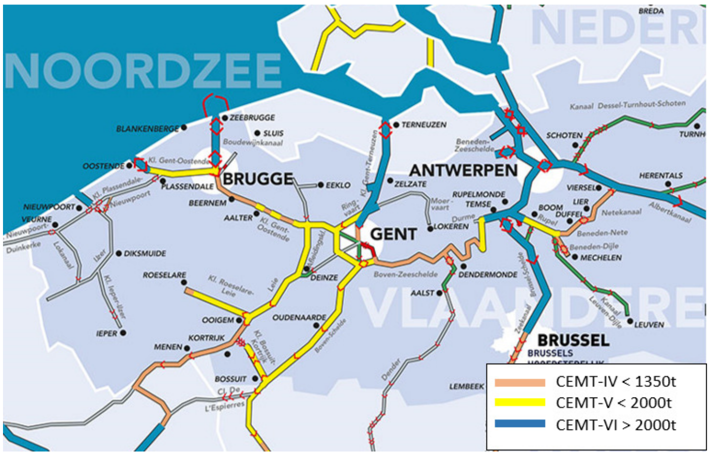

Figure 2-4 : Inland waterways connecting Zeebrugge to the hinterland.[9]

2.3 Royal Decree 2007

The Belgian legislation introduced in 2007 focuses on the role of the flag state in the safety of the vessel: ensuring the safety of the crew and protecting the marine environment. As the vessels need to be certified by a classification society, these class rules ensure the safety of the ship itself and the cargo it carries (Truijens, Vantorre, & Vanderwerff, 2006). An estuary vessel is conceived as an inland vessel with increased strength, and as such it needs to comply with the rules for inland vessels described in the European standard ES-TRIN (CESNI, 2017).

The strength of the vessel falls under the responsibilities of the classification society, and is not explicitly regulated in RD2007. The legislation RD2007 stipulates all the other requirements that the inland vessel needs to comply with in order to navigate at sea between Belgian coastal ports. Inland vessels are conceived to perform journeys on rivers and canals, which means that little to no wave action is present and that the crew is always at a relatively short distance to shore. As the flag state is responsible for the wellbeing of the crew, there are strict demands regarding, among other matters, fire safety (A60 doors), rescue equipment (FRC) and navigational equipment (sea radar). Since the inland vessel is performing a sea journey, it needs to comply with MARPOL (prevention of population of ships), without certificate, and COLREG (preventing collisions at sea).

A substantial part of the decree deals with the stability and behaviour in waves of the vessel. These two aspects will be briefly described in the following.

2.3.1 Stability requirements

The stability requirements imposed by the decree closely mirror the criteria prescribed by the IMO International Code on Intact Stability (IMO, 2008). The requirements for the righting lever curve and the weather criterion are the same ones valid also for ocean going ships, despite the fact that the estuary route is short and very close to the coast, where calmer met-ocean conditions can be expected. Moreover, inland vessels are only allowed to start a sea voyage when the wave height does not exceed a certain value.

Due to the very low flooding angles of inland vessels, it is almost impossible for such vessels to comply with the IMO requirements on stability. A modification of the stability requirements for inland vessels at sea, which takes into account both the typical structure of such vessels and the much more controlled environmental conditions, is proposed in section 5.

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[9] Taken from https://www.binnenvaart.be/waterwegen-en-havens/waterwegenkaarten

2.3.2 Behaviour in waves

Assuming that the stability (see above) and the strength of the vessel (responsibility of the class) are sufficient, shipping of water and slamming are the prime concerns for the safety of an inland vessel. Slamming causes high peak loads at the bow and vibrations of the vessel, load cases which are not considered when building an inland vessel. Shipping of water (green water) can lead to heavy loading of the deck, but also to flooding of cargo holds and deckhouse.

The behaviour of the vessel in waves is evaluated according to a risk analysis, which is described in an attachment of the decree. Tankers and closed hatch vessels which want to sail in favourable conditions (up to 1.2 m H_s), are exempted from the risk analysis, and they can be authorized to sail at sea provided that they comply with deterministic requirements on the freeboard, aimed at limiting the risk of shipping of water. The deterministic requirements are a copy of the demands mentioned in the service rule of 1962 (see 2.1). These rules prescribe a minimum freeboard as a function of the vessel length: $F_{min} = 0.5m + \left(L_{pp} - 50\right) * 0.005m$. Moreover, a minimum hatch height of 0.9m is prescribed for closed hatch vessels.

2.4 Worldwide estuary traffic

The access to maritime ports by adapted inland vessels has already been the subject of PIANC report 118 (PIANC, 2013). Apart from the Belgian situation described in this paper, there are several other cases where this topic is of great interest. In Europe the following cases are well known:

- France (1): Connection between *Port 2000* and the river Seine, using a northern (2 nm) and southern (20 nm) trajectory.
- France (2): Connection between Port of Marseille terminals (Golfe de Fos) and the river Rhone.
- France (3): Connection between Port of Sète and river Rhône (using various canals), two paths: 1.24 nm and 4.44 nm, depending on size of the vessel. A breakwater has been constructed to shelter the trajectory from the incoming waves.
- Italy: Coastal journey between (A) Venice and Porto Levante (33 nm) and (B) Ravenna and Porto Levante (55 nm). Additional connection between Porto Levante and Porto Mantova Valdaro (Mantova-Adriatic sea canal, 70 nm). The weather conditions are denoted as ‘good’ all year around (Adriatic Sea).

Outside of Europe, an application is the connection between the Beilun district and the Yongjiang river. (6 nm) in China. For an elaborate overview of the applications and specific regulations worldwide, the reader can refer to (PIANC, 2013).

3 WAVE CLIMATE

The Belgian Royal Decree states that the response of the ship must be calculated based on directional wave spectra measured during one year. This requirement imposes the use of wave data measured by buoys and precludes the use of hindcast data. However, hindcast wave data have some advantages over the measured ones, as explained below, and were used in this study. A change in RD2007 to allow the use of hindcast data is one of the proposed reviews to the regulation.

Buoy data are based on physical measurements, which do not require a validation process apart from the removal of erroneous measurements (spikes). However, despite the dense network of measuring buoys in the coastal zone between Zeebrugge and the Western Scheldt estuary, the measured data are only representative of the wave climate in the immediate surroundings of the buoy. This issue becomes more relevant as the areas of interest shift more towards coastal areas, where the influence of bathymetry on wave propagation induces a higher spatial variability of wave climate. When assuming the measured data to be representative of a large coastal area, some inaccuracies are unavoidably introduced. At least a broad estimation of the magnitude of such inaccuracies should always be performed and considered in the interpretation of the results of further calculations.

On the other hand, wave hindcast simulations can be designed to produce results at high spatial resolutions, allowing to describe in higher detail the wave climate in the area of interest. In this case, the shortcoming is the validation process which must be performed to ensure the accuracy of the simulated results. On top of that, taking into account the geographical variability of the wave climate complicates the risk analysis calculations.

