DEVELOPMENT OF A PROBABILISTIC ADMITTANCE POLICY FOR THE FLEMISH HARBOURS

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Abstract

Deep-draughted ships approaching the harbour of Zeebrugge or the Western Scheldt, the river giving access to the harbours of Antwerp and Ghent, make use of the sea channels *Scheur West/East* and *Pas van het Zand.* Due to depth limitations, shipping traffic is subject to tidal windows for drafts exceeding 12.20 m. At present, these tidal windows are determined in such a way that a gross under keel clearance of 15% of the ship's draft is guaranteed. This access policy accounts for water level fluctuations due to tidal action and for the ship's draft, but does not make any distinction regarding other ship characteristics, weather conditions or wave climate.

A potential optimisation of the access policy could consist of the introduction of tidal windows adapted to the actual hydrological and meteorological conditions. For this purpose, among others, a hydro-meteo system was installed by the Division Coastal Waterways of the Waterways and Maritime Affairs Administration in the 1990s, providing the nautical authorities with accurate data about the actual and expected water level and wave climate in the channels.

An optimised access policy requires a reliable estimation of the ships' vertical motions due to their response to the waves and to squat effects, so that the probability of bottom touch during the passage can be assessed. In order to obtain such data, a very comprehensive model test program was carried out by Ghent University in the *Towing Tank for Manoeuvres in Shallow Water* at Flanders Hydraulics (Antwerp, Belgium).

The test results were collected in a database that can be considered to be unique, not only from the point of view of response of ships in waves in (very) shallow water conditions, but also regarding squat. These data were used to evaluate the reliability and accuracy of two ship motion calculation programs, based on strip theory and on a 3D-panel method, so that missing conditions in the database could be extrapolated.

Based on this database, a calculation procedure was developed, which can be considered as the main tool for establishing a probabilistic admittance policy for the Flemish harbours.

1.0. Introduction

Deep-drafted ships, sailing to the Ports of Antwerp or Ghent on the Scheldt Estuary, have to use the *Scheur* channel (see figure 1). To reach the Port of Zeebrugge ships also have to sail through the

Pas van het Zand channel. Due to the limited depth of these channels shipping is subjected to tidal windows once the draft exceeds 12.20 m. At present, these tidal windows are to guarantee a gross under keel clearance of 15% of the ship's draft during the passage. This access policy accounts for water level fluctuations due to tidal action and for the ship's draft, but does not make any distinction regarding other ship characteristics, weather conditions or wave climate.

A potential optimisation of the admittance policy would be the determination of tidal windows for the actual hydrological and meteorological conditions. Indeed, a hydro-meteo system provides the nautical authorities with accurate data about the actual and expected water level and wave climate in the channels. It was installed in the 1990s by the Coastal Waterways Division of the and consists of a network of sensors (Monitoring Network Flemish Banks), data-acquisition centres, a data processing centre and an oceanographic-meteorological station.

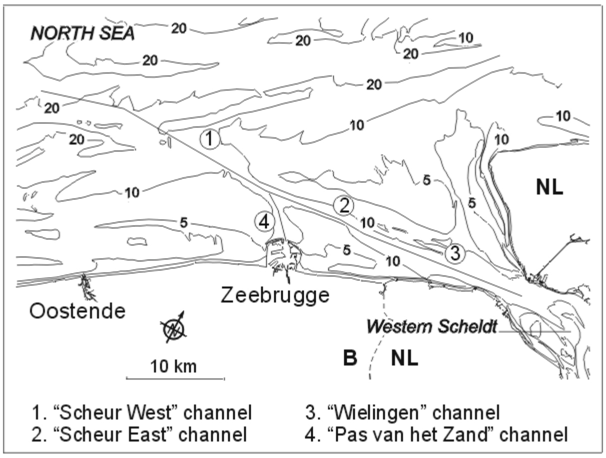


Figure 1. Approach channels to the Western Scheldt mouth and Zeebrugge

An optimised admittance policy requires a reliable estimation of the ships' vertical motions due to their response to the waves and to squat effects, so that the probability of bottom touch during the passage can be assessed. In order to obtain such data, a comprehensive experimental program was carried out by Ghent University in the *Towing Tank for Manoeuvres in Shallow Water* at Flanders Hydraulics in 1996-1999. Four representative ship types were selected; draft, under keel clearance, speed, wave conditions and wave direction were systematically varied.

The test results were collected in a database that can be considered to be unique, not only regarding the response of ships in waves in (very) shallow water conditions, but also from the point of view of squat. These data allowed the evaluation of two ship motion calculation programs, based on strip theory and on a 3D-panel method, so that missing conditions in the database could be extrapolated.

Based on these data, a calculation procedure was developed, which can be considered as the main tool for establishing a probabilistic admittance policy for the Flemish harbours. For given input data, such as the ship's main characteristics, ship speed, tidal data, wave data (directional spectra), bathymetry, trajectory and departure time, the procedure calculates the probability of bottom touch during the passage through the channel. A tidal window can be determined if the authorities decide on an acceptable value for this probability.

This paper gives an overview of the experimental data, compares the latter with numerical results, describes the philosophy of the calculation procedure, and illustrates the methodology with some examples. Finally, the outlines of future planning for implementing this procedure into a probabilistic access policy for the Flemish harbours is discussed.

