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ON THE DESIGN OF SHIPS FOR ESTUARY SERVICE

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SUMMARY

The Belgian Federal Service for Mobility and Transport recently issued a draft proposal for new risk based regulations for the design of so-called estuary ships. These are basically inland waterways vessels strengthened and equipped to the extent that they can safely operate in the coastal waters between the West Scheldt estuary and the port of Zeebrugge when weather conditions are favourable.

In an earlier version of the regulations the weather window was limited to sea states with significant wave heights up to 1.2 m. The new rules allow operation in higher sea states, provided that the ship-owner presents a risk assessment study showing that the design of his ship meets all requirements in all sea states up to the proposed limiting seaway.

As the new regulations are aimed at avoiding excessive ship motions, shipping of green water and wave impact loading, the risk analysis for the design of these ships can be based on well-proven linear strip theory calculations for the determination of wave loads and ship motions. Accordingly, a risk analysis procedure has been developed which is now being used for the actual design of such ships.

1. INTRODUCTION

The Flemish deep-sea port of Zeebrugge is very successful as a ro-ro terminal. Its development as a container transit port however is hampered to some extent by the lack of an adequate connection of the Bruges – Zeebrugge area with the Belgian inland waterways network. The port of Antwerp for instance is at the hub of three main inland waterways, and there 27% of hinterland traffic is carried by inland navigation, whereas this figure is only 2 to 3% for Zeebrugge.

The Belgian inland waterways network is very dense and can be considered as excellent, with most rivers and canals allowing at least European class IV traffic (1350 tonnes, 3 TEU across the beam x 3 TEU high) between the most important industrial areas, including the north of France. From Ghent and Antwerp the river Maas, The Netherlands and hence the Rhine can even be reached with class VI vessels and push-barge convoys (up to 9000 tonnes).

From Zeebrugge to the inland port of Bruges the existing canal also allows class VI traffic, but the old canal from Bruges to Ghent starts with a reach skirting Bruges' historical centre. As this reach includes a number of picturesque swing- and draw-bridges leading to the old town-gates, it can hardly be improved above its present profile (beam 9.5 m, draft 2.3 m, 900 to 1000 tonnes), and will always remain a bottle-neck for modern inland navigation. A new diversion encircling the city farther from its centre is also practically out of the question, as the area is densely populated.

The obvious long-term solution is a new canal running more or less straight from Zeebrugge to the port of Ghent. Plans exist (the "Noorderkanaal"), but due to budgetary restrictions and environmental concerns these will take a long time to materialize, if they ever do so at all.

It goes without saying that in the meantime attention is focused on the "free for all" sea-route leading along the coast to the mouth of the West Scheldt. At present, there are a number of river-sea going vessels moving limited amounts of transit cargo to the Rhine. For arbitrary cargoes this is not an economically viable operation however, as the sea leg of the tour is much too short in comparison with the inland part. River-sea going ships are designed, equipped and manned as coasters, complying with all international regulations for sea-going ships, and much more expensive both in acquisition and in operation than inland waterways vessels.

Other possibilities which have been considered include a sea-going barge pushed by a sea-going tug from Zeebrugge to the West Scheldt, where it was to be taken over by an inland push-boat, and a so-called dock ship, which was basically a lift ship transporting inland vessels and barges piggy-back style over the sea-route. Both ideas were abandoned as, again, the economics of such new-buildings combined with rather complicated operations were unfavourable. For the dock ship cost figures are not available, but it was stated that the building and operating costs for such a vessel should be at the public expense. For the sea-going barge combination a simulation calculation showed that on the route Zeebrugge – Duisburg for instance transport costs per TEU with a newly-built 332 TEU barge (62 hours round trip) would on the average still be 5 to 6% higher than with an existing 90 TEU inland vessel (90 hours round trip over inland waterways only).

Instead of using expensive sea-going vessels on what is finally only a very short sea trip coupled to a long inland voyage for which these ships are over-designed and over-staffed, it is also possible to work the other way around. Ever since 1962, the Belgian Shipping Inspectorate (BSI) issued regulations [1] concerning so-called estuary vessels. These are basically inland waterways ships strengthened and equipped to the extent that they can safely operate between Zeebrugge and the West Scheldt, given adequate freeboard and "favourable weather and wave conditions". The favourable weather and wave conditions are not specified in the rules, but empirically the limits have been set at Beaufort 5, which corresponds in this area with a significant wave height H_S of approximately 1.2 m. The existing fleet built according to these regulations is not large and consists mostly of tankers, for which it is easy to fulfil the additional strength and safety requirements. It is of interest here to note that these entirely empirical old rules must have been quite consistent, as over the years not a single incident with these ships has been reported.

The weather window mentioned above has become too low for present day requirements of trade in Zeebrugge, as it implies that estuarine traffic is not possible for 60 days a year on the average, whereas other maritime traffic in and out of Zeebrugge is only suspended at Beaufort 8. Accordingly, BSI received an ever growing number of requests from various ship owners to consider an extension of the limiting conditions, e.g. up to significant wave heights of 1.6 to 1.8 m. The Inspectorate was quite willing to enter into this matter (see e.g. [2]), and took the initiative to consult with Lloyd's Register of Shipping (LR) Antwerp. These contacts led to the conclusion that the problem could be tackled in a first stage by applying modern probabilistic design procedures to each separate project. The proposed methodology includes risk analysis with respect to criteria which take due account of the limitations inherent to the design of inland waterways vessels. The ship could then be designed and built respecting proven inland waterways arrangements, while at the same time incorporating design features and construction details derived from sea-going practice.

A first design based on the provisional criteria formulated by the Belgian Shipping Inspectorate and by Lloyd's Register of Shipping was completed at the end of January 2004: see [3]. These car carriers can operate in significant wave heights up to 1.75 m. The actual design calculations were started by MARIN (The Netherlands), but finalized by the Division of Marine Technology of Ghent University (UGent), as the latter had direct access to wave data registered along the Flemish coast.

In June – July 2004, two newly built estuary tankers (figure 1 shows one of them) were granted permission for estuary service up to H_S = 1.6 m, based on a re-analysis of their design according to the new calculation procedure. Another example showing that interest in estuary ships with extended operating conditions was growing was the project of an open hatch container carrier for the route Antwerp – Zeebrugge. All this caused the authorities to take notice of the new developments. At the end of last year, after an additional parametric study by UGent concerning container carriers, the Belgian Federal Service for Mobility and Transport issued a draft proposal for a royal decree containing an elaborated version of the criteria governing the design and operation of estuary ships in general. At present, at least two new-building projects for container carriers up to 350 TEU are in the preliminary design stage, with UGent again responsible for the risk analysis part of the design work, and with the Flemish Ministry of Public Works providing prototype support funding.

In the present paper, an overview is presented of the 1962 regulations and the new design criteria as stated in the Belgian royal decree proposal, of the design methodology as used at UGent, and of the questions which require further elucidation and research.

2. THE REGULATIONS OF 1962

Service rule no. 8 [1] of the Belgian Shipping Inspectorate stipulates that estuary ships have to fulfil in the first place all the regulations concerning inland waterways vessels, together with additional requirements as enumerated in the service rule. If all requirements are met, then BSI can allow such vessels to operate between the West Scheldt and Zeebrugge when weather conditions are favourable, which means in practice that significant wave height should be 1.2 m at most, as has been mentioned before.

A number of the additional requirements have to do with equipment, life-saving appliances, etc. As they have no bearing on the basic design of these ships, they need not concern us here.

The structure of an inland waterways ship is designed to withstand still water loads only. So a number of requirements in [1] are clearly aimed at making certain that adequate longitudinal strength can be attained for operating in waves:

- The vessel's depth should be at least 2.60 m, and the ratio of length between perpendiculars over depth may not be larger than 25.
- A ballast tank must be arranged amidships, to be filled while at sea in ballast, in order to decrease the still water hogging moment.

