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Development of Decision Supporting Tools for Determining Tidal Windows for Deep-drafted Vessels

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ABSTRACT: A decision supporting tool named ProToel for determining tidal windows for deep-drafted vessels arriving at or departing from the Belgian harbours, based on both deterministic and probabilistic criteria, has been developed. The program is presently being evaluated as a short-term decision tool by the pilots and waterways authorities for optimising the shipping traffic to the coastal harbour of Zeebrugge. The software can also be applied for long-term considerations, as is illustrated in the case of the port of Antwerp. Some reflections are made considering the extension of the tool to include other factors that may affect the safety of shipping traffic, such as interaction with banks and with other shipping traffic.

1 INTRODUCTION

Access channels to harbours are often subject to tide, so that arrival and departure of ships may be limited to a certain window. This window is mainly determined by the variations of the water level and is therefore of particular importance for deep-drafted vessels, but also other parameters such as lateral and longitudinal current components, or penetration of the keel into soft mud layers may be limiting factors.

In particular, tidal windows have to be imposed to deep-drafted ships arriving at and departing from the Belgian seaports of Zeebrugge and Antwerp. The *Scheur West* channel links the deeper *Wandelaar* area in the southern North Sea via the *Pas van het Zand* to the port of Zeebrugge, and via the *Scheur East* and *Wielingen* channels to the mouth of the river *West Scheldt*, which gives access to the port of Antwerp, where deep-drafted ships can either berth on one of the river terminals or the tidal *Deurganck Dock*, or enter the *Zandvliet* or *Berendrecht Locks*.

For the sea channels giving access to the Belgian harbours, a decision supporting software tool has been developed. This tool results into an advisable tidal window, based on a number of criteria that can be both deterministic and probabilistic. In a deterministic mode, the gross under keel clearance (UKC), relative to both the nautical bottom and the top of fluid mud layers, and the magnitude of current components are taken into account. In case probabilistic considerations are accounted for, a positive advise will only be given if the probability of bottom touch during the voyage – due to squat and response to waves – does not exceed a selected maximum value. The following input data are taken into consideration: ship characteristics, waterway characteristics, trajectory, nautical bottom level, top mud level, speed over ground and through the water, tidal elevation, directional wave spectra, current, departure time.

The tool, called *ProToel*, can either be used for supporting short term decisions for a particular ship, or for long term estimations for the maximum allowable draft. *ProToel* is presently in an evaluation phase for supporting decisions taken by the Flemish Pilotage and Shipping Assistance in a short term approach for ships arriving at and departing from the harbour of Zeebrugge. For the harbour of Antwerp, to be reached by sea channels and the river Scheldt, the program can also be used as an approach policy supporting tool for long term considerations; extensions to support short term decisions are considered.

A description of the *ProToel* software will be given, followed by practical examples of its use for determining tidal windows for ships arriving at or departing from Zeebrugge. Next, some applications for the shipping traffic to Antwerp will be considered, and finally possible extensions will be covered.

2 DESCRIPTION OF THE PROTOEL SOFTWARE

2.1 *General principle*

Based on a specified route and departure time, the ProToel program calculates the UKCs and bottom touch probabilities for a specific ship following the route with a chosen speed along the trajectory. The route is split into several intervals. In each interval, the UKCs are calculated based on bottom depth, up-to-date current and tide data and the speed dependent squat. The bottom touch probability is calculated from the directional wave spectrum for that time, location and the motion characteristics of the ship. The results for each interval are stored and can be displayed after computation.

ProToel requires the availability of a number of databases:

– a ship database with dynamic response characteristics and squat data for a large range of ship dimensions and types, valid for a realistic range of forward speeds, drafts and water depths;
– a database of trajectories and trajectory points, containing recent soundings (or design depths);
– forecasts or measurements of hydro-meteorological data for a number of locations as a function of time: tidal elevation, current speed and direction, directional wave spectra, water density.

The software is developed in an object oriented programming environment, making use of Java.

2.2 *Operational use*

The graphical user interface (GUI), see Figure 1, allows an easy selection of the desired ship, represented by her beam and length. The user specifies the loading condition, namely the draft at the fore and aft perpendicular and optionally the metacentric height. Furthermore, the time of departure, the route to follow and the speed of the ship along this route – either through water or over ground – are inserted. Additionally, a number of travels can be specified before and after the desired time of departure to create a tidal window, based on a number of deterministic and/or probabilistic criteria. The menu allows specifying the data source (locally stored data, remote data) of each environment condition (tidal elevations, current, waves, bottom) separately. Recent predictions and measurements of tide, waves and current are stored in a remote database on a server that can be connected by the user, while a local database may contain long-term predictions, e.g. astronomic tide data.

The output of the computations is stored in xml format and contains the UKCs and cross currents at significant locations along the route. If a probabilistic approach is chosen, the bottom touch probability for the entire route is also given. The results can be viewed directly in ProToel and exported as a report in pdf format. An example is shown in Figure 2.