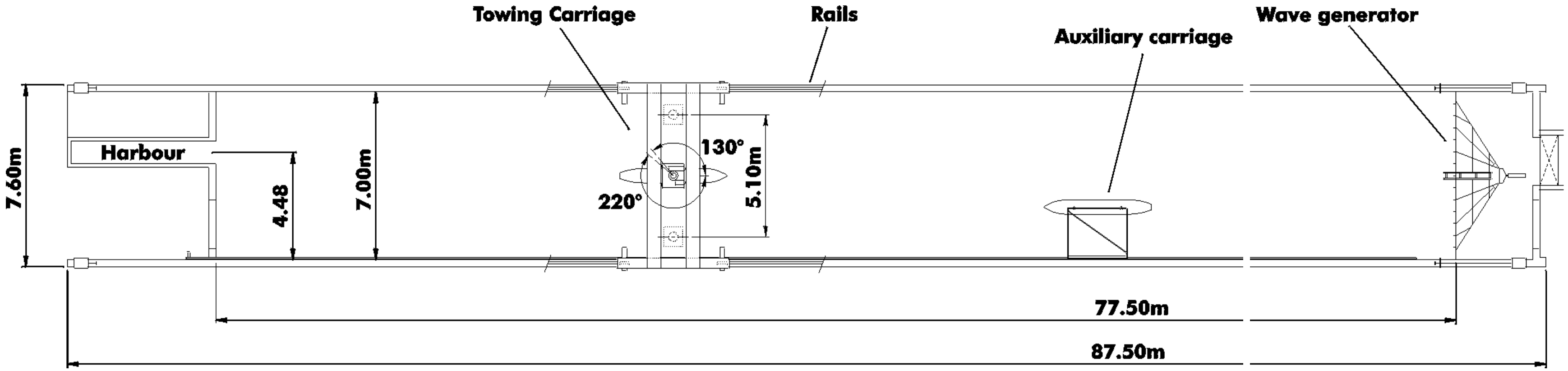


Figure 2. Towing Tank for Manoeuvres in Shallow Water, Flanders Hydraulics.

Table 2.
Ship Models: Main Characteristics.

		D		E		F		G	
Ship type		container carrier		tanker / bulk carrier		Container carrier		tanker / bulk carrier	
Scale	(-)	1	1/75	1	1/85	1	1/50	1	1/50
Length over all	(m)	300.00	4.000	343.00	4.035	200.00	4.000	190.00	3.800
Length between perpendiculars	(m)	291.13	3.882	325.00	3.824	190.00	3.800	180.00	3.600
Beam	(m)	40.25	0.537	53.00	0.624	32.00	0.640	33.00	0.660
Maximum draft	(m)	15.00	0.200	21.79	0.256	11.60	0.232	13.00	0.260
Depth	(m)	25.00	0.333	28.30	0.333	18.00	0.360	19.00	0.380
Displacement volume	(m^3)	106 000	0.251	319 400	0.520	42 000	0.336	66 000	0.528
Block coefficient	(-)	0.60	0.60	0.85	0.85	0.60	0.60	0.85	0.85
Propeller									
Diameter	(m)	8.15	0.109	8.76	0.103	5.50	0.110	5.00	0.100
Pitch	(m)	7.91	0.105	5.70	0.067	5.50	0.110	4.38	0.088
Pitch ratio	(-)	0.97	0.970	0.65	0.650	1.00	1.000	0.88	0.875
Expanded area ratio	(-)	0.80	0.800	0.62	0.620	0.56	0.560	0.58	0.577
Number of blades	(-)	5	5	4	4	4	4	4	4
		Ship	Model	Ship	Model	Ship	Model	Ship	Model

2.0 Experimental Study

Test infrastructure

Flanders Hydraulics (Antwerp, Belgium), the hydraulic research laboratory of the Waterways and Maritime Affairs Administration of the Ministry of the Flemish Community, is particularly concerned with research in ship hydrodynamics for problems in relation with the concept, adaptation and operation of navigation areas. For this reason, the *shallow* and *very shallow water* ranges are the main research domain. For the investigation of nautical aspects of such problems, the availability of experimental facilities was considered as a requirement. At present the facilities consist of a shallow water towing tank, equipped with a planar motion carriage, a wave generator and an auxiliary carriage for ship-ship interaction tests. Thanks to fully computerised control and data-acquisition, tests can be carried out fully automatically and continuously without operator. The *Towing Tank for Manoeuvres in Shallow Water (co-operation Flanders Hydraulics – Ghent University)* is an ITTC member organisation since 1993. The main tank characteristics and the range of the mechanism's kinematics are summarised in Figure 2 and Table 1. The piston type wave maker, allowing generation of both regular and irregular waves, is driven by an electro-hydraulic unit with stroke 0.3 m, maximum velocity 0.6 m/s and acceleration of 4.4 m/s².

Table 1.
Tank characteristics.

Length over all	88.0 m
Useful length	67.0 m
Width	7.0 m
Maximum water depth	0.5 m
Maximum longitudinal speed	2.0 m/s
Maximum lateral speed	1.3 m/s
Maximum rate of turn	16.0 deg/s
Ship model length	3.5 - 4.5 m

3.0 Test Program

Test types

The test program consisted of captive model tests, during which the horizontal trajectory of a ship model is forced by the planar motion mechanism, while the resulting forces and moment in the horizontal plane are measured. On the other hand, the ship model is free to move in the vertical motion modes (heave, pitch, roll). Figure 3 gives an overview of the measuring equipment. Following types of captive tests were executed: still water tests, carried out in the absence of waves; tests in regular waves, and tests in irregular wave spectra.

Ship models.

Four ship types were selected, two full and two slender hull forms. Two of them, ship models D and E, were at the start of the project considered to be the largest vessels bound for the Flemish harbours. The other two ships (models F and G), with panamax beam but with a relatively small length, have rather moderate dimensions, but are expected to have a more important response to the local wave climate. Table 2 summarises the main characteristics.

Ship and waterway dependent test parameters

Loading condition. The ship models were not only tested at design draft, but also in partially laden and in trim conditions. The draft was varied between 11.0 m, the smallest draft causing a non-negligible probability for bottom touch in the Western Scheldt according to Savenije (1996), and the ship's maximum draft. For ship model E, the draft was limited to 15.0 m, taking account of the maximum draft of ships bound for the harbours of Antwerp and Zeebrugge in 1996, when the project was started. Nowadays, ships with drafts up to 15.54 m can reach the port of Antwerp; maximum draft for Zeebrugge is 15.86 m.

Water depth. During the tests, the water depth was varied between 13.4 m and 18.0 m (full scale). These values take account of the bottom level of the channels, the shallowest section being located at 13.4 m below MLLWS, and the tidal heights, varying between 0.40 m and 4.80 m for spring tide conditions at Zeebrugge. Combinations of loading condition and water depth were selected in such a way that the gross under keel clearance was varied between 7 and 20% of draft; the latter also explains the maximum water depth of 18 m.