Of course, although this is not mentioned in [1], this tank serves the additional purpose to increase draft while in ballast, to avoid excessive slamming and racing of the propeller.

Service rule no. 8 does not state what would be adequate longitudinal strength, but instead refers the designer to the rules of Bureau Veritas (or equivalent) for estuary vessels. It is not known if Bureau Veritas ever published such rules, but a whole chapter of the 1974 regulations of the former Belgian classification society Unitas NV [4] is devoted to this type of ships. In general, hull scantlings have to be increased by 10% over those of regular inland ships, and from the rules concerning hull section modulus it is apparent that the additional design wave bending moment is held to be approximately equal to the design still water bending moment for the ship at full draft.

Other requirements related to strength are that cross-ties are necessary between gangways in ships with long hatch openings, to improve torsional and transverse strength, and that hatch covers must be able to resist loads up to 450 kg/m^2 and should be closed watertight while at sea. Clearly, no provision is made in the rules for open top hatch-coverless container carriers and, in general, for modern single-hold double-skin designs with ballast capacity in the wing tanks.

In inland navigation, ships may be loaded down to a load-line tangent to the underside of the gangway plating, resulting in very low reserve buoyancy. This is not permissible at sea, and accordingly [1] requires a freeboard of 600 mm (tankers 500 mm) for ships with a length between perpendiculars of 70 m and 500 mm (tankers 400 mm) for ships with a length of 50 m. For other lengths freeboard values may be obtained by linear interpolation or extrapolation. Together with a minimum sheer of 900 mm at the bows and 500 mm aft, this requirement also yields some protection against shipping of green water while operating in a seaway.

The intact stability of inland waterways vessels has to be in accordance with the regulations for navigation on the Rhine. [1] does not include any additional requirements with respect to the stability of estuary ships. This was not necessary, as high deck loads of containers did not occur at the time, and as these ships with their high B/T values always had ample initial stability.

Compliance with service rule no. 8 has been found empirically to allow safe operation of estuary ships in seas with H_S up to 1.2 m. It is clear however that this rule gives absolutely no guidance on the design of modern ship types required to operate in higher sea states.

3. THE NEW CRITERIA BASED ON RISK ANALYSIS

In Lloyd's Register's current rules for inland waterways vessels 3 operational zones are defined: zone 3 where H_S does not exceed 0.5 m, and zones 2 and 1 where H_S does not exceed 1.0 m and 1.6 m respectively. In general, the rules in [5] are valid for ships operating in zone 3 only. Scantlings and arrangements for ships intended to operate in zones 1 and 2 have to be specially considered, i.e. they have to be determined for instance by direct calculation procedures.

BSI has extended this line of thought to include the determination of other basic design parameters affecting the behaviour and the safety of estuary ships while crossing the sea zone between the West Scheldt and Zeebrugge. Criteria are provided concerning various aspects of the safety of estuary vessels operating in a seaway, and the designer or owner is expected to prove that these criteria are met for his particular design and for a related maximum sea state. To this effect, the designer can make use of direct calculation procedures, model tests, or both, but in any case he is requested to submit a detailed report, to the satisfaction of the Inspectorate.

The provisional criteria originally framed by BSI in close consultation with LR have now been superseded by those in the draft decree of the Belgian Federal Service for Mobility and Transport. In deriving them, an underlying principle has been that estuary ships must remain what they are basically meant to be: inland waterways vessels strengthened and equipped to allow safe operation in certain sea states for a limited period of time, but not to the extent that their hull and equipment becomes as expensive as those of sea-going ships of comparable deadweight.

The following criteria must be met, for an estuary ship operating in seaways encountered on the route West Scheldt – Zeebrugge and back:

3.1 SLAMMING

Emergence of the most forward point of the ship's keel from the water, due to excessive vertical motions of this point relative to the wave surface, should not occur more than once a year.

It is clear that if this criterion is satisfied, then the probability of occurrence of serious slamming and its potential catastrophic effect on the hull girder will be even lower than once a year, as a slam will only occur upon re-entry of the forefoot when the relative velocity of the forefoot and the water surface exceeds a certain threshold value. The philosophy behind this requirement is that if the incidence of slamming is sufficiently low, then it does not have to be taken into account for the determination of the design wave bending moment, and there is also no need for extra strengthening of the forward bottom plating.

In a given wave climate, the criterion will provide a lower bound on draft, e.g. in the ballast condition. Conversely, given a certain draft the criterion will yield an upper limit for the sea states in which the ship can operate.

3.2 SHIPPING OF WATER BY THE BOW AND BY THE STERN

Shipping of green water over the bulwarks on the forecastle and on the aft deck may occur only once in a lifetime. Closed bulwarks at the ends should extend at least 7% of the length between perpendiculars aft or forward of the corresponding perpendicular.

In determining the relative vertical motion at the bows, the height of the bow wave and the dynamic piling-up must be taken into account. (The decree provides a formula for estimating this height, in case no empirical data from model tests or full-scale measurements are available.)

When these requirements are met, then weather deck structures, superstructures and deck equipment can be arranged as is customary for inland navigation, i.e. without having regard to direct wave impacts as expected on sea-going vessels. Nevertheless, the fundamental principles of the 1966 Loadline Convention have to be judiciously applied (openings leading below the freeboard deck, strength of doors and closing appliances, sill heights, windows, etc.)

For existing ships, from this criterion a relation between H_S and required freeboard in the loaded condition can be derived. For a new design, guidance can be obtained on required freeboard in combination with sheer and bulwark height at both ends. Again, given a certain draft the criterion will yield an upper limit for the sea states in which the ship can operate.

3.3 SHIPPING OF WATER OVER THE TOPSIDES

The probability of occurrence of the water level at the side of the ship rising above a prescribed reference level may not exceed once in a lifetime.

For ships with watertight steel hatch covers the reference level is at the top of the hatch coamings.

For open top ships the reference level is the lower of:

- *0.90 m above the deck-line at side;*
- *80% of the vertical distance from the waterline to the top of the coaming above the waterline.*

For ships having a continuous watertight deck (tankers), the reference level is at 0.90 m above the deck-line at side at half length, and at 1.35 m above the deck-line at both ends of the cargo tank zone.

For a given design, the criterion will again lead to a relation between H_S and required freeboard in loaded condition. It can also be of help in deciding whether to install bilge keels or not, as relative vertical motions at the ship's sides depend on the amplitude of the roll motion as well.

3.4 MAXIMUM ROLL ANGLE

A maximum roll angle, defined as the lesser of 15°, or two thirds of either the angle of flooding θ_f or the angle at which the stability curve reaches a maximum if this angle is less than θ_f, should not be exceeded more than once in a lifetime.

Just as in IMO Resolution A.749 [6], θ_f is defined as the angle of heel at which openings in the hull, superstructures or deck-houses which cannot be closed weathertight immerse.

The safety margin of 33% is left to account for the dynamic heeling effect of wind gust loading, as this would be an additional complication if it would have to be considered in a direct calculation procedure or in model tests.

3.5 INTACT STABILITY

The intact stability of estuary ships should fulfil the regulations of *IMO Resolution A.749* [6] *for cargo vessels*, except that the requirements concerning the position of the top of the stability curve are relaxed somewhat: the maximum righting arm for an estuary ship should occur at an angle of heel preferably exceeding 25° but not less than 20°. The value of the wind pressure P to be used in the verification of the IMO weather criterion may be reduced, subject to the approval of BSI.