3.1 Bol van Heist buoy measurements

In previous studies performed by the UGent Maritime Technology Division to assess the seaworthiness of estuary vessels, the readings of the Bol van Heist measuring buoy (BVH, +051.400 N +003.217 E) were used as a reference, according to the requirements of RD2007. The wave climate measured by the buoy was considered to be representative for the estuary trajectory between Zeebrugge and the mouth of the Western Scheldt. The assumed trajectory is 16 nm long with a direction almost parallel to the coastline (70°/250°, relative to the North direction, positive clockwise).

As the measuring buoy BVH is located more offshore than the trajectory of interest, the measured wave climate is more severe than the one which could be encountered by vessels along the trajectory (Figure 3-1). This approach, in line with the requirements formulated in the Royal Decree, yields conservative results.

3.2 SWAN hindcast simulations

An analysis based on hindcast simulations performed in (Verelst, 2006) clearly shows that the wave heights in the area of interest decrease when approaching the coast as well as when moving towards the mouth of the river. As an example, in Figure 3-2 the significant wave height simulated at a specific time frame is plotted for 14 points along the trajectory (line connected). The wave height measured by BVH is plotted as a separate point (star). The 14 points considered are the points along the trajectory shown in Figure 3-1.

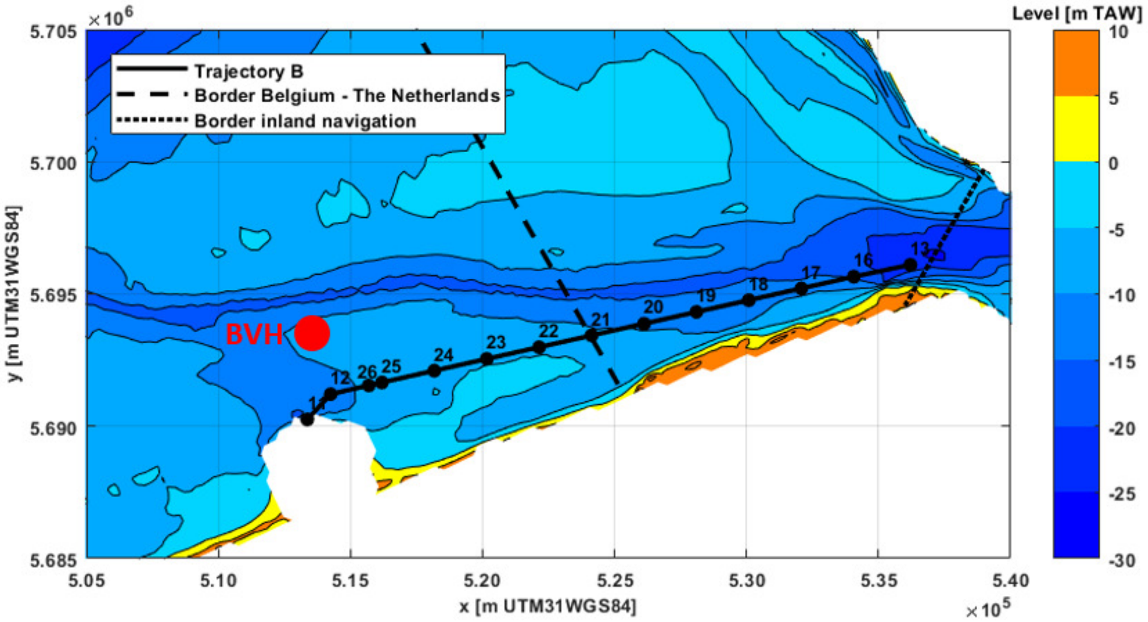

Figure 3-1: Bol Van Heist buoy and sea trajectory.

In this case, calculations of the ship responses based on simulated wave spectra along the trajectory are expected to deliver less conservative and more realistic results with respect to the ones obtained using the buoy data as a reference. This also means that a safety factor, which was introduced by the use of BVH wave data, is no longer present in the calculations.

For all the calculations shown in this paper, hindcast wave data were used as an input. The simulated data were produced by Flanders Hydraulics Research (FHR) with the spectral wave model SWAN, and validated using the BVH buoy measurements from the year 2013 (Suzuki, Hassan, Kolokythas, Verwaest, & Mostaert, 2016). The data provided cover an entire year, for all the two hourly timeframes where a valid measurement by BVH is available. Wave data are provided for each of the 14 points shown in Figure 3-1. In Figure 3-3 the cumulative distribution of H_s along the different points of the trajectory is outlined.

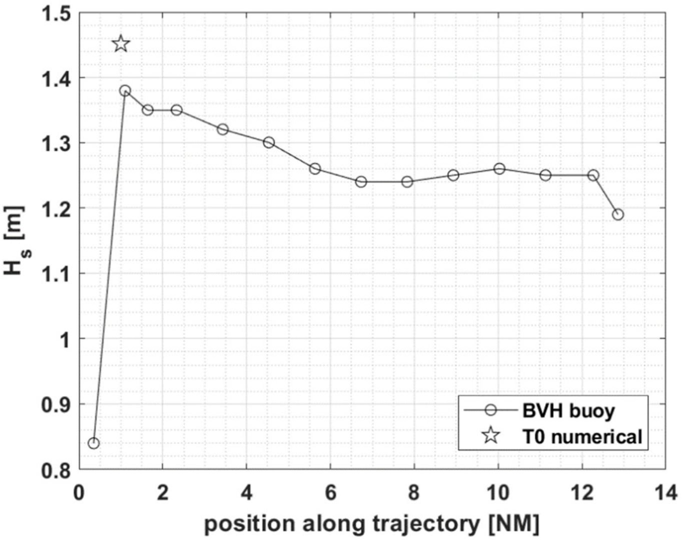

Figure 3-2: Wave climate variations along the trajectory.

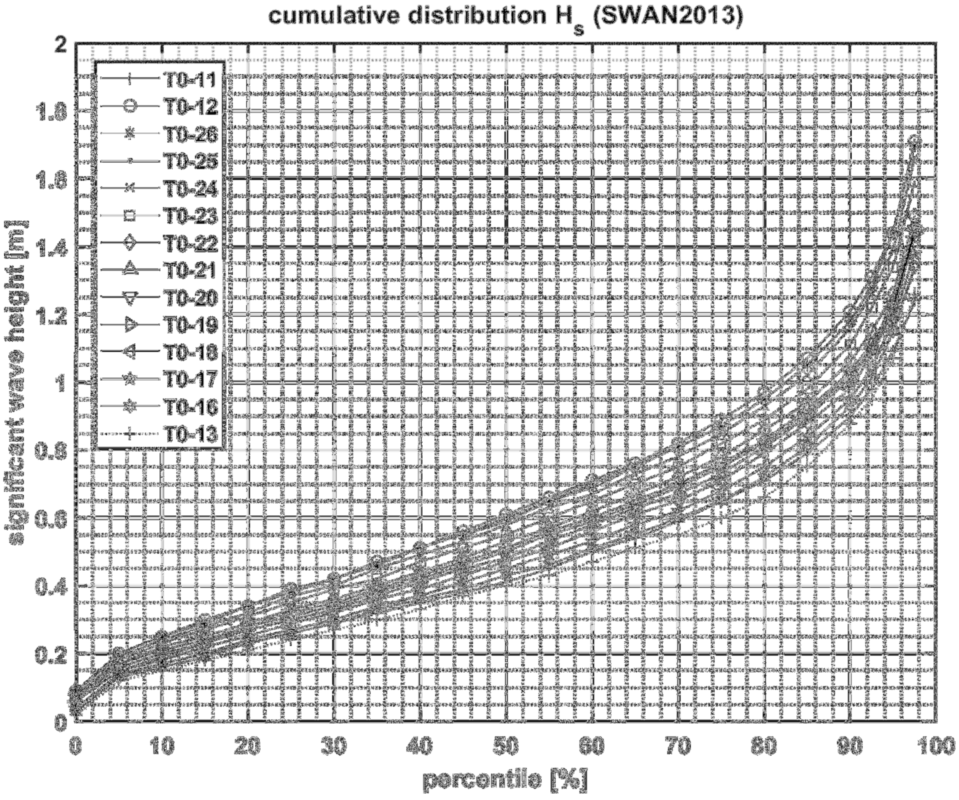

Figure 3-3: Cumulative distribution significant wave heights, based on SWAN output (validated using BVH 2013 measurements).