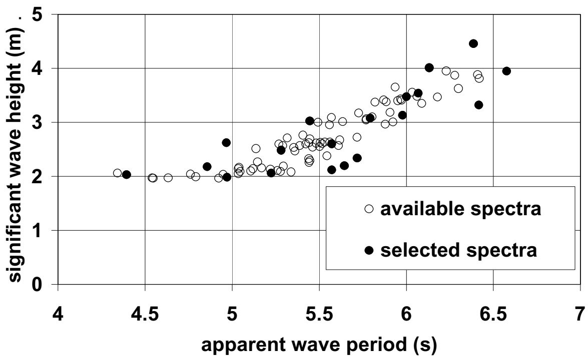


Figure 3. Measuring buoy at Akkaert Bank: available and selected wave spectra

Ship's speed. Ships approaching Zeebrugge or Flushing (Western Scheldt mouth) are expected to sail at a speed of minimum 12 knots. During the model tests, speed was varied between 8 and 16 knots. Tests were also executed at zero speed.

Wave dependent test parameters

Regular waves. Tests were performed in regular waves in order to determine the response amplitude operators (RAO) for heave, pitch and roll. The wave frequency range was selected based on local wave characteristics and expected ship response. Frequencies between 0.3 and 1.2 rad/s were chosen, with emphasis on 0.6 – 1.2 rad/s which is the peak range of the spectra occurring in this coastal area, corresponding with wave lengths between 40 and 120 m. This implies that especially wavelengths were considered that are rather small compared to ship length.

Irregular waves. Model tests were also carried out in wave spectra that are typical for the Belgian coastal area. A systematic analysis of registered wave data from five wave measuring buoys of the Monitoring Network Flemish Banks was performed by Truijens (1992) in order to define the wave climate in the Zeebrugge area; average wave spectra were determined in function of location, wind direction, significant wave height H_S, average apparent wave period T_0 and water level. For the present study, a number of wave spectra from the Akkaert Bank with $H_S > 2$ m was selected; figure 3 displays the combinations (H_S ; T_0) of the selected spectra.

Wave direction. Due to the tank dimensions, the tests were carried out in head waves (180 ± 10 deg) and in following waves (0 ± 10 deg). At zero speed, other wave directions were applied as well.

4.0 Test Results

Still water tests

Tests in absence of waves were carried out for determining the self-propulsion point of the model, the squat characteristics and the roll damping parameter at the different test speeds. An illustration of the squat characteristics resulting from the tests is given in figures 4 and 5. It is clear that the reliability of squat data is of utmost importance, as the fraction of the gross under keel clearance taken by sinkage and trim may be quite significant, especially for full ships.

Regular wave tests

Regular wave tests resulted into the amplitude and phase characteristics for heave, pitch and roll motions of the ship models in different combinations of water depth, loading condition, speed and angle of incidence.

The experimental data were compared with the results of two linear numerical methods for calculating wave-induced loads on ships and motions of ships in a seaway, the first being based on the ordinary and the modified strip theory (Journée, 2001), the second on a 3D boundary element method (BEM). Both methods are frequency domain based, suitable for deep and shallow water and support ship motions in six degrees of freedom.

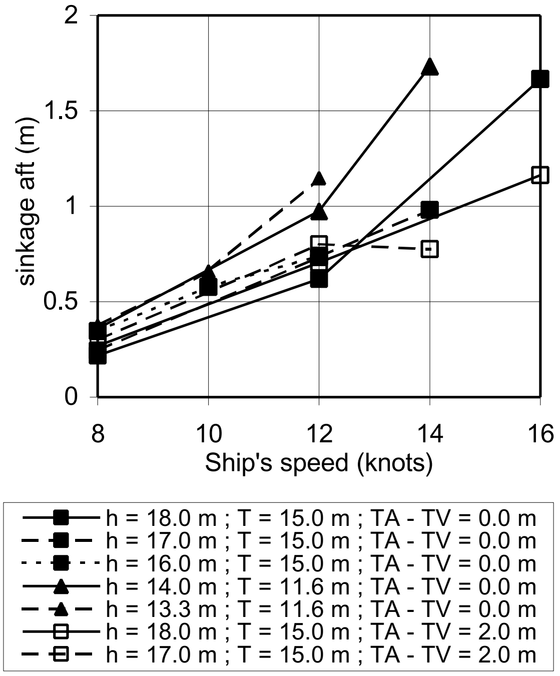


Figure 4. Ship model D: maximum squat

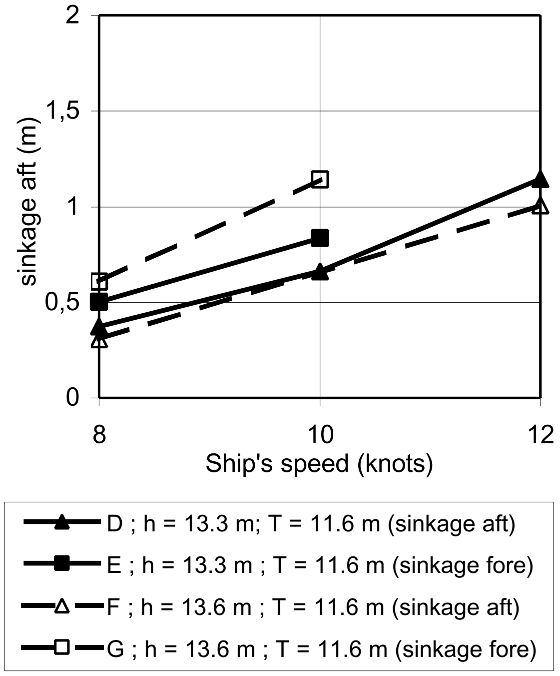
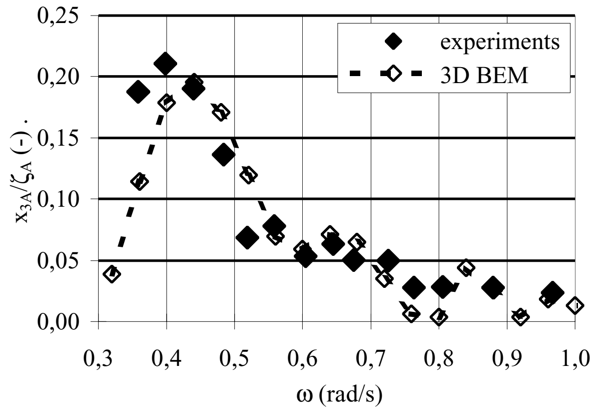
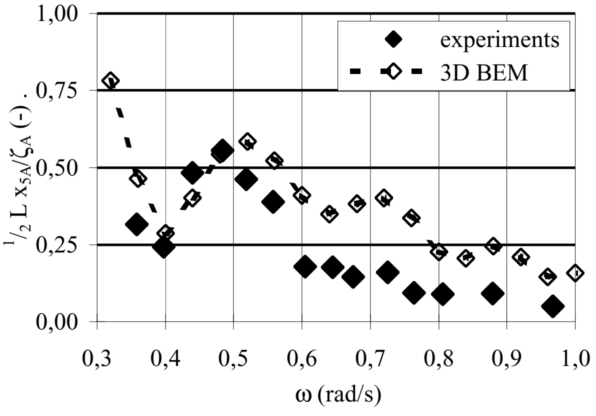