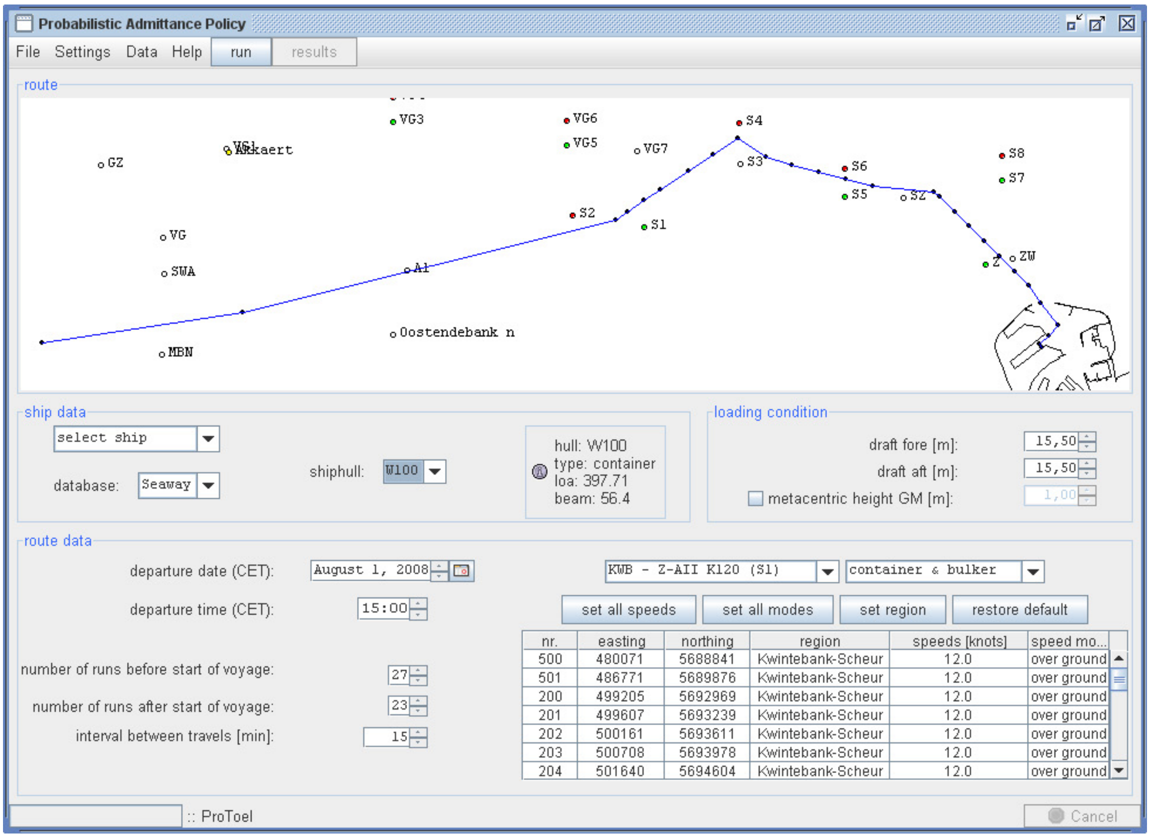
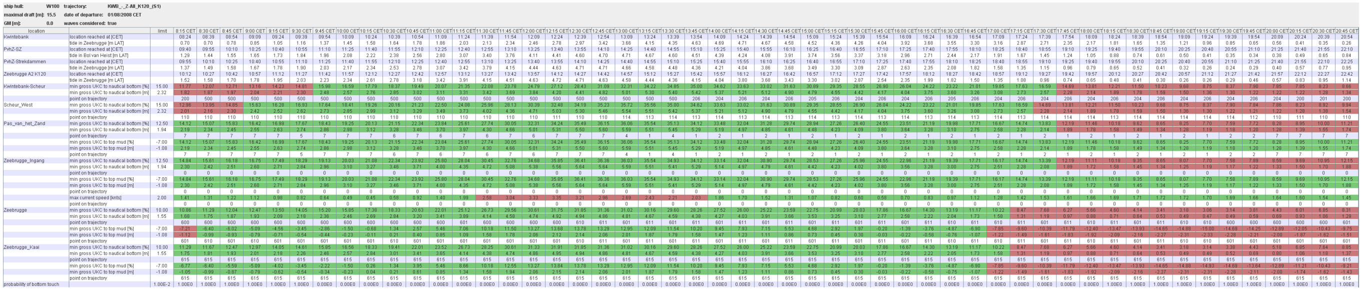


Figure 1. ProToel's graphical user interface.