4 DESIGN VESSELS

To assess the feasibility of an extension to inland vessels with open hatches of the deterministic rules in RD2007, a comprehensive campaign of calculations was performed. The navigating fleet was studied and a limited number of recurring vessel designs was outlined. Four “*design vessels*” were selected to represent the entire fleet of open hatch inland vessels with lengths of 110 m and above, which are of prime interest due to their large loading capacity and their inability to reach the inland waterway network in another way.

4.1 Belgian and European inland fleet

The design vessels were selected based on an extensive research on two different databases: the W&Z (Waterwegen en Zeekanaal NV, now merged to De Vlaamse Waterweg NV) database, representing the Belgian inland vessel fleet, as well as an online database of European inland vessels[10]. The analysis of the databases was complemented by the pre-existing knowledge of the UGent Maritime Technology Division in performing studies for estuary vessels on the sea-trajectory. The database of W&Z contains extensive information on the main ship dimensions (length, width, draft and available freeboard) for 40 vessels. In the European online database, 518 vessels with the required characteristics can be found, including the vessels present in the W&Z database. A disadvantage of this database is that the depth of the vessels is not available. The number of vessels in the database is plotted in Figure 4-1 against the overall length and breadth of the vessels. Four main clusters of vessels sharing the same main dimensions are clearly visible.

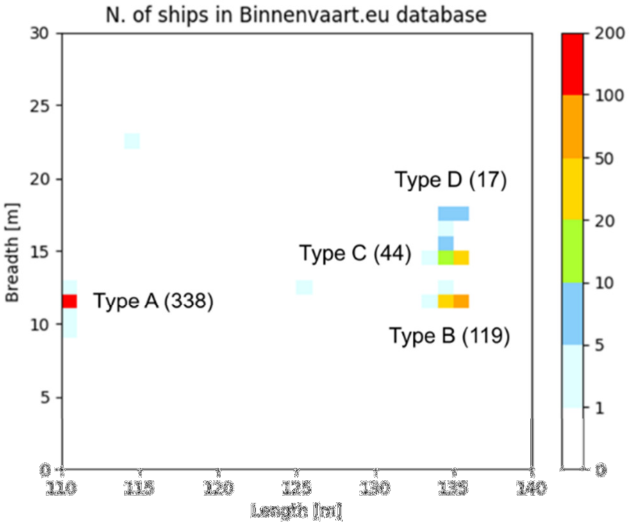

Figure 4-1: Number of vessels in the binnenvaart.eu database.

4.2 Main dimensions

The vessels found in the databases can be subdivided based on their main dimensions, as shown in Figure 4-1. The overall length of the vessels is well defined, with hardly any deviation from standard reference values. The breadth is mostly based on the number of container rows which the dry cargo vessel can accommodate. Slight differences are present, which can be explained by the fact that some vessels are primarily built for transporting bulk cargo instead of containers, allowing the breadth to differ from a multiple of the container width. The dimensions selected for the design vessels are summarized in Table 4-1. It is relevant to point out that the design draft is the one for inland service. The table shows also Rijkswaterstaat 'RW' classes (Rijkswaterstaat, 2011). The types A to D considered in this study coincide with the RW classes M8, M9, M11 and M12. M10 is a motor vessel with a length of 110 m and a breadth of 13.20 m, which is a typical value for tankers. No dry cargo vessel with such dimensions was found in the database.

Type	**RW class**	L_{OA}	B_{OA}	T_{design}	D
		[m]	[m]	[m]	[m]
A	**M8**	110.00	11.45	3.55	3.65
B	**M9**	135.00	11.45	3.60	4.25
C	**M11**	135.00	14.20	4.00	4.80
D	**M12**	135.00	17.10	4.00	5.50

Table 4-1:Design dry cargo vessels.

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[10] https://www.binnenvaart.eu

4.3 Loading conditions

The behaviour of a ship in waves is strongly influenced by the vessel's loading conditions. Both the mass distribution and the coordinates of the centre of gravity play a significant role in defining the ship responses. When calculating the performance of a ship in waves it is thus very important to make a good estimation of the loading conditions in order to get accurate results.

The focus of this study was not on a specific ship, but rather on a wide class of similar ships, represented by the four design vessels. Therefore, a precise estimation of the loading conditions was not possible. However, some simplifying assumptions were introduced in order to outline a range for the possible loading conditions.

A reduced draft was taken as the reference draft for each vessel, assuming that the vessels would not be able to sail the estuary route when loaded up to their inland design draft:

$$T_{red} = 0.8 \cdot T_{design}$$

This draft reduction was estimated based on preliminary calculations described in (Vantorre & Van Zwijnsvoorde, 2016). The mass distribution of the cargo was modelled in a simplified manner by assuming standard values for the roll, pitch and yaw radii of gyration:

$$k_{xx} = 0.37 \cdot B_{OA}$$

$$k_{yy} = k_{zz} = 0.25 \cdot L_{OA}$$

Concerning the vertical position of the centre of gravity, $\overline{KG}$, a range of possible values for this parameter was calculated for each type of ship. Since the inland vessels under investigation are used as both container vessels and bulk carriers, the lowest and highest position of the centre of gravity were calculated for both bulk and container loading conditions. This calculation was based on simplified assumptions about the cargo distribution.

For container loading conditions the cargo arrangements for the four design vessels was deduced from the database information, as shown in Figure 4-2. The lowest possible $\overline{KG}$ was calculated considering 20 ft High Cube containers loaded at the maximum of their mass capacity, namely 30 t, placed as low as possible in the number needed to reach the defined reduced draft. On the other hand, the highest $\overline{KG}$ was calculated considering the vessels loaded with the maximum number of containers, each assumed to have the same uniform weight. The uniform weight was calculated as the one needed to reach the defined draft.