Figure 5. Squat: comparison between models





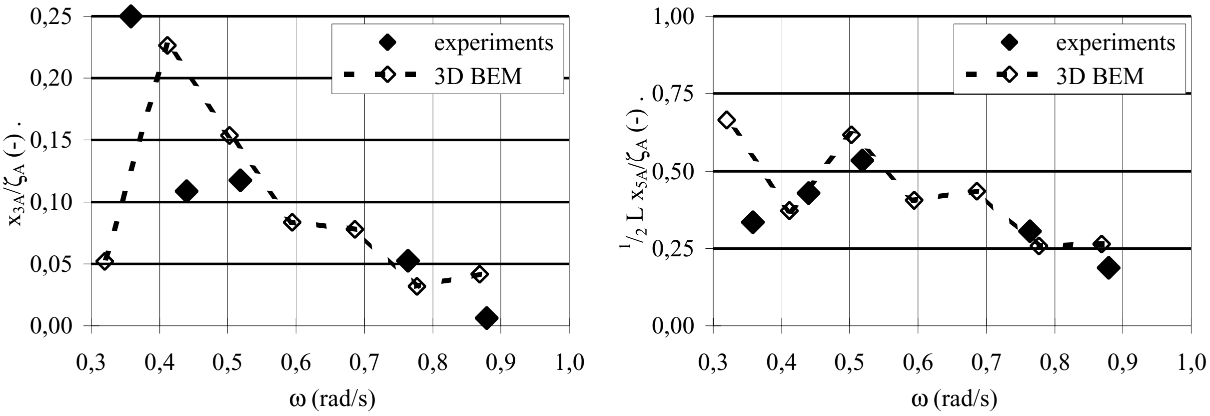


Figure 6. Ship model D: $T_A = T_F = KG = 15$ m; $V = 8$ kn; $\mu = 0°$. Heave and pitch amplitude characteristics: tests in regular waves, 3D BEM. Above: $h = 18$ m; below: $h = 16$ m.

Examples of the model test results compared with the output of the numerical methods are shown in figures 6-7. Generally, it can be concluded that the agreement between the experimental data and the results of the 3D BEM is acceptable, even in very shallow water. The reliability of the results of the strip theory based method depends greatly on the way of calculating the exciting wave loads. If special attention is paid to the calculation of wave loads in very shallow water (by using a diffraction method) and the modified strip theory method is applied, a fair agreement is obtained (see figure 7); traditional strip theory methods, however, usually lead to an overestimation of ship motions.

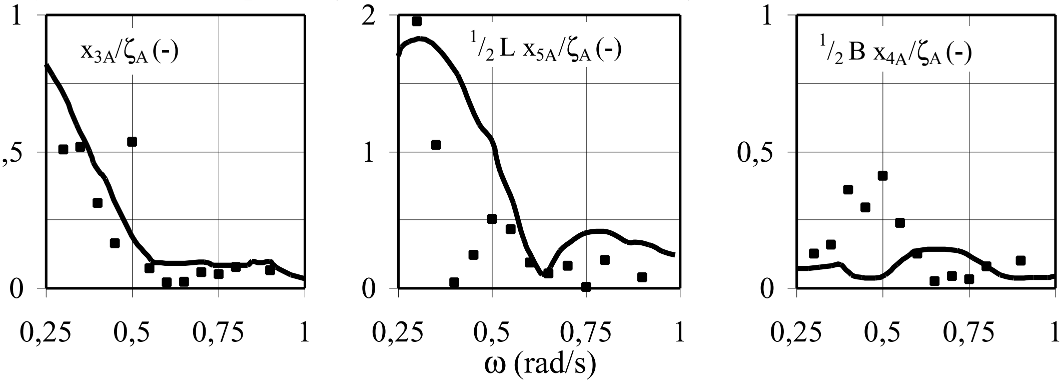


Figure 7. Ship model F: $T_A = T_F = 11.6$ m; $KG = 11.6$ m; $h = 13.6$ m; $V = 12$ kn; $\mu = 10°$. Amplitude and phase characteristics for heave, pitch and roll: tests in regular waves, modified strip theory with adapted calculation method for wave loads.

Irregular wave tests

The results of the model tests in irregular waves were used to evaluate the validity of the linear response theory in realistic seaways. For this purpose, the time histories of the heave (x_3), pitch (x_5) and roll (x_4) motions were determined for each test, and the average value $\overline{x_i(t)}$ and standard deviation $\sigma_{x_i} = \sqrt{\overline{\left(x_i(t) - \overline{x_i(t)}\right)^2}}$ of each motion mode were calculated.

In a linear approach, the average value of the ship's position in each of the mentioned degrees of freedom can also be obtained from the results of still water tests: $\overline{x_3(t)}$ and $\overline{x_5(t)}$ correspond with the static sinkage and trim, respectively. The standard deviation can be derived from tests in regular waves. Indeed, the spectral density of motion mode i can be determined as follows:

$$S_{x_i}(\omega) = S_\zeta(\omega) \cdot Y^2_{x_i\zeta}(\omega)$$

$S_\zeta(\omega)$ being the spectral density of the wave elevation and $Y_{x_i\zeta}(\omega)$ the amplitude characteristic of the vertical motion of point i. σ_{x_i} can be calculated through following expression:

$$\sigma_{x_i} = \sqrt{\int_0^{+\infty} S_{x_i}(\omega)d\omega}$$

In this way, the results of tests in spectra can be used for introducing correction factors for the static sinkage and trim as determined from still water tests and for the standard deviation of heave, pitch and roll motions as determined from tests in regular waves. Figure 8 shows a comparison between the average sinkage and trim in still water and in irregular seaways, while figure 9 illustrates the correlation between the standard deviation determined from tests in irregular waves and the values calculated from the results of tests in regular waves.