The weather criterion is included to warrant the safety of container vessels, and of other ships with high deck loads. The relaxation of the rule concerning the angle of heel at which the maximum value of GZ occurs is inspired by the fact that most inland waterways vessels not carrying deck loads have a high initial metacentric height combined with a rather low freeboard.

3.6 OTHER REQUIREMENTS

Apart from these criteria which are valid in general for all estuary ships, additional calculations and information for specific ship types or equipment may be required. For instance, if an estuary ship is equipped with a telescopic wheelhouse, then the once in a lifetime lateral accelerations of the wheelhouse at maximum extension will have to be computed, to enable checking of the structural integrity and of the habitability. And for container carriers, it may be required to calculate vertical and lateral accelerations of containers in selected locations, to ascertain the required strength level for the lashing arrangements.

As is usually the case in such texts, reference is made to the classification societies for all questions regarding the structural integrity of estuary ships. According to LR, the value of the permissible stress to be used for the calculation of the hull section modulus may be derived from the formula given in the rules for sea-going ships for the permissible combined (still water plus wave) stress for hull vertical bending. In the present case the design vertical wave bending moment is the once in a lifetime bending moment as derived from the risk analysis calculations. For open hatch container carriers the once in a lifetime horizontal wave bending moment and torque loading have to be computed as well.

As the hull structure is subject to fatigue from wave loading, structural details must, in general, be up to the standards of good design and workmanship for sea-going ships. This means that some structural arrangements which are regularly used in inland waterways ships and barges will not be acceptable for estuary vessels. A typical example is shown in figure 2.

It will be clear that the above is only a review of the most important requirements as laid down in the draft royal decree proposed by the Belgian Federal Service for Mobility and Transport. For design work reference should be made to the original document, which also contains requirements for equipment, navigational aids etc.

4. THE DIRECT CALCULATION PROCEDURE AS IMPLEMENTED BY UGENT

4.1 PRINCIPLE

To prove that a particular design meets the new criteria for a projected maximum sea state, the designer has to obtain long term statistics of a number of ship responses from voyage simulations. In general, for a sea-going ship some of the responses involved may be highly nonlinear processes, for which reliable long term statistics can only be derived from time domain simulations or from model tests. An important example is the design value of the vertical bending moment on a ship in a seaway, which is composed of a low-frequency wave-induced load and a high-frequency whipping load due to slamming. To account for the whipping stresses, a nonlinear hydro-elastic time domain strip theory has been used – see for instance [7] or [8]. Fortunately such a complicated approach is not necessary in the present case, as the new criteria for estuary ships are aimed precisely at avoiding excessive ship motions and wave impact loading. In consequence, it is admissible to use a regular, linear frequency domain strip method, if it is kept in mind that results will only be sufficiently accurate up to the limiting seaway.

The Division of Marine Technology of Ghent University has a licence for the use of the *Seaway* program (nowadays incorporated in *Octopus*) developed by Journeé Shipmotions bv (Pijnacker, The Netherlands). This state-of-the-art program is based on a modified strip theory, and as such well suited for the determination of motions in waves of long and relatively narrow hull forms such as those of estuary vessels. Moreover, it can handle ship motions in limited water depths as well, which is also a requirement for these voyages close to the Flemish coast.

Like all of these programs, *Seaway* allows calculation of response spectra and short term response statistics, given wave spectrum, ship speed and dominant wave incidence angle. In the present case however long term response statistics per year and over the ship's lifetime are required. This means that a large number of input wave spectra have to be processed, for various ship speeds, loading conditions and heading angles. To limit computer time for the present application, *Seaway* is used only to generate tables of response amplitude operator values for all relevant wave component frequencies, incidence angles and ship conditions. These tables are then used by a suite of specially developed routines to derive response spectra and short term statistics, to combine the latter over the ship's lifetime and to produce output data which can readily be checked against the criteria.

4.2 WAVE DATA

To provide the nautical authorities with accurate marine meteorological forecasts enabling them to optimise vessel traffic, the Flemish Waterways and Maritime Affairs Administration (AWZ), Coastal Waterways Division, has set up the so-called *Hydro Meteo System*. This system consists of a real-time monitoring network at sea and a marine meteorological forecast centre. The monitoring network includes small measuring platforms, a number of wave-measuring buoys, tidal stations along the coast and a meteo-park at the port of Zeebrugge. All measured data on water levels, temperatures, wind, waves, etc. are transmitted in real-time to the shore, processed, stored in a database and made available to the users [9].

The data acquired since July 1997 by the wave-measuring buoy *Bol van Heist* (51°22'46"N, 3°12'28"E), being of the *Wavec* type, appear to be most appropriate for the present application, not only because of the buoy's location close to the route followed by the estuary ships (see figure 3), but also because it provides information on spectral distribution as a function of both wave frequency and direction.

For the characterization of the wave climate at *Bol van Heist* and along the 16 nautical miles sea stretch between Zeebrugge and the West Scheldt, several sources of information were available.

(1) A first collection of wave data from *Bol van Heist* consists of 11 average spectra, computed from a database containing 9741 one-dimensional wave spectra recorded by means of a *Waverider* buoy over the period 1979-1987. The average spectra were obtained by classifying the original spectra

according to their H_S value, and averaging in each class the spectrum ordinates at each of the 20 frequencies (2+3i)/128 Hz, with i = 1 to 20 [10]; a sample is shown in figure 4. The collection can be considered to be representative of the long term wave climate, but it has the drawback that it offers practically no information on the wave directionality: at the time only visual observations of the wind direction at a nearby shore station were available.

(2) To overcome this problem, use could be made of another database (by courtesy of the Coastal Waterways Division, Ostend) covering the period July 1997 – July 2002 and containing significant wave height at 30 minutes time intervals together with average period between zero-crossings, direction of the waves with period 2 to 5 seconds, and direction of the waves with period longer than 10 seconds. From this information, the joint probability distribution of H_S and dominant wave direction has been derived, as shown in figures 5 and 6.

(3) For the same period July 1997 – July 2002 complete directional wave spectra at 30 minutes time intervals are available as well, from the *Wavec* buoy replacing the former *Waverider* buoy at *Bol van Heist* (also by courtesy of the Coastal Waterways Division). This database contains the spectral densities, and the average and the standard deviation of the wave direction for 100 frequencies between 0.005 and 0.5 Hz. It is clear that this collection of about 87000 directional wave spectra is by far the most appropriate to obtain accurate long term response statistics from voyage simulations over the lifetime of the ships.

Initially, it was intended to use the collection of average spectra (1), in combination with the directional data (2), during the design phase or for a feasibility study. Taking account of the large number of calculations involved in using the directional wave spectra (3), the latter would only be used for fine tuning and final checking. However, the results of the calculations with average spectra appeared to be very sensitive to assumptions made about the directional distribution, and turned out to be far too conservative for practical use. The inevitable conclusion was that the risk analysis had to be based on data (3) in any stage of the design process, notwithstanding the time-consuming character of the calculations.

To facilitate subsequent calculations, each of the directional spectra (3) was converted into a directional spectrum table with dimensions 100 (frequencies) x 36 (directions).

4.3 SHIP RESPONSE CALCULATIONS

The new criteria for estuary ships imply that the following ship response functions have to be calculated by means of the *Seaway* software, for all relevant wave frequencies and wave incidence angles:

- the relative vertical motion of a number of selected points:
  - the most forward point of the ship's keel (slamming criterion);
  - one or more points on the bulwark of the forecastle (shipping of water by the bow);
  - a number of points on the main deck or on the rim of the hatch side coamings, port and starboard (shipping of water over the sides);
  - one or more points on the bulwark on the aft deck (shipping of water by the stern);
- the roll motion;
- internal loads (vertical bending moment, hydrodynamic torque,…);
- acceleration components at a number of selected points (wheelhouse, cargo,…).