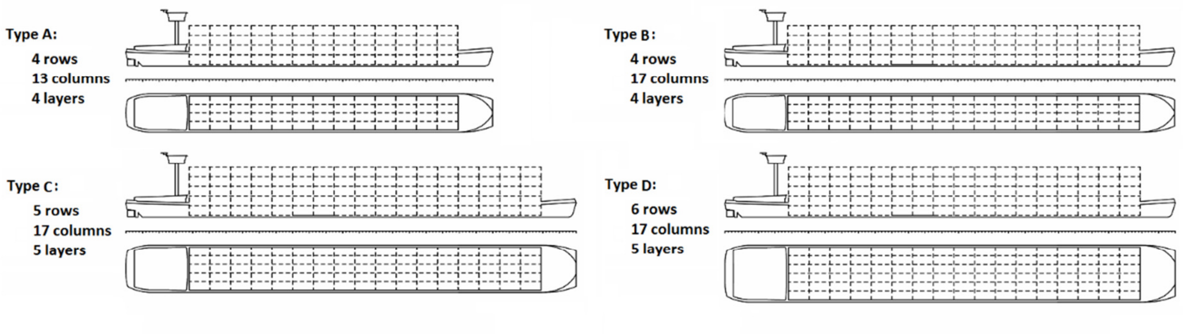
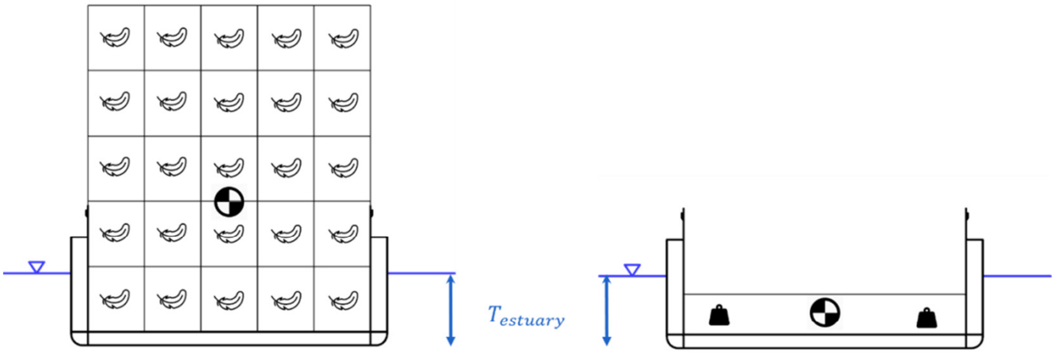


Figure 4-2: Container arrangement of the four design vessels.

Similar considerations were applied for bulk cargo. Since the higher $\overline{KG}$ value obtained for bulk cargo conditions was very close to the lower $\overline{KG}$ value for container cargo, the distinction between bulk and container cargo was dismissed. At the end, three loading conditions were considered for each design vessel, corresponding to three vertical positions of the centre of gravity:

- *LC1* corresponds to the highest $\overline{KG}$ obtained for container cargo (see Figure 4-3).
- *LC3* corresponds to the lowest $\overline{KG}$ obtained for bulk cargo (see Figure 4-3).
- *LC2* was chosen between the other two conditions based on the natural roll period, as described below.



Highest CoG ($\overline{KG}$) Lowest CoG ($\overline{KG}$)

Figure 4-3: Highest and lowest $\overline{KG}$ configurations.

The roll natural periods, T_φ, corresponding to the two extreme loading conditions were calculated and the loading condition *LC2* was chosen as the one leading to a roll natural period which is halfway between the two extreme values. The three loading conditions adopted for each type of ship are summarized in Table 4-2.

	LC1			***LC2***			***LC 3***		
Type	$\overline{KG}$	$\overline{GM}$	T_φ	$\overline{KG}$	$\overline{GM}$	T_φ	$\overline{KG}$	$\overline{GM}$	T_φ
	[m]	[m]	[s]	[m]	[m]	[s]	[m]	[m]	[s]
A	4.52	0.94	10.33	3.79	1.67	7.69	1.31	4.15	5.03
B	4.66	0.73	11.77	4.00	1.39	8.44	1.38	4.01	5.09
C	6.34	0.62	16.22	5.61	1.35	10.82	1.47	5.49	5.45
D	6.78	2.68	9.38	5.31	4.15	7.53	1.77	7.69	5.70

Table 4-2: Loading conditions of the four design vessels, expressed as $\overline{KG}$ and corresponding $\overline{GM}$ and T_φ.

4.4 Speed

A constant cruise speed along the trajectory of 10 knots was considered in this study for all design vessels.

4.5 Reference points and levels

Concerning shipping of water, RD2007 prescribes that the relative vertical motion at different control points along the vessel should not exceed a threshold value more than once in a lifetime (20 years, 300 round trips per year). The threshold value not to be exceeded by the relative motion is defined in the RD2007 as a distance between a reference level and the calm water free surface.

RD2007 prescribes the following control points and reference levels (see Figure 4-4):

- Foremost point of the bow (*F5C*). The reference level is the top of watertight bulwark. The relative motion to be considered needs to be increased due to the dynamic effect of the bow wave, according to the formula:

  $$\delta z = 0.2 \cdot z + 0.6 \cdot V^2/(2 \cdot g)$$

  where δz is the increase in the relative motion, z is the calculated relative motion, V is the speed of the vessel in m/s and g is the gravitational acceleration.
- Aftmost points of the fore deck, at both sides (*F4S, F4P*). The reference level is the top of watertight bulwarks.
- Aftmost, foremost and central points of the cargo deck, at both sides (*F2S, F2P, F3S, F3P, F4S, F4P*). The reference levels are:
  - 0.9 m above the main deck (1.35 m above for tankers).
  - the top of the coamings for closed hatch dry cargo ships and tankers.

  - 0.8 * the distance between the top of the coamings and the still water free surface below the previous value for open hatch dry cargo ships.
- Aftmost and foremost points of the aft deck, at both sides (*F1S, F1P, F2S, F2P*). The reference level is the top of watertight bulwarks.

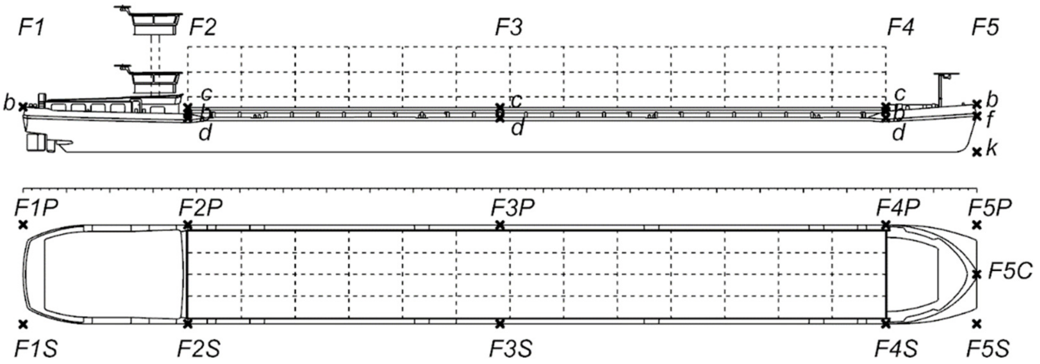


Figure 4-4: Position of selected points for vessel type A.

As for slamming, RD2007 requires to check the vertical relative motion at the intersection between the vertical line passing through the foremost point of the ship and the keel line. A slamming event is considered to happen when this relative motion exceeds the forward draft and the keel emerges from the water. A maximum of one slamming event per year is prescribed by RD2007. Point *F5C* needs therefore to be checked, considering the forward draft of the vessel as the reference level.