Database

A comprehensive database of vertical ship motion parameters was realised consisting of:

- static vertical motion data (average sinkage and trim) based on the experimental results;
- dynamic response characteristics for heave, pitch and roll (motion amplitude relative to wave amplitude and phase lag as a function of wave pulsation and angle of incidence of wave) , derived from the results of tests in regular waves for an angle of incidence range [-10 deg ; 10 deg] and [170 deg ; 190 deg]; the other ranges are covered with numerical data which may be corrected taking account of the comparison between numerical and experimental data;
- correction factors for response in irregular seaways.

These data are available for a large number of combinations of ships, loading conditions (draft fore and aft, vertical position of centre of gravity), water depths and ship's speeds.

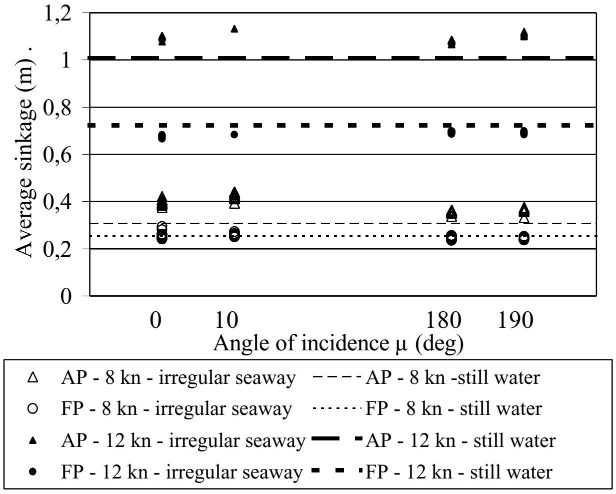


Figure 8. Ship model F, T=11.6 m, h=13.6 m. Squat: still water tests compared with tests in irregular seaways.

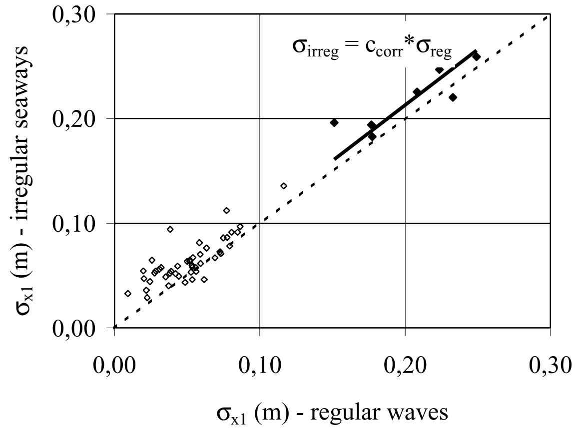
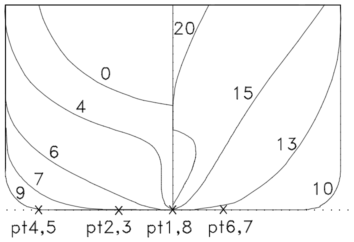


Figure 9. Ship model F, T=11.6 m, h=13.6 m. Standard deviation of heave motion: comparison between tests in regular and irregular waves.



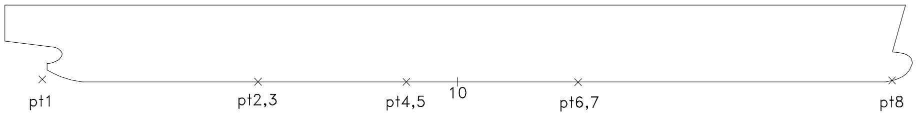


Figure 10. Ship model D: selection of critical points

In order to obtain a database covering a larger range of ship dimensions, the experimental data were transformed to full scale data with different scale factors, in the range 70 to 100 % for ship models

D and E, and 100 to 130 % for ship models F and G. A complete overview of the combinations (ship, loading condition, water depth) is shown in Table 3.

5.0 Procedure

The present calculation procedure consists of an input data module, a calculation program and an output data module. Two versions of the program are available:

- a basic version calculates the probability of bottom touch for one particular departure time;
- an extended version calculates a safe tidal window over the next 13 hours satisfying the condition that the probability of bottom touch does not exceed a imposed value (e.g. 10^{-4}).

Input data module

Following data have to be introduced:

- *Ship hull*: at present a selection can be made between 21 ship hulls (see table 3), derived from the four tested models. Each hull is characterised by its length between perpendiculars, beam and block coefficient. On the hull, a number of critical points are defined, which can be considered as critical from the point of view of bottom touch (see figure 10).
- *Draft* fore and aft.
- Ship's *speed*, considered to be constant over the complete trajectory.
- *Trajectory*: four options can be selected: from/to Flushing, from/to Zeebrugge (see figure 1).
- *Date* and *time* of departure.
- *Tidal data* have to be available for three measuring stations of interest (Zeebrugge, Cadzand, Flushing). Based on these data, the tide height at any location and at any time can be calculated.
- *Wave conditions*. The calculation procedure is based on the availability of following functions of wave frequency: spectral energy density, average and standard deviation of angle of propagation-for several locations.

Table 3.