For each selected ship speed and loading condition, the response functions mentioned above are calculated at each of the 100 frequencies for angles of incidence 0, 10, 20, …, 350 degrees, and stored in 100 x 36 tables comparable with those of the directional wave spectra.

For the two heading angles corresponding with the passages West Scheldt – Zeebrugge and vice versa, all required response spectra - again represented in 100 x 36 tables - are calculated for each directional wave spectrum. From each response spectrum, the significant response magnitude and the average time between zero-crossings of the response are computed by means of the classical methods and formulas.

4.4 REPRESENTATION OF RESULTS

One or more critical values are prescribed for each of the ship responses considered. For each directional wave spectrum, the number of times a critical value is expected to be exceeded during a crossing can be calculated. The spectra are then grouped in significant wave height classes with an interval of 0.01 m. For each interval, the minimum, maximum and average number of times the critical value is expected to be exceeded during a crossing are determined and plotted as functions of the significant wave height – see figure 7 for a typical example. In the figures, these values are referred to as the *conditional minimum / maximum / average number of events*, as they express the number of exceedances that can be expected during one crossing on the condition that the significant wave height has a specific value.

A fourth curve expresses the average number of times the critical value is expected to be exceeded during any crossing, if the significant wave height indicated by the abscissa is considered as a maximum allowable value and is therefore never exceeded. In the figures, this average is called the *cumulative average number of events*.

These functions of significant wave height being determined, the following particular values can be defined:

- Assuming that n crossings per year are carried out, the critical value is expected to be exceeded once a year if the *cumulative average number of events* equals n^{-1}. Typical values of n will range from 100 to 300.

- The critical value is expected to be exceeded once in a ship's lifetime of m years (usually m = 20 to 30) if the *cumulative average number of events* equals $(mn)^{-1}$.

- In marginally acceptable conditions, the number of events expected to occur during one crossing will lie between the *conditional minimum and maximum numbers of events*, with an average value determined by the *conditional average number of events*. If the latter equals 1, on the average one event per crossing can be expected in a seaway with a significant wave height indicated by the abscissa.

Depending on the criterion which is applicable, the value of H_S corresponding with one of the above probabilities according to the *cumulative average* curves determines the limiting conditions in which the ship can be allowed to operate.

If no critical value for a given response function is available, the conditional and cumulative probabilities that the response exceeds a selection of values during a crossing are calculated as a function of significant wave height. In this way, a relationship between a specified exceedance level and the maximum allowable significant wave height can be determined.

5. EXAMPLES OF RECENT DESIGNS

5.1 GENERAL

Figure 6 shows the relation between the permissible significant wave height for which an estuary ship is designed and the number of days per year this ship will actually be able to sail. From the figure, it is clear that the old 1.2 m limit implied that an estuary ship was not allowed to set out to sea approximately 60 days a year, or 16.4 % of the time. If the limit is raised to 1.75 m, then the weather window is increased to approx. 95 % of the time. As in many cases a storm will not last a whole day, the above actually means that 95 % of the time the ship will not suffer any delay on account of the weather. This seems to be considered as adequate by even the most demanding ship owners. For a limiting H_S of 1.6 m which is much easier to attain, the corresponding weather window amounts to 93 % of the time, which is only marginally less than for H_S = 1.75 m. The minimum to obtain prototype support funding from the Flemish Ministry of Public Works has been set at H_S = 1.70 m.

5.2 BUNKERING TANKERS

In 2004, BSI approved two inland tankers, *Tanzanite* (figure 1, Wiljo nv, Antwerp, Belgium) and *Texas* (Verbeke Bunkering nv, Sint-Job in 't Goor, Belgium), for estuary traffic between Antwerp and Zeebrugge in sea states with a significant wave height up to 1.6 m, and provided that the draft in the limiting seaway does not exceed 4.0 m. The service experience with these ships has been rather good so far. After several voyages in borderline weather conditions one of the owners even stated that he thought his ship to be able to cope with sea-states with significant wave heights up to 1.8 m.

For these tankers, the risk analysis was carried out by the UGent Division of Maritime Technology. Both ships have the same overall dimensions (L_{OA} = 110 m, B = 13.5 m, depth 5.32 m, scantling draft 4.2 m), and comparable forms. For the risk analysis, four loading conditions were considered: fully loaded (4.2 m draft, even keel), partially loaded (3.8 and 3.6 m draft, even keel) and maximum ballast (draft fore 2.0 m, aft 2.4 m).

The hydrodynamic characteristics of the vessels were calculated by means of the *Seaway* program, except for roll damping. The non-dimensional roll damping coefficient κ was assumed to be 0.10. This value is based on the results of roll damping tests carried out at the Towing Tank for Manoeuvres in Shallow Water (co-operation Flanders Hydraulics Research – Ghent University) in Antwerp with a model of an inland vessel with comparable characteristics, and can be considered as a realistic approximation for the ship without bilge keels. The addition of bilge keels results in an increase of the non-dimensional damping coefficient, to an estimated value of approximately 0.13. Most calculations have been carried out both with κ = 0.10 and with κ = 0.13.

The following response functions were calculated (figure 8):

- the vertical motion of the foremost point of the keel (point 1) relative to the free surface, to appraise slamming;
- the relative vertical motion of the foremost point of the forecastle (point 2), to appraise shipping of water by the bow;
- the relative vertical motion of points 3 – 8 located on the main deck, to appraise shipping of water over the topsides;
- the relative vertical motion of points 9 – 10 on the poop, to appraise shipping of water by the stern;
- the lateral acceleration of the centre of gravity of the telescopic wheelhouse (point 11);

- the roll motion;
- the vertical bending moment in a number of sections near amidships.

The results obtained for the relative vertical motion of point 1 exceeding the draft in ballast condition are shown in figure 7. Assuming that 100 round trips per year are carried out, and taking account of a lifetime of 30 years, it can be concluded that a probability of bow emergence of once in the ship's lifetime (cumulative average number of exceedances per crossing = $3.3\mathrm{x}10^{-4}$) is only reached for a maximum permissible significant wave height of 1.68 m. A return period of one year (cumulative average no. of exceedances per crossing = 0.01) is obtained if the permissible significant wave height would be 2.40 m.

Shipping of water by the bow or by the stern does not appear to be an issue either. Even if an almost unrealistic value of 1.6 m is selected as an estimate for the bow wave height, it is found that shipping of water over the bow would occur once in a lifetime for a permissible significant wave height of 1.75 m.

The limitation on draft in loaded condition in seas with H_S = 1.6 m follows from the consideration of shipping of water over the sides. To investigate this, calculations were carried out for the ship in three loading conditions with two values for the non-dimensional roll damping coefficient and for several reference levels above the waterline. Also, as requested by BSI at that time, a fictitious ship was considered, with the same dimensions as the *Tanzanite*, but with a freeboard according to the old service rule no. 8, viz. 0.70 m for a tanker with a length of 110 m. Such a ship would be allowed to operate in significant wave heights not exceeding 1.2 m.

For the fictitious ship, the probability of shipping of water up to certain levels above the deck line at side was calculated. Figure 9 gives a summary of the results: a relationship is plotted between the permissible significant wave height and the overtopping level (as measured from the waterline) reached with typical frequencies of occurrence (once per crossing, once a year, once in a lifetime). The difference between the exceedance levels corresponding with H_S = 1.6 m and H_S =1.2 m can be interpreted as the additional freeboard which is required to allow an increase of the permissible significant wave height from 1.2 to 1.6 m without raising the frequency of occurrence and the intensity of shipping of water over the sides.

In the figure, the extra freeboard is measured between curves with different values of the non-dimensional roll damping coefficient κ. The reason is that the *Tanzanite* and the *Texas* are equipped with bilge keels, which are not required by [1] for estuary ships in general. Thus, it is justified to use κ = 0.10 for the reference ship, and κ = 0.13 for the actual ships.