Several inland vessels in the database, especially the larger ones, show considerably flared bow sections, with flare angles lower than 20°. These shapes allow to achieve a wider fore deck, but on the other hand could cause dangerous impact phenomena when the ship is sailing in waves. The Royal Decree does not require to assess a risk of bow flare impacts since the probabilistic study was originally developed for vessels explicitly designed for the estuary service, which do not have flared bows. In the present study, which focuses on an analysis of existing inland vessels, the risk of bow flare impact was also assessed. Bow flare impacts are assumed to happen when the vertical relative motion exceeds the distance between the lowest point of the flared bow and the free surface. In accordance with the requirements of RD2007 for slamming, one exceedance per year was considered as the maximum allowed value. The lateral points of the flared bow at both sides, *F5S* and *F5P*, were selected as control points, with a reference level given by the height of the lowest point in the foremost section where the flare angle is smaller than 20°.

5 MODIFIED STABILITY REQUIREMENTS

5.1 Flooding angle

RD2007 does not explicitly request a minimum flooding angle, but the requirements for the righting lever curve set an implicit lower limit of 30°. Inland vessels, however, because of their own peculiar geometry, show very low flooding angles, often far below 30°. In the proposed modification of the stability requirements the minimum flooding angle is lowered to 17°, as prescribed in the French Decree for the navigation of inland vessels between the container terminal Port 2000 and the historic harbour of Le Havre (Legifrance, 2014).

5.2 Righting lever curve

RD2007, reflecting (IMO, 2008) paragraph 2.2, prescribes that the area under the righting lever curve should be:

- not less than 0.055 m·rad up to an angle of 30°.
- not less than 0.090 m·rad up to 40° or the flooding angle, whichever the lowest.
- not less than 0.030 m·rad between 30° and the lowest among 40° and the flooding angle.

The last two requirements are impossible to be met for inland vessels with a flooding angle lower than 30°. To account for low flooding angle vessels, an exception is proposed in the proposed renewal for the decree:

- If the flooding angle is less than 30°, the area under the righting lever curve up to the flooding angle should not be less than 0.055 m·rad. This replaces the other three requirements.

Therefore, ships are allowed to have flooding angles as low as 17° provided that they possess a dynamic stability up to the flooding angle which is at least equal to the one required by (IMO, 2008) up to an angle of 30°.

5.3 Weather criterion

RD2007 prescribes a weather criterion equal to the one described in (IMO, 2008). According to (IMO, 2008), the wind pressure which needs to be taken into account for the weather criterion is 504 Pa (which corresponds with Beaufort 10 wind conditions), while the initial heel angle due to the wave action needs to be calculated with simplified formulas as a function of the ship's dimensions and natural roll period.

A different way to calculate both the wind pressure and the initial roll angle is proposed, accounting for the calmer met-ocean conditions expected on the estuary route with respect to the open ocean. Concerning the wind pressure to take into account, its proposed value is given as a function of the maximum H_s for which the certificate is requested, according to Table 5-1. The values in the table are derived from the indications of Bureau Veritas (Bureau Veritas, 2014). Such indications were found to be close to the correlation between H_s measured in Zeebrugge and the associated maximum wind speed measured at Bol van Heist.

H_s	[m]	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0
P	[Pa]	214	231	247	262	277	290	303	315	327	339	350	361	371	381	391

Table 5-1: Proposed wind pressures for the weather criterion.

As for the initial heel angle θ_1, it is prescribed to be equal to the roll angle expected to occur once in a lifetime according to the risk analysis. For those ships exempted from the risk analysis (up to H_S=1.2 m), deterministic values based on the probability analysis performed for the four design vessels are proposed (Table 5-2).

H_s	[m]	0.6	0.7	0.8	0.9	1.0	1.1	1.2
Θ_1	[°]	7.0	7.7	8.3	9.0	9.7	10.3	11.0

Table 5-2: Proposed initial heel angles for the weather criterion in the new decree.

6 RISK ANALYSIS FOR DESIGN VESSELS

In order to assess the feasibility of new deterministic freeboard requirements for open hatch vessels, the performances of the four design vessels described in section 4 with respect to the probabilistic requirements of RD2007 were analysed. For each of the vessels, a full risk analysis was performed for all three loading conditions outlined in paragraph 4.3. The possibility for the vessels to sail up to H_s of 1.2 m was investigated according to the requirements of RD2007. The calculations showed that this is possible for all the four vessels, with reasonable drafts between 80% and 100% of the inland design draft.

6.1 Methodology

A vertical relative motion RAO (response amplitude operator) was obtained with the code *Seaway* (Journée & Adegeest, 2003) for each ship, loading condition and selected point. *Seaway,* originally developed by J.M.J. Journée[11] and currently part of ABB's software *Octopus*, is a frequency-domain

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[11] The Knowledge Centre Manoeuvring in Shallow and Confined Water (Flanders Hydraulics Research – Ghent University) wishes to pay tribute to prof. ir. Johan Journée who passed away on December 15th, 2017, at the age of 76. We remember a very nice co-operation in validating the *Seaway* code for (very) shallow water conditions by model test results performed at FHR in Antwerp.

seakeeping code based on linear strip theory. As for the wave data, the simulated directional spectra described in paragraph 3.2 were used.

By combining the wave data with the calculated RAOs, the number of times that a threshold value is exceeded during one round trip along the trajectory can be calculated for each of the available wave spectra, as described in (Vantorre, Eloot, & Delefortrie, 2010). The number of exceedances per round trip will be referred to as NER in the following. The calculated NER values can be grouped in wave height classes, but to do so, a single source of time dependent wave data should be chosen as representative of the wave conditions along the whole trajectory. In this study, the simulated wave data along the trajectory were used to calculate space and time dependent NER values, as pointed out in paragraph 3.2, while the H_s measurements from BVH were used as a common reference to split the NER values into wave height classes.

By averaging the grouped exceedance numbers, a *cumulative average number of exceedances* per round trip, NER_{AVG}^{cum}, can be calculated for each H_s class. The H_s leading to a number of exceedances per round trip equal to the maximum one prescribed by RD2007 (see paragraph 6.2) can be subsequently derived. A comprehensive explanation of the procedure can be found in (Vantorre, Eloot, & Delefortrie, 2010).

The following calculations were repeated for each design vessel, loading condition and control point. An array of threshold relative vertical motions (z_{rel}^{thr}) was introduced, with values ranging from 0.6 m to 1.8 m. For each of these values, the H_s leading to a number of exceedances of the threshold value equal to the maximum prescribed by RD2007, $NER_{AVG}^{cum}(z_{rel}^{thr}) = NER_{MAX}$, was calculated. These values of $H_S = f(z_{rel}^{thr})$ were interpolated through a second degree polynomial fit, and the threshold relative motions corresponding to discrete values of H_s (between 0.6 and 1.2 m with a step of 0.1 m) were calculated. Therefore, relations of the type $z_{rel}^{thr} = f(H_S)$ were derived. Finally, an available margin for the relative motion was calculated as a function of H_s by subtracting z_{rel}^{thr} from the distance between the free surface and the reference level associated with the considered control point (see paragraph 4.5).