Ship	Scale factor	L (m)	B (m)	h (m)	T (m)	V (kn)
D	1,00	289,80	40,25	18,0	15,0	8,0 - 14,0
				17,0	15,0	
				16,0	15,0	
				14,0	11,6	
				13,3	11,6	
	0,95	275,31	38,24	17,1	14,25	7,8 - 13,6
				16,15	14,25	
				15,2	14,25	
	0,90	260,82	36,23	16,2	13,5	7,6 - 13,3
				15,3	13,5	
				14,4	13,5	
	0,85	246,33	34,21	15,3	12,75	7,4 - 12,9
				14,45	12,75	
	0,80	231,84	32,20	14,4	12,0	7,2 - 12,5
E	1,00	325,00	53,00	18,0	15,0	8,0 - 14,0
				17,25	15,0	
				16,5	15,0	
				14,0	11,6	
				13,3	11,6	
	0,95	308,75	50,35	17,1	14,25	7,8 - 13,6
				16,39	14,25	
				15,68	14,25	
	0,90	292,50	47,70	16,2	13,5	7,6 - 13,3
				15,53	13,5	
				14,85	13,5	
	0,85	276,25	45,05	15,3	12,75	7,4 - 12,9
				14,66	12,75	
	0,80	260,00	42,40	14,4	12	7,2 - 12,5

Ship	Scale factor	L (m)	B (m)	h (m)	T (m)	V (kn)
F	1,00	190,00	32,00	13,6	11,6	8,0 - 14,0
				14,5	11,6	
				14,5	12,5	
				15,5	12,5	
	1,05	199,50	33,60	15,23	12,18	8,2 - 14,3
				15,23	13,13	
				16,28	13,13	
	1,10	209,00	35,20	14,96	12,76	8,4 - 14,7
				15,95	12,76	
				15,95	13,75	
				17,05	13,75	
	1,15	218,50	36,80	15,64	13,34	8,6 - 15,0
				16,68	13,34	
				16,68	14,38	
				17,83	14,38	
	1,20	228,00	38,40	16,32	13,92	8,8 - 15,3
				17,4	13,92	
				17,4	15	
				18,6	15	

Ship	Scale factor	L (m)	B (m)	h (m)	T (m)	V (kn)
G	1,00	180,00	33,00	13,6	11,6	8,0 - 14,0
				14,5	11,6	
				14,5	13	
				15,5	13	
	1,05	189,00	34,65	14,28	12,18	8,2 - 14,3
				15,23	12,18	
				15,23	13,65	
				16,28	13,65	
	1,10	198,00	36,30	14,96	12,76	8,4 - 14,7
				15,95	12,76	
				15,95	14,3	
				17,05	14,3	
	1,15	207,00	37,95	15,64	13,34	8,6 - 15,0
				16,68	13,34	
				16,68	14,95	
				17,83	14,95	
	1,20	216,00	39,60	16,32	13,92	8,8 - 15,3
				17,4	13,92	
				17,4	15,6	
				18,6	15,6	
	1,25	225,00	41,25	17	14,5	8,9 - 15,7
				18,13	14,5	

Calculation scheme

In the basic version of the program, following steps are executed consecutively.

- *Determination of the depth.* Based on the departure time and the ship's speed, the instantaneous water depth at the ship's position is calculated as a function of time, taking account of the local bottom depth and the tidal data.
- *Partition into sub-trajectories.* The trajectory is divided into sub-trajectories (j=1,…,n) in which the (local and instantaneous) water depth is approximately constant. The difference between the deepest and shallowest point of each sub-trajectory should not exceed a limiting value, the latter depending on and increasing with gross under keel clearance. The actual water depth h in each point of the trajectory is replaced by the minimum depth h_j of the sub-trajectory (see figure 11).

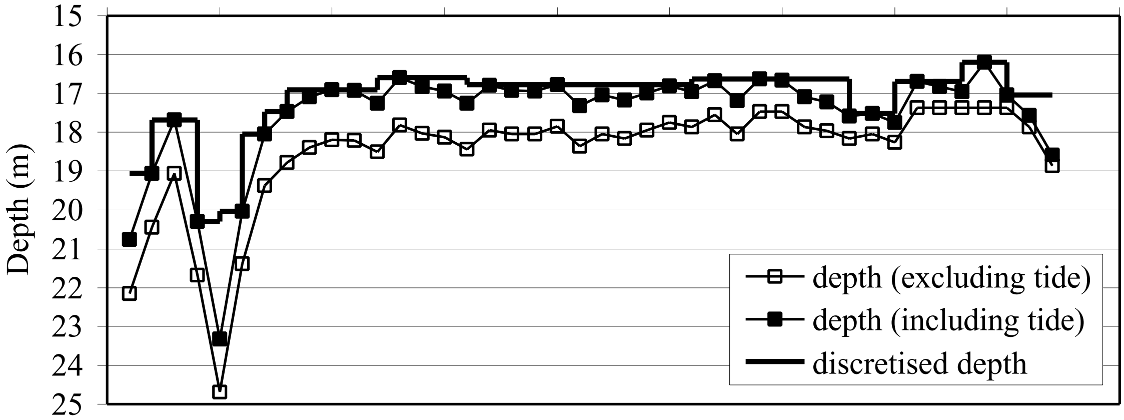


Figure 11. Example of Discretisation into Sub-Trajectories

- *Database consultation.* For each sub-trajectory, two conditions (combinations water depth - draft) are selected in the database which give the best approximations for the actual condition. For this purpose, a score is awarded to each condition, taking account of the draft and the under keel clearance percentage. For each condition, two speed values are selected in the database, and a weight factor w_i is attributed to each selected combination (T_k, h_k, V_k), k = 1, … ,4.
- *Input of squat data.* The values for sinkage and trim are calculated by weighted averaging of the static vertical motion data for the four selected combinations (T_k, h_k, V_k), corrected for irregular seaways. This allows computation of the static sinkage $\overline{z_\ell}$ of each critical point on the ship hull.
- *Input of spectral data.* For each sub-trajectory, the nearest position for which wave data are available is selected; the values for the spectral density S?(?), the average angle of propagation and the standard deviation of this angle are introduced. Taking account of the average heading of the sub-trajectory, a table S?(? ,µ) of the spectral density of the irregular seaway as a function of angle of incidence and pulsation is obtained.
- *Computation of combined motion characteristics.* Based on the motion characteristics for the four selected combinations (T_k, h_k, V_k), the spectral density table S?(? ,µ) and the experimentally determined correction factors for response in irregular seaways, weighted average amplitude and phase characteristics $Y_{x_i\zeta}(\omega)$ and $\varepsilon_{x_i\zeta}(\omega)$ for heave (i=3), pitch (i=5) and roll (i=4) are computed. This allows the computation of the amplitude characteristic of the vertical motion of each critical point $Y_{Z_\ell\zeta}(\omega)$ (l = 1,…,N).
- *Computation of the probability of bottom touch in each sub-trajectory.* The spectral density function of the vertical response of critical point l can be computed as

$$S_{Z_\ell}(\omega) = S_\zeta(\omega) \cdot Y^2_{Z_\ell\zeta}(\omega)$$

which allows computation of: $m_{0,Z_\ell} = \sigma^2_{Z_\ell} = \int_0^{+\infty} S_{Z_\ell}(\omega)d\omega$; $m_{2,Z_\ell} = \int_0^{+\infty} S_{Z_\ell}(\omega)\omega^2 d\omega$