From figure 9, the total freeboard required for the *Tanzanite* in seas with H_S = 1.6 m turns out to be 0.70 + 0.62 = 1.32 m, which means that the draft has to be limited to 4.0 m on the route Zeebrugge – West Scheldt. On the return trip the corresponding figure would be 4.1 m according to the calculations, but of course it would only lead to confusion if this distinction would be allowed in practice. Judging from the general aspect of the curves in figure 9 between H_S = 1.2 m and H_S = 1.6 m, it would also be possible to allow linear interpolation for obtaining the additional freeboard required in seaways with intermediate values of H_S.

Calculations such as those reported above are no longer required for regular design work. They are included here to give an idea of the background work which went into the determination of the reference levels as adopted in criterion 3.3 for shipping of water over the topsides.

5.3 CAR CARRIERS

Cobelfret nv, Antwerp, is operating 3 estuary car carriers *Waterways 1, 2, 3*, the first of which was put into service in January 2004. It is known that two of these ships regularly call at Zeebrugge, but for proprietary reasons more details cannot be disclosed about them than have been given in [3] and in the information sheets "Damen River Liner 1145 Car Carrier – M.V. Waterways 1, 2 and 3" from Damen Shipyards Bergum (The Netherlands).

The ships have been designed for operation in significant wave heights up to 1.75 m. This resulted in a rather high freeboard, as shipping of water by the sides is not acceptable at all during the ship's lifetime, since the cars on the main deck should be protected from sea-water at all times. For the same reason, the rolling motion had to be restricted by the addition of approx. 80 m long bilge keels.

5.4 OPEN HATCH CONTAINER VESSELS

As has been stated in the Introduction, there is considerable interest in this type of estuary ships, and accordingly a number of possible designs are under investigation at present. All designs are of double hull construction, and most of them have a length over all of 110 m and a maximum draft of 3.5 m, which are popular dimensions in inland navigation. Again all designs have a rather large freeboard + coaming height, to avoid shipping of water over the rim of the coaming. Typical values for total height keel to top of coaming are 7.3 to 7.7 m.

Beam variations which are considered are 11.40 m (4 container rows across the beam x 4 tiers), 15 m (5 rows) and 17 m (6 rows). 15 m probably yields the design with the lowest investment per TEU, as its inherent stability allows operation with 5 tiers x 5 rows. The 17 m ship cannot take full advantage of its even better stability, as air draft limitations restrict it to 6 rows x 5 tiers anyhow.

To obtain comparably low investment costs, the length of the 17 m ship could be increased, perhaps to 125 m or even 134 m, giving it the same dimensions as the *Jowi* and the *Amistad*, (see for instance [11]), which are still the largest inland vessels on the Rhine.

The 110 m x 11.40 m ship will definitely require higher investment costs per TEU, but these principal dimensions remain popular among inland ship-owners as they offer the advantage of a very wide range of action on the European inland waterways network (European class Va, large Rhine vessels, deadweight 1500-3000 tonnes). A container vessel with this beam presents some additional design problems however, due to the very narrow gangways and wing tanks (only approx. 0.67 m, when the ship is built around 4 rows of containers):

1) The stability with 4 tiers of fully loaded containers may be critical.
2) The ADNR regulations [12] for the carriage of dangerous goods on the Rhine require additional reinforcements of the double hull structure.
3) The narrow wing tanks combined with 2) above make it difficult to obtain satisfactory accessibility for inspection and maintenance.

There are recent examples of such vessels built for inland navigation only [13]. For estuary ships further complications are that the ship's structure should be able to resist the additional vertical and horizontal wave bending moments and the hydrodynamic torque, and that freeboard and rolling characteristics should be such that shipping of green water over the top of the coaming does not occur.

A feasibility study performed by students of the Division of Marine Technology of Ghent University has shown that it is possible indeed to design a class Va open top multi-purpose ship which fulfils all the criteria for estuary service in significant wave heights up to 1.75 m.

6. RECOMMENDATIONS FOR FURTHER RESEARCH

To evaluate whether an inland vessel can be considered as suitable for estuarine traffic and to determine the limits of the allowable conditions formulated in terms of wave climate and loading conditions, a reliable estimate must be available for the ship's loads, the ship's motions and the relative motion of a number of critical points on the ship with respect to the free water surface, as a function of the wave characteristics.

The reliability of current numerical techniques can generally speaking be considered as satisfactory as far as the prediction of ship motions is concerned. On the other hand, the execution of such a numerical study has to be based on a number of hypotheses that can only be verified by model tests, full scale observations or, preferably, a combination of both. If no test results are available, one has to appeal to empirical information. For the vessel types considered here, this may raise problems because research into ship behaviour in waves has mainly been focused on sea-going ships.

More specifically, additional information is required on the ship's roll damping characteristics (including the effect of bilge keels), on wave patterns and squat caused by the ship's speed in calm water, and on the dynamic rising of the water surface due to diffraction and radiation.

Another item of concern has to do with dynamic ship loading. One of the new criteria deliberately rules out whipping of the hull girder as a consequence of slamming, but another phenomenon which may occur with these slender and flat hull forms is springing due to resonance of the 2-node vertical hull vibration mode with certain wave spectral components. It is thought that this will not present a problem in the case of the bunkering tankers and the car carriers, as these ships with closed or multiple decks have a relatively high bending stiffness. The situation may be quite different however for general cargo ships and container carriers with their long and wide hatchways. For lack of experience, for the first designs at least it will be necessary to compute the natural frequency of the 2-node hull vibration mode, and to check that this does not correspond with encounter frequencies of wave components with significant energy content.

7. CONCLUDING REMARKS

A review of the problems involved in designing inland waterways vessels for operation in coastal waters can be found in [8]. The conclusions of this author were:

"Nonlinear problems of ship hydro-elasticity have to be solved. Suitable calculation models must be developed for an elastic ship interacting with the surrounding shallow water", and

"Comprehensive finite element models of the ship structure itself and of the fluid domain contacting the moving ship are necessary".

At the time this approach must have looked very promising for major research institutions, but it did not have much to offer the small to medium size businesses operating inland waterways vessels, which are seldom in a position to support fundamental research, model tests etc. In contrast to this, the approach of the Belgian Shipping Inspectorate has been much more pragmatic, ever since 1962 when the first rules concerning estuary ships were published. In fact, it could be said that the BSI approach is based on the very down-to-earth observation that *any* ship or boat can sail the sea provided that some elementary precautions are taken, and above all provided that the sea is calm enough, and will remain calm enough while the vessel is in transit from one port to the next.

In the old BSI rules for estuary traffic along the Belgian coast from the West Scheldt to Zeebrugge, the upper limit of the weather window was set at Beaufort 5, which corresponds roughly with a sea state with a significant wave height of 1.2 m. This weather window proved to be too narrow for present-day requirements of trade. Accordingly, the Belgian Federal Service for Mobility and Transport has provided new risk-based criteria concerning various aspects of the safety of estuary ships regardless of the weather conditions. The designer or ship-owner is now free to choose the severity of the seaway in which he wants to operate the ship, but he has to prove by means of a risk analysis that the criteria are met for his particular design and for the chosen maximum sea state.

The new criteria have been formulated keeping in mind that an estuary ship should basically remain an inland waterways vessel, with a bare minimum of additional equipment and structural reinforcement. An important example of this concern is that the draft in ballast condition and the freeboard in loaded condition at sea must be determined such that wave impact loading due to slamming or shipping of green water is practically out of the question. In consequence in designing these ships it is not necessary to address problems of hydro-elasticity, and up to the limiting seaway use can be made of linear strip theory calculations for the determination of wave loads and ship motions.