6.2 Number of journeys per year

The Royal Decree does not explicitly impose a NER_{MAX} value. It defines a minimum return time for exceeding a threshold value of a ship response. For example, these return periods are the lifetime of the ship (20 years) for the vertical relative motions related to the risk of water overtake, and 1 year for the relative motions related to slamming phenomena.

In order to calculate a NER_{MAX}, a number of round trip journeys along the estuary trajectory in one year must be assumed. RD2007 assumes that an estuary vessel performs 300 journeys per year. This means that the ship sails the trajectory almost on a daily basis. This number is proposed to be lowered to a minimum of 100 journeys per year, like in the French legislation (Legifrance, 2014), which seems a much more realistic value when assuming that the vessels will sail in inland waters for a good share of their operational cycle. If a vessel wants to perform more estuary trips, this should be mentioned in the certificate, which could be handed over only after performing a full risk analysis.

Based on the reduction of the number of trips per year described above, the following maximum numbers of exceedances per round trip were assumed in this study:

- $NER_{MAX} = 0.0005$ for the risk assessment of water intake.
- $NER_{MAX} = 0.01$ for the risk assessment of slamming and bow flare impact.

6.3 Results

The results of probabilistic calculations indicate that the four design vessels can obtain a certificate to sail the estuary trajectory in H_s up to 1.2 m according to RD2007. Compliance with requirements for shipping of water can be achieved, for all plausible vertical positions of centre of gravity, with a reasonable reduction of the design draft for inland service, in line with the one assumed in paragraph 4.3.

Based on the results of the probabilistic calculations a maximum allowable draft was calculated as a function of H_s for each of the vessel types and loading conditions. To do so, available margins for the relative motions were calculated for each of the control points along the vessel, as described in paragraph 6.1. The lowest amongst the available margins was added to the reduced draft used in the probabilistic calculations to yield the maximum allowable draft. The results of this approach are summarized in Figure 6-1a.

For ship types B, C and D the draft assumed in the calculations, equal to 0.8 times the inland design draft, is always sufficient to ensure compliance with RD2007 requirements, while for ship type A it is found to be acceptable only up to H_s = 1.1. Higher values of H_s can be reached if a limitation to the metacentric height (loading condition) is imposed. Concerning ship type D, the relative motion margins are sufficiently high to allow the compliance with RD2007 even with the design draft for inland service (4.0 m), up to H_s = 1.2 m for the lowest $\overline{GM}$ loading condition and up to 1.0 m for the other two loading conditions.

When flared bow sections are considered, the study outlines some criticalities: apart from type D, all the considered design vessels are expected to face severe limitations on the draft or the allowed H_s in order to prevent excessive occurrences of bow flare impacts. This is clearly outlined by the minimum drafts (Figure 6-1 - right), which for ship types A, B and C are significantly lower than the ones obtained for conventional bow shapes (Figure 6-1 - left).

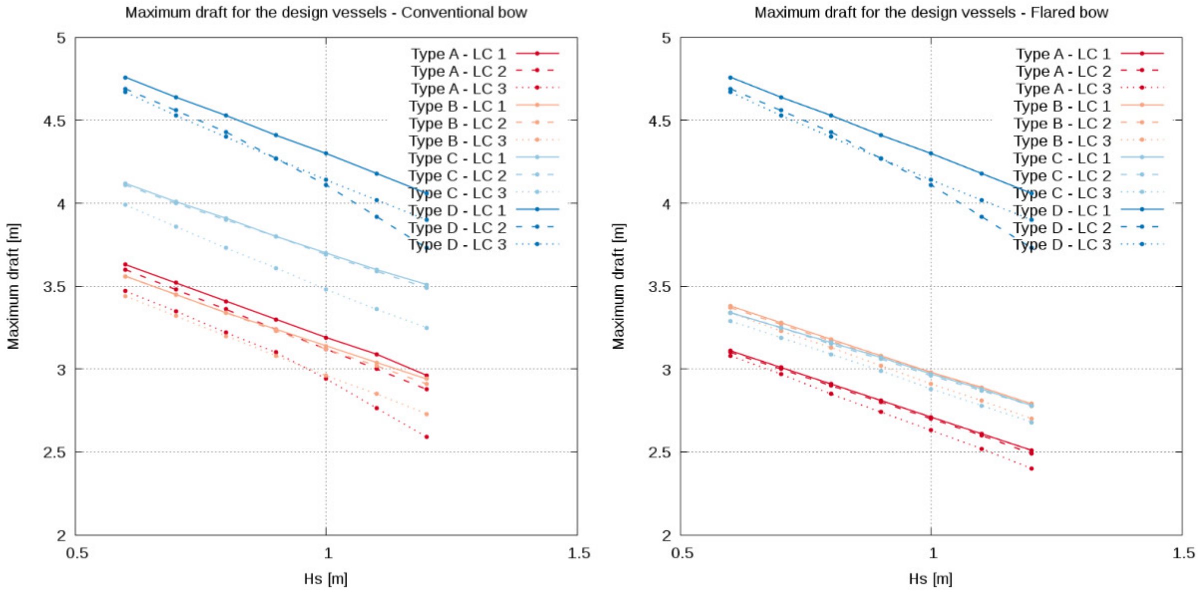

Figure 6-1: Maximum allowable draft for the design vessels.

7 NEW DETERMINISTIC REQUIREMENTS

The information collected through the probabilistic analysis of design vessels was used as a base to develop new deterministic freeboard criteria which could extend the deterministic rules for tankers and closed hatch vessels in RD2007. The new criteria are designed to exempt from the risk analysis all inland vessels with a length between 110 m and 135 m which request to sail the estuary trajectory between the port of Zeebrugge and the Western Scheldt up to a significant wave height of 1.2 m (measured at Bol van Heist).

In order to generalize the results of the probabilistic calculations described in section 6, the threshold vertical relative motions of control points for each of the considered ships and loading conditions were thoroughly analysed. A simplified relation between the threshold relative motion and H_s was derived for each of the control points, as described in paragraph 7.1.

The simplified formulas for the calculation of threshold relative motions were combined with the reference levels prescribed by RD2007. Minimum values for the height of specific points along the topsides of a vessel were finally determined as a function of H_s. The minimum values for the freeboard of inland vessels prescribed by a resolution from (UNECE, 2011) were also considered.

7.1 Threshold values for the vertical relative motions

The threshold vertical relative motions calculated for the design vessels at four of the control points are reported in Figure 7-1. The results related to water intake at foremost point (point *F5C*, $NER_{MAX} = 0.0005$) were increased for the dynamic effect due to the presence of the bow wave.