The probability of bottom touch of critical point l during the passage of the ship in sub-trajectory j with length L_j at speed V can be expressed by:

$$P_{j,\ell} = P\left[Z_\ell > 2\left(h_j - T_\ell - \overline{z_\ell}\right)\right] = \frac{1}{2\pi}\sqrt{\frac{m_{2,Z_\ell}}{m_{0,Z_\ell}}}\,\frac{L_j}{V}\,e^{-\frac{\left(h_j - T_\ell - \overline{z_\ell}\right)^2}{2m_{0,Z_\ell}}}$$

P_j = max ($P_{j,l}$) can be considered as the probability of bottom touch in sub-trajectory j.

- *Computation of the probability P of bottom touch in full trajectory.* P is computed as:

$$P = 1 - \prod_{j=1}^{N}\left(1 - P_j\right)$$

This value is compared to a critical value that is agreed to be the maximum allowable probability of bottom touch, so that an advice can be formulated.

The extended version of the program first determines the minimum gross under keel clearance over the trajectory as a function of time of departure. Four characteristic values are determined: the minimum value UKC_{min} (to be replaced by 5 % if $UKC_{min} < 0.05$ T); the maximum value UKC_{max} (to be replaced by 18 % if $UKC_{max} > 0.18$ T), and two values between both extremes. The departure times corresponding with these under keel clearance values are determined, and the basic version of the program is run for these particular departure times.

Table 4.
Tidal windows for ships approaching Flushing with draft 14 m in significant wave height 2.5 m. (high tide at destination: 11:20; distance: 27.2 nm)

ship	ship's speed (knots)	tidal window based on 10^{-4} bottom touch probability			tidal window based on 15% UKC		
		opening time	closing time	minimum UKC (%)	opening time	closing time	probability of touch
D095	12.0	07:04	14:13	10.8	07:44	13:32	1.0 E-15
	13.5	07:45	14:04	13.2	08:00	13:47	1.3 E-08
E085	10.0	06:58	13:29	12.7	07:19	13:06	2.8 E-11
	12.0	08:00	13:16	16.6	07:44	13:32	5.3 E-01

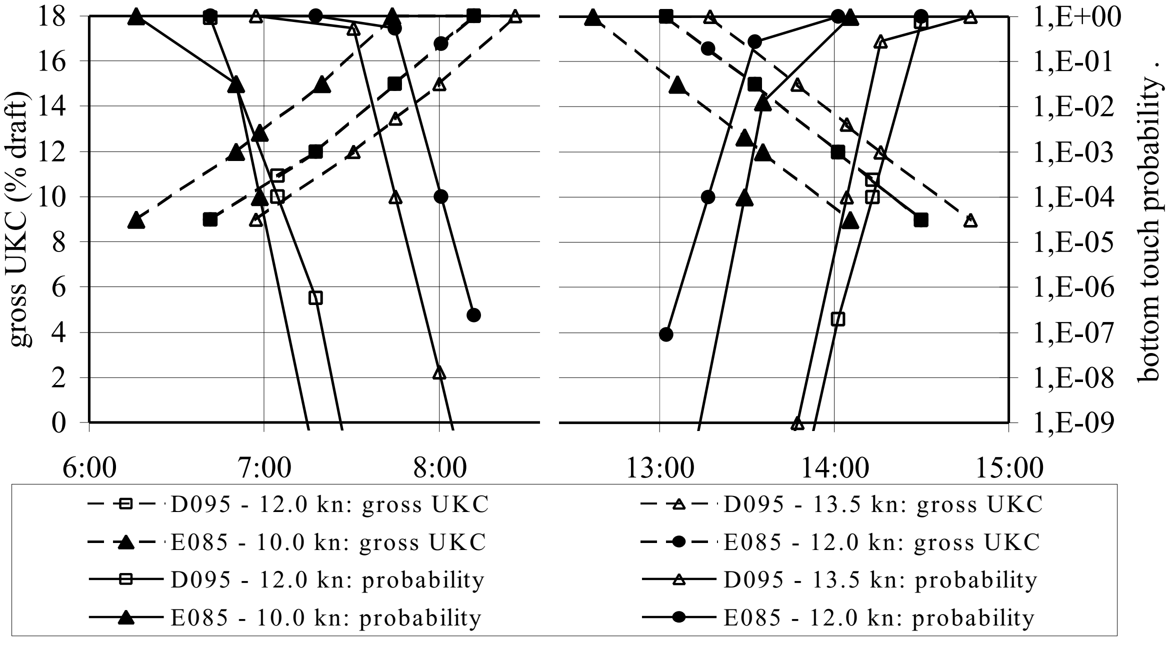


Figure 12. Tidal windows calculated for ships D095 and E085 approaching Flushing with draft 14 m in significant wave height 2.5 m. Effect of ship type and speed