In the present paper an account has been given of the new rules and of the risk analysis procedure developed by the Division of Marine Technology of Ghent University. It is thought that the criteria and the design procedures as proposed for the Belgian estuary ships may readily be adapted for other coastal regions where the wave climate is sufficiently moderate for a sufficient amount of time.

No doubt there will be legal aspects involved, when using ships which are basically inland waterways vessels in international waters, but questions of international maritime law are quite outside the scope of the present technical paper.

Yet another non-technical problem is the training of the crew members of such ships. The crews of inland waterways vessels have normally not received any maritime training, and will be faced with conditions that are unusual in inland navigation. In Belgium, the captain of an estuary vessel is required to hold a special certificate issued by BSI after an examination ad hoc, which will become more difficult as more of these ships come into service. Perhaps simulator techniques can be of help in training larger numbers of crew members in the future.

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Figure 1. Estuary bunker tanker MV Tanzanite (by courtesy of Wiljo NV, Antwerp)

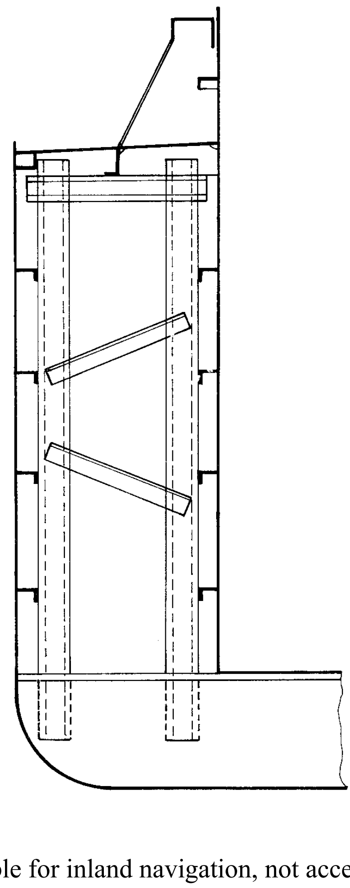

Figure 2. Acceptable for inland navigation, not acceptable for sea-going ships.

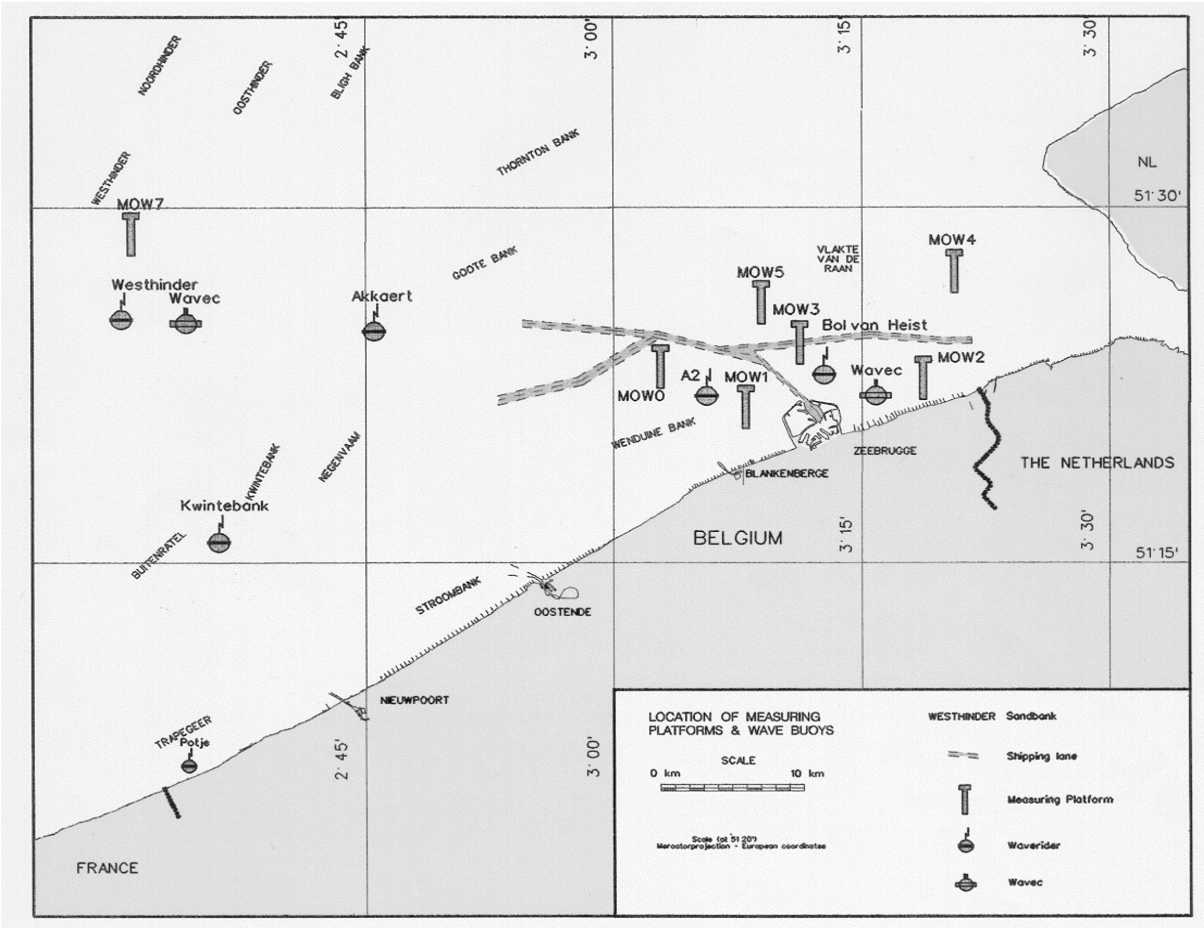

Figure 3. Monitoring network Flemish Banks

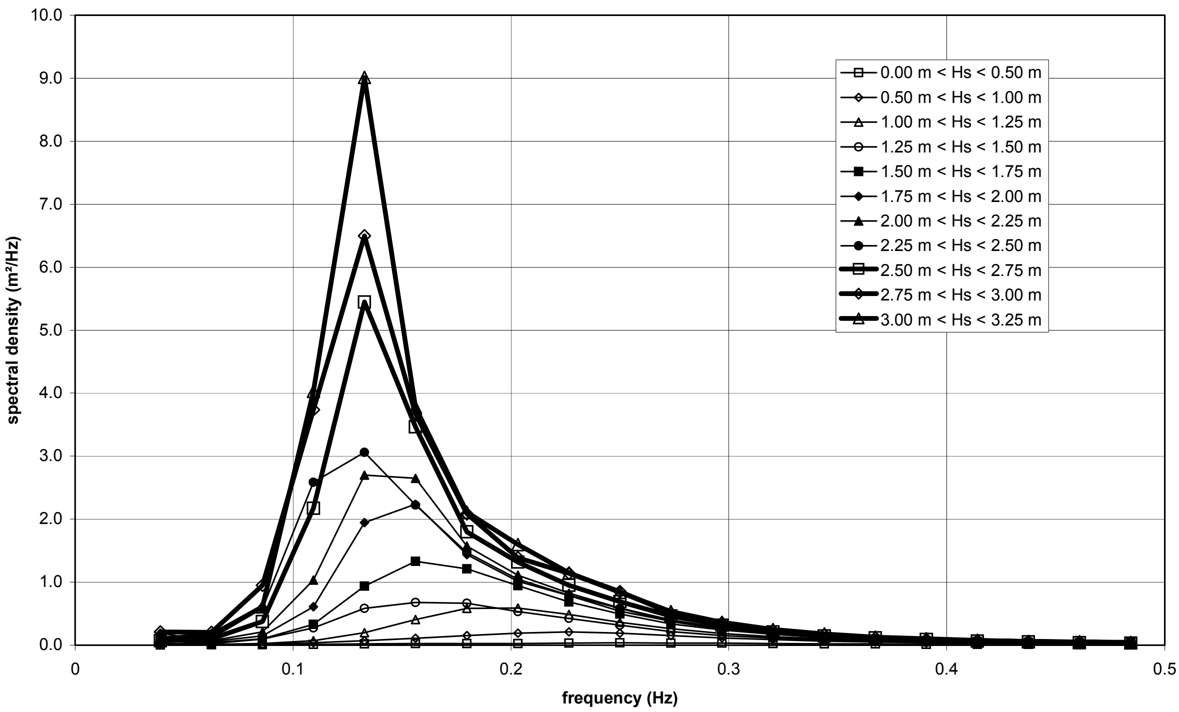

Figure 4. Average spectra at location *Bol van Heist* for wave height classes, based on average spectra by Truijens (1992).