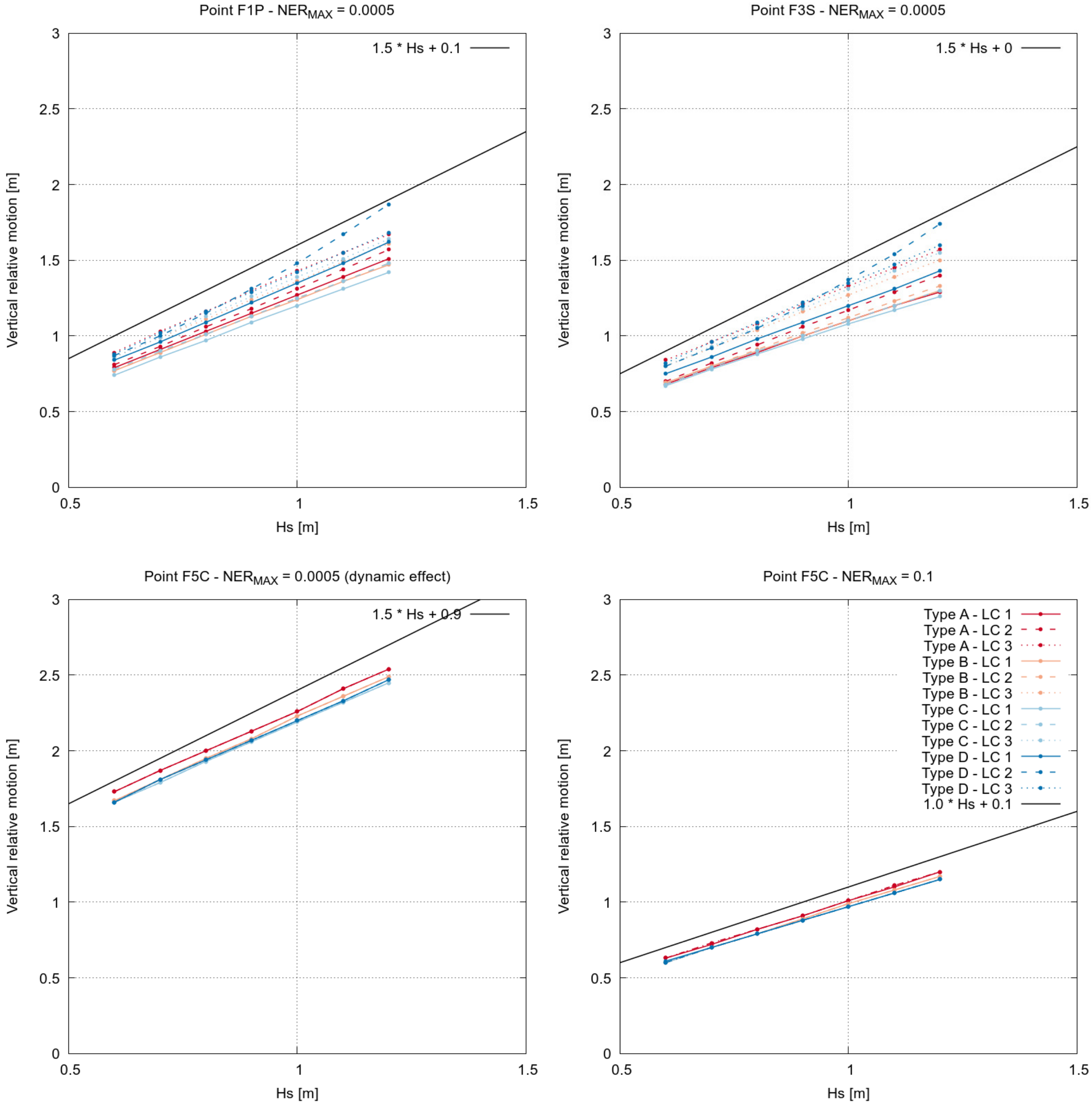

Figure 7-1: Threshold vertical relative motions at four control points.

Each of the plots in Figure 7-1 describes one control point, illustrating the results obtained for the 12 combinations of ship type and loading condition (see paragraphs 4.2 and 4.3). The complete series of plots which include all the control points is not shown here for space reasons. In any case, the plots not included in this paper show the same trends outlined by the plots in Figure 7-1.

In order to simplify the development of simplified equations for the threshold relative motions, the envelope of the highest relative motion curves was considered for each point. Therefore, simple relations were derived for an estimation of the threshold vertical relative motion (z_{rel}^{thr}) as a function of H_s only. These functions are summarized in Table 7-1 and, graphically, as a black curve on each of the plots in Figure 7-1.

The probabilistic requirements of the Royal Decree also prescribe to assess the risk of water reaching the level of two specific additional points: the lowest non watertight opening in the hull and the lowest point of the aft deck, if such point is lower than the main deck. The position of these points along the vessel can be very different from ship to ship, leading to different relative motions.

In order to keep the formulation simple, a generic equation was derived for the two additional points, independently from their specific position. Following a conservative approach, the equation leading to the highest motions among the ones derived for the other control points (excluding the one influenced by the dynamic factor) was chosen.

Point	NER_{MAX}	z_{rel}^{thr}
	[-]	[m]
F1 (S/P)	0.0005	$1.5 \cdot H_S + 0.1$
F2 (S/P)	0.0005	$1.5 \cdot H_S$
F3 (S/P)	0.0005	$1.5 \cdot H_S$
F4 (S/P)	0.0005	$1.5 \cdot H_S + 0.1$
F5 (C+dyn)	0.0005	$1.5 \cdot H_S + 0.9$
F5 (C)	0.01	$1.0 \cdot H_S + 0.1$
F5 (S/P)	0.01	$1.2 \cdot H_S$
Opening	0.0005	$1.5 \cdot H_S + 0.1$
Aft deck	0.0005	$1.5 \cdot H_S + 0.1$

Table 7-1: Simplified functions for the calculation of the threshold vertical relative motion at control points.

7.2 Minimum distances above free surface

By combining the simplified equations for the calculation of threshold vertical relative motions (Table 7-1) with the prescriptions of RD2007 about the control points and reference levels (see paragraph 4.5), minimum vertical distances between the considered reference level and the still water free surface were derived for each of the different control points.

According to the different reference levels to be considered, different equations were derived for ships with a watertight closed deck (*tankers*), dry cargo ships with closed hatches and dry cargo ships with open hatches.

The final equations for the minimum vertical distance above the free surface, $VDAFS$, for each of the control points and reference levels are summarized in Table 7-2. Most of the reference levels in the table were already described in paragraph 4.5. The exceptions are the keel level at the longitudinal foremost point of the ship (k) and the vertical position of a specific opening (o).

As a matter of fact, the deterministic rules can be considered as a simplified version of the risk analysis, where the threshold vertical relative motions are approximated by simplified equations (see Table 7-1) instead of being calculated by means of a full probabilistic sea-keeping study. Since the simplified equations were designed to be conservative with respect to the actual calculations, the satisfaction of the deterministic requirements guarantees that the vessel is able to comply with the risk analysis prescribed by RD2007.