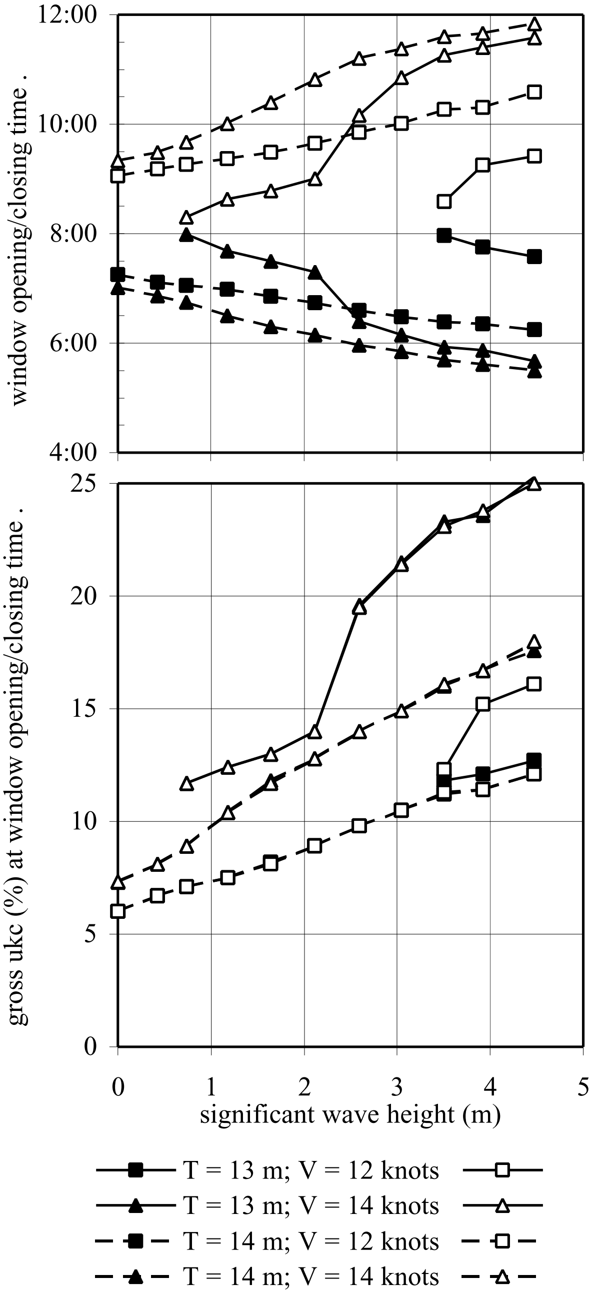


Figure 13. Container ship D100 approaching Zeebrugge: opening (open symbols) / closing (closed symbols) time of tidal window based on 10^{-4} bottom touch probability and corresponding gross under keel clearance in function of wave height. Low tide at destination: 8:30. Average wave direction: -45 deg (from NW); standard deviation: 10.3 deg.

6.0. Output

The basic version of the program returns the global probability of bottom touch and compares this value with an accepted probability, so that the passage can be evaluated as safe or unsafe. The probability for each sub-trajectory is also listed. The minimal gross under keel clearance is displayed as well. The extended version displays the characteristic times of departure with their minimum under keel clearance percentage and the corresponding probability of bottom touch. Comparison with an acceptable probability results into a safe tidal window.

As an example, the procedure was applied to following ships approaching Flushing: container ship D095 (L = 275 m, B = 38.2 m, T = 14 m, V = 12 - 13.5 knots), and bulk carrier E085 (L = 276 m, B = 45.1 m, T = 14 m, V = 10 - 12 knots). The wave characteristics are based on observed data with 2.5 m significant wave height. The results, summarised in figure 12, illustrate the influence of speed and vessel type. Table 4 shows the tidal windows based on an acceptable bottom touch probability of 10^{-4}, and makes a comparison with tidal windows based on a minimum gross under keel clearance of 15% of draft. It is shown that introducing a probabilistic access policy may lead to an extension of tidal windows, but not necessarily; for the bulk carrier, the 15% UKC rule may result into an unsafe situation if the ship's speed is too high. In such a case, the procedure can be successfully applied as an advisory instrument for the pilot concerning speed control.

The influence of the significant wave height on tidal windows for a container ship approaching Zeebrugge is illustrated in figure 13. Two drafts (13 - 14 m) and two speeds (12 - 14 kn) were considered. Although realistic wave spectra were used as input data, constant values for the average angle of wave propagation and its standard deviation were selected; therefore, the results must not be generalised. In the given conditions, the 15% gross under keel clearance guideline appears to lead to a narrower tidal window compared to the 10^{-4} bottom touch probability criterion for wave heights up to a critical value that strongly depends on draft and speed. In calm seas, the required under keel clearance appears to take very small values (6-7%); it is expected that other restrictions (e.g. manoeuvrability), will dominate the access policy in this case.

7.0 Future developments

Finally, the developed procedure should result into the implementation of a probabilistic admittance policy for the Flemish harbours. However, the operational application of this procedure and the development of a policy supporting system requires a number of actions:

- optimisation of the present procedure, in order to improve the quantity and the quality of the input data, and to include a number of additional effects which may be of importance;
- validation of the output of the procedure, by comparison with actual practice;
- implementation of the procedure: development of robust methods for introducing input data into the system, customising of output data.

In the first place, the system should be merely advisory, supporting the pilot in taking decisions concerning navigation through the channels. Indeed, for the implementation of a probabilistic admittance policy, some additional elements have to be taken into account:

- Present regulations demand a minimum gross under keel clearance of 15% in all conditions. This value is based on the ICORELS report (PIANC, 1980; see also Bruun, 1989). However, the actual text of the report only suggests 15% at a preliminary stage:

  2.2.2.8. Consequently it is not possible to establish ACCURATE RULES concerning the minimum depth of port approaches because of the major importance of local conditions. At the stage of a preliminary plan … following characteristics may be helpful: ….

  2.2.2.8.3. Channel: sections exposed to strong and long swell, gross underkeel clearance to be about 15% of draught

  2.2.2.8.4 Channels less exposed to swell, gross underkeel clearance to be about 10% of draught.
- Reduction of under keel clearance greatly affects the ship's manoeuvring and steering behaviour. The minimal under keel clearance should therefore not only be determined from the point of view of vertical motions.
- Speed is an important parameter; in general, the probability of bottom touch decreases with decreasing speed. In some circumstances, however, a minimum speed should be maintained, e.g. in cross current or in cross winds.
- For ships with destination Antwerp or Ghent, the procedure should be extended with the trajectory over the river Scheldt. For ships with destination or origin Zeebrugge, the procedure should take account of a tidal window due to cross currents.
- A probabilistic admittance policy implies that an acceptable risk level must be agreed.

8.0 Conclusion

An advisory support system to calculate the tidal windows in the access sea channels to the Ports of Antwerp, Ghent and Zeebrugge, based on model tests for four relevant ship types and mathematical modelling derived from the model tests, is available for the Vessel Traffic Services of the Western Scheldt and its estuaries. After optimisation and validation actions, the developed procedure may result into the implementation of a probabilistic admittance policy for the Flemish harbours.

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