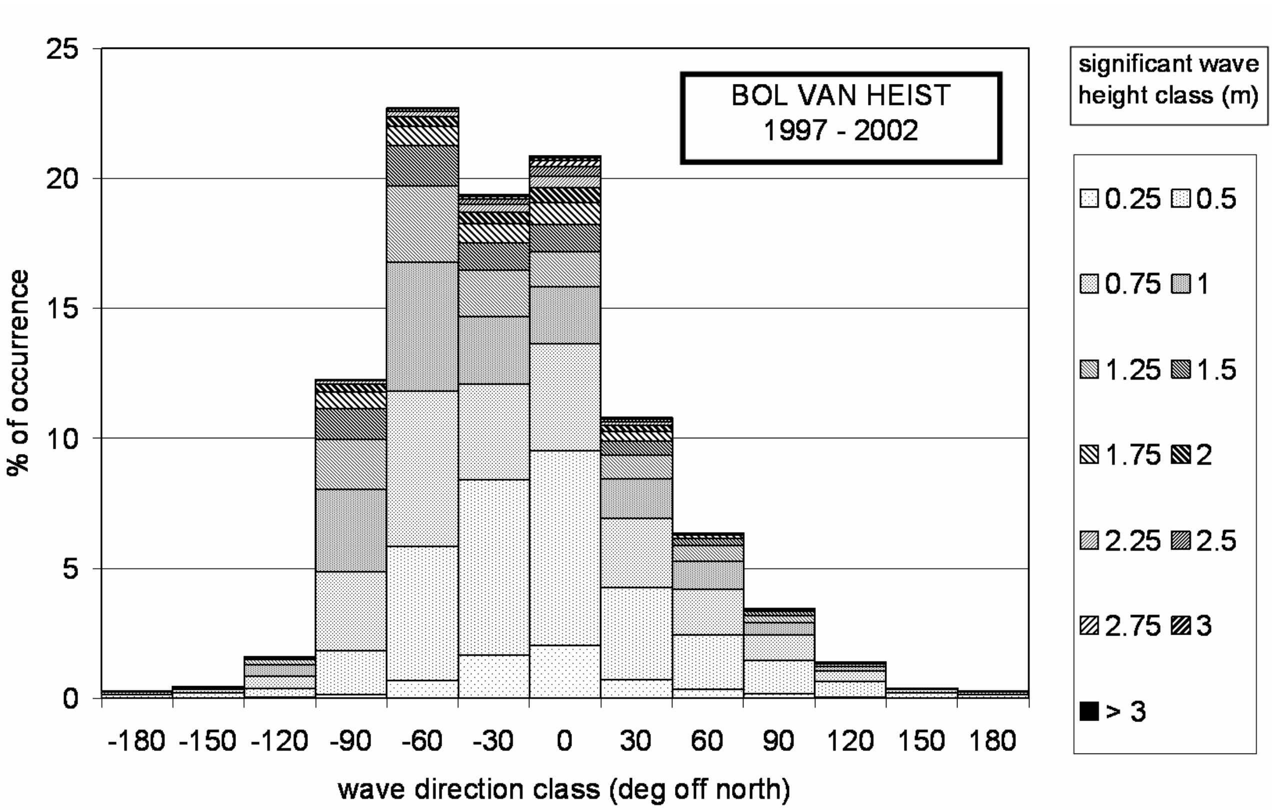

Figure 5. *Bol van Heist* (July 1997 – July 2002): Distribution of significant wave height and wave direction: percentage of occurrence.

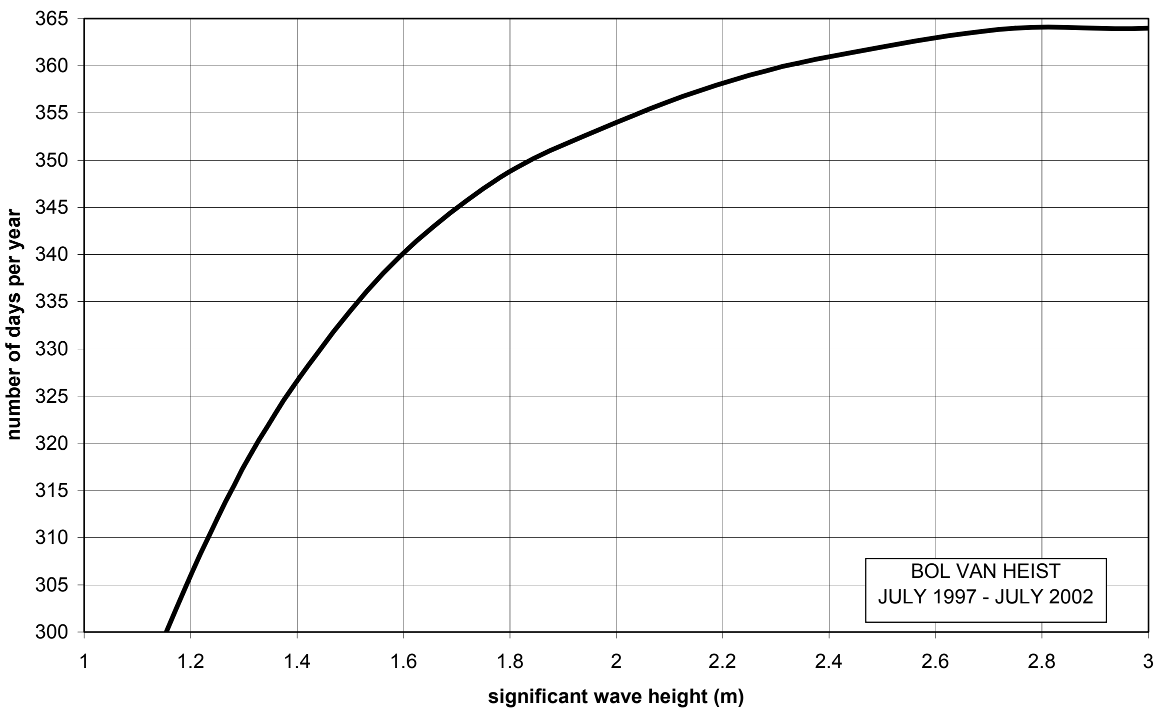

Figure 6. *Bol van Heist* (July 1997 – July 2002): Cumulative distribution of significant wave height in days of occurrence per year.