Response	Point	Level	NER_{MAX}	$VDAFS_{min}$		
			[-]	*open hatches*	*closed hatches*	*tankers*
				[m]	[m]	[m]
Aft deck water intake	*F1 (S/P)*	b	0.0005	$1.5 \cdot H_S + 0.1$	$1.5 \cdot H_S + 0.1$	$1.5 \cdot H_S + 0.1$
	F2 (S/P)	b	0.0005	$1.5 \cdot H_S$	$1.5 \cdot H_S$	$1.5 \cdot H_S$
Loading compartment water intake	*F2 (S/P)*	d	0.0005	$1.5 \cdot H_S - 0.9$	$1.5 \cdot H_S - 0.9$	$1.5 \cdot H_S - 1.35$
	F2 (S/P)	c	0.0005	$1.875 \cdot H_S$	$1.5 \cdot H_S$	-
	F3 (S/P)	d	0.0005	$1.5 \cdot H_S - 0.9$	$1.5 \cdot H_S - 0.9$	$1.5 \cdot H_S - 0.9$
	F3 (S/P)	c	0.0005	$1.875 \cdot H_S$	$1.5 \cdot H_S$	-
	F4 (S/P)	d	0.0005	$1.5 \cdot H_S - 0.8$	$1.5 \cdot H_S - 0.8$	$1.5 \cdot H_S - 1.25$
	F4 (S/P)	c	0.0005	$1.875 \cdot H_S + 0.125$	$1.5 \cdot H_S + 0.1$	-
Fore deck water intake	*F4 (S/P)*	b	0.0005	$1.5 \cdot H_S + 0.1$	$1.5 \cdot H_S + 0.1$	$1.5 \cdot H_S + 0.1$
	F5 (C+dyn)	b	0.0005	$1.5 \cdot H_S + 0.9$	$1.5 \cdot H_S + 0.9$	$1.5 \cdot H_S + 0.9$
Bow impact	*F5 (S/P)*	f	0.01	$1.2 \cdot H_S$	$1.2 \cdot H_S$	$1.2 \cdot H_S$
Slamming	*F5 (C)*	k	0.01	$1.0 \cdot H_S + 0.1$	$1.0 \cdot H_S + 0.1$	$1.0 \cdot H_S + 0.1$
Opening	*Open point*	o	0.0005	$1.5 \cdot H_S + 0.1$	$1.5 \cdot H_S + 0.1$	$1.5 \cdot H_S + 0.1$
Aft deck	*Lowest point*	d	0.0005	$1.5 \cdot H_S + 0.1$	$1.5 \cdot H_S + 0.1$	$1.5 \cdot H_S - 1.25$

Table 7-2: Deterministic $VDAFS$ requirements.

7.3 Range of application and minimum freeboard values

In agreement with the existing exemptions of the current Royal Decree, the new deterministic rules are designed to be applied up to $H_S = 1.2\ \mathrm{m}$. Moreover, a lower limit of $H_S = 0.6\ \mathrm{m}$ is introduced: if the requested sailable H_S is below this threshold, the requirements for $H_S = 0.6\ \mathrm{m}$ must be applied.

When an H_S of 0.6 m is considered, null or even negative values for the vertical distance between the main deck and the free surface are obtained from the equations in Table 7-2. This means that a null freeboard would be sufficient for the vessel to comply with the risk analysis. Such peculiar result follows from the definition in RD2007 of the reference level not to be reached by water more than once in a lifetime, which is set between 0.90 m and 1.35 m above the deck level. Nevertheless, a null freeboard should obviously never be allowed. Therefore, additional requirements for the minimum freeboard are introduced in the deterministic rules.

For this purpose, the minimum freeboards recommended by the harmonized Europe-wide technical requirements for inland vessels published in (UNECE, 2011), are used as a reference. In these recommendations the minimum freeboard is expressed as a function of the ship type and length. Moreover, different minimum freeboards are recommended for three inland navigation zones, each characterized by a maximum wave height ($H_{1/10}$). Assuming a Rayleigh distribution for the wave heights, the $H_{1/10}$ wave height can be converted to the significant wave height through the relation:

$$H_S = 0.787 \cdot H_{1/10}$$

Focusing on ships with a length between 110 m and 135 m sailing in wave conditions below $H_S = 0.6\ \mathrm{m}$, the lowest allowed wave height, the minimum freeboards prescribed by (UNECE, 2011) are:

- In Zone 3 ($H_{1/10} < 0.6\ \mathrm{m};\ H_S < 0.47\ \mathrm{m}$): 0.15 m.
- In Zone 2 ($H_{1/10} < 1.2\ \mathrm{m};\ H_S < 0.94\ \mathrm{m}$): 0.60 m for open hatches vessels, 0.34 for vessels with closed watertight hatches and 0.22 m for tankers.

These values were linearly interpolated to obtain freeboard requirements for $H_S = 0.6\ \mathrm{m}$:

- For tankers: 0.17 m
- For closed hatch dry cargo vessels: 0.20 m
- For open hatches dry cargo vessels: 0.27 m

In the final proposed deterministic rules, the equations in Table 7-2 are considered, together with an explicitly enforced minimum value for the distance between a reference level and the free surface. For all the reference levels except the deck level, the minimum allowed distance is the result of the equations for $H_S = 0.6\ \mathrm{m}$. When the deck level is considered, on the other hand, the three values described above are introduced as the minimum freeboard instead of the null or negative values resulting from the corresponding equation.

8 CONCLUSION

The connection between the Flemish coastal ports and the main European inland waterway network is limited for large inland vessels. In order to increase the amount of cargo transported through waterways, some inland vessels were allowed on the estuary trajectory between Belgian ports and the mouth of the River Scheldt by the Belgian Shipping Inspectorate since the ‘60s. Certificates to sail at sea, in controlled met-ocean conditions, were given to inland vessels based on individual assessments.

A more structured approach was introduced with the Belgian Royal Decree of 2007, which enforces general rules to allow inland vessels on the estuary trajectory. Together with other requirements, the IMO stability regulations must be respected and a full probabilistic study must be performed to assess the risk of water overtake. An exemption from the last point is granted to tankers and closed hatch vessels which want to sail up to significant wave heights of 1.2 m.

For container and bulk cargo vessels the strict requirements of RD2007 mean in practice that only vessels which are specifically designed for the estuary service can be allowed on the trajectory. As of today, only a very restricted number of such vessels are allowed at sea. The aim of this paper was to study the behaviour at sea of standard inland vessels with respect to the requirements of RD2007, and check the feasibility of new deterministic rules to exempt also open hatch vessels from the risk analysis.

An update to the stability requirements of RD2007, deemed as too strict for the coastal nature of the sea trajectory, was proposed. From the stability point of view, this would allow inland vessels with low values of the flooding angle to sail the trajectory provided that they show a sufficient dynamic stability up to the flooding angle.

Moreover, four design vessels were outlined based on the information contained in two databases. Plausible loading conditions were derived as well. The compliance with the probabilistic requirements about the risk of water overtake contained in RD2007 was positively ascertained for all the design vessels and loading conditions, requiring only reasonable reductions of the design draft for inland service. New deterministic exemptions were designed based on the results of the probabilistic calculations on the design vessels. These new rules could allow existing inland vessels on the trajectory, in controlled met-ocean conditions, without the need of a risk analysis.

The approach described in this paper could help to increase the waterborne transport share in the modal split of the Flemish ports, and to tackle lacks in the inland waterways network with temporal and economic scales orders of magnitude lower than the ones associated with a renewal of the waterways infrastructure. While the study is specifically focused on the Belgian coastal situations, the general concepts described in the paper can be applied to any other area of interest where an extension of the operational range of inland vessels could benefit the total efficiency of waterborne transport.

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