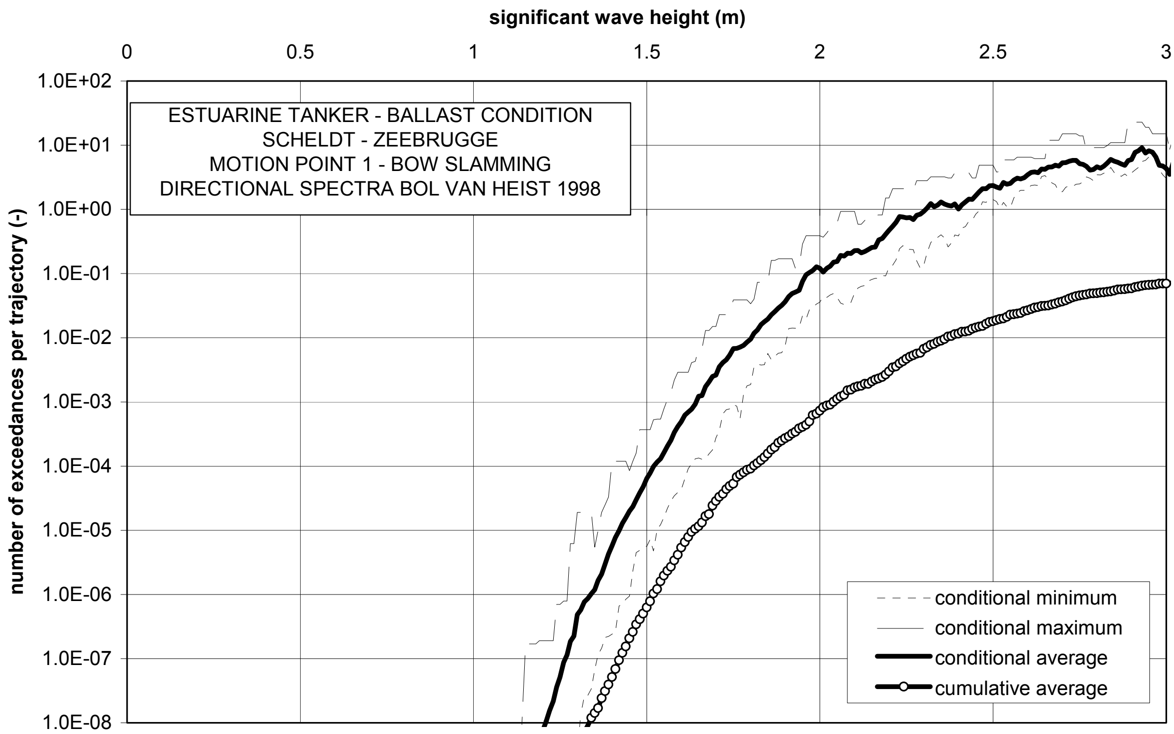

Figure 7. Example of a plot showing the relation between the actual significant wave height and the (conditional) minimum, maximum and average number of times a given critical level is expected to be exceeded during a crossing, as well as the relation between the maximum allowable significant wave height and the (cumulative) average number of times the critical value is expected to be exceeded during any crossing.

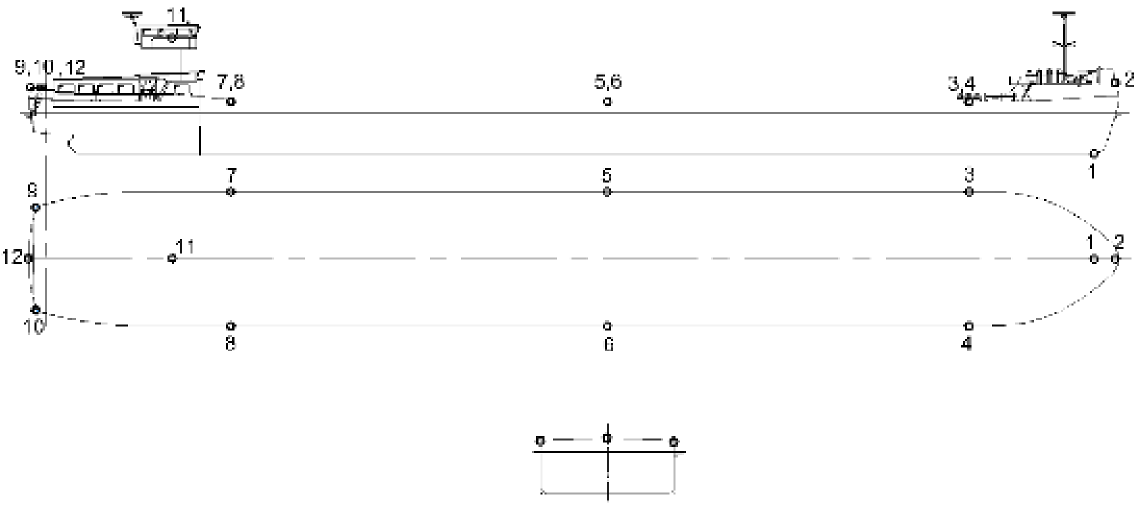

Figure 8. Estuary tanker: selected points for calculation of motions.

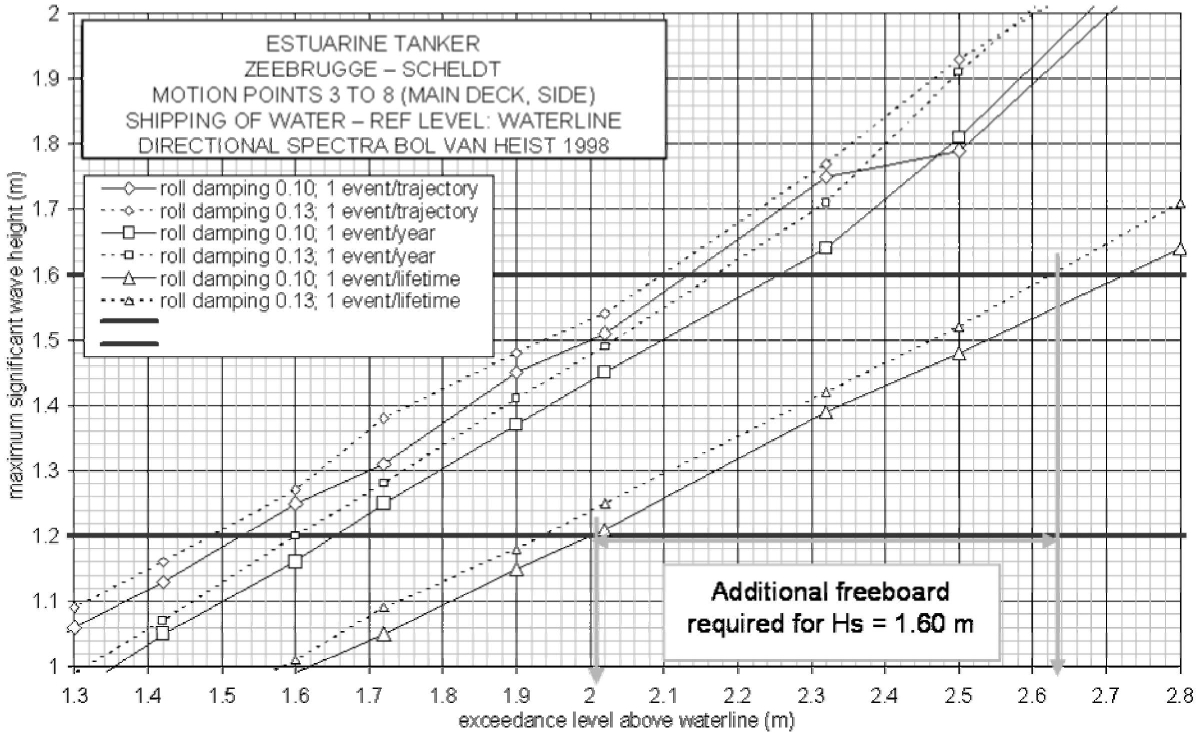

Figure 9. Additional freeboard required for allowing a limiting significant wave height greater than 1.20 m.