ship hull:	W100	trajectory:	KWB_-_Z-All_K120_(S1)	
maximal draft [m]: 15.5		date of departure:	01/08/2008 CET	
GM [m]:	0.0	waves considered:	true	

location		limit	8:15 CET	8:30 CET
Kwintebank	location reached at [CET]		08:24	08:39
	tide in Zeebrugge [m LAT]		0.70	0.70
PvhZ-SZ	location reached at [CET]		09:40	09:55
	tide in Bol van Heist [m LAT]		1.29	1.44
PvhZ-Strekdammen	location reached at [CET]		09:55	10:10
	tide in Zeebrugge [m LAT]		1.37	1.49
Zeebrugge A2 K120	location reached at [CET]		10:12	10:27
	tide in Zeebrugge [m LAT]		1.52	1.58
Kwintebank-Scheur	min gross UKC to nautical bottom [%]	15.00	11.77	12.07
	min gross UKC to nautical bottom [m]	2.32	1.82	1.87
	point on trajectory		200	500
Scheur_West	min gross UKC to nautical bottom [%]	15.00	12.96	13.95
	min gross UKC to nautical bottom [m]	2.32	2.01	2.16
	point on trajectory		110	110
Pas_van_het_Zand	min gross UKC to nautical bottom [%]	12.50	14.12	15.07
	min gross UKC to nautical bottom [m]	1.94	2.19	2.34
	point on trajectory		7	7
	min gross UKC to top mud [%]	-7.00	14.12	15.07
	min gross UKC to top mud [m]	-1.08	2.19	2.34
	point on trajectory		7	7
Zeebrugge_Ingang	min gross UKC to nautical bottom [%]	12.50	14.84	15.61
	min gross UKC to nautical bottom [m]	1.94	2.30	2.42
	point on trajectory		0	0
	min gross UKC to top mud [%]	-7.00	14.84	15.61
	min gross UKC to top mud [m]	-1.08	2.30	2.42
	point on trajectory		0	0
	max current speed [knts]	2.00	1.41	1.31
	point on trajectory		0	0
Zeebrugge	min gross UKC to nautical bottom [%]	10.00	10.86	11.29
	min gross UKC to nautical bottom [m]	1.55	1.68	1.75
	point on trajectory		600	600
	min gross UKC to top mud [%]	-7.00	-7.21	-6.40
	min gross UKC to top mud [m]	-1.08	-1.12	-0.99
	point on trajectory		601	610
Zeebrugge_Kaai	min gross UKC to nautical bottom [%]	10.00	11.29	11.67
	min gross UKC to nautical bottom [m]	1.55	1.75	1.81
	point on trajectory		615	615
	min gross UKC to top mud [%]	-7.00	-6.77	-6.40
	min gross UKC to top mud [m]	-1.08	-1.05	-0.99
	point on trajectory		615	615
probability of bottom touch		1.00E-2	1.00E0	1.00E0

Figure 2. ProToel output file, showing waypoints and criteria as a function of departure time.

Beam [m]	Length over all [m]											
	180.0 - 199.9	200.0 - 219.9	220.0 - 239.9	240.0 - 259.9	260.0 - 279.9	290.0 - 299.9	300.0 - 319.9	320.0 - 339.9	340.0 - 359.9	360.0 - 379.9	380.0 - 399.9	400.0 - 419.9
30.0 - 32.9	G100	F100		D080								
33.0 - 35.9	G105	F105	F110		D085							
36.0 - 38.9	G110	G115	F115	F120	D090	D095						
39.0 - 41.9		G120	G125		F130	W072	D100					
42.0 - 44.9					E080	F140	W078	D105	D110			
45.0 - 47.9					E085	E090	W080	W085	D115	D118		
48.0 - 50.9							E095		W090	D120	D125	
51.0 - 53.9								E100		W095		
54.0 - 56.9											W100	

Source Containership — Containership
Source Bulkcarrier — Bulkcarrier

Figure 3. Combinations of ship length and beam covered by the database. The code refers to ship model (container carriers D, F, W; bulk carriers/tankers E, G) and scale factor (%).

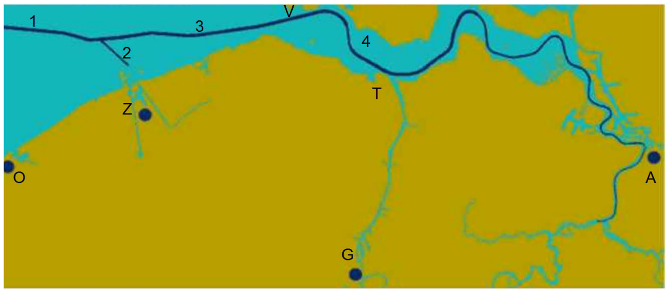


Figure 4. Access channels: 1: Scheur West, 2: Pas van het Zand, 3: Scheur East, 4: West Scheldt. Harbours: A: Antwerp/Antwerpen (B), G: Ghent/Gent (B), O: Ostend /Oostende (B), T: Terneuzen (NL), V: Flushing/Vlissingen (NL), Z: Zeebrugge (www.maritiemetoegang.be).

2.3 *Background information*

The ship data bank consists of squat and dynamic response data on a large number of slender and full hull forms, see Figure 3. The content of this databank is based on seakeeping tests carried out with five ship models in the *Towing tank for manoeuvres in shallow water (co-operation Flanders Hydraulics Research – Ghent University)* in Antwerp and additional numerical calculations with the 2D strip method *Seaway* and the 3D BEM *Aqua+*. The database covers a large number of draft – water depth combinations, and also contains data for a variation of metacentric heights.

Squat data can be directly obtained from the database by interpolation; for container vessels, the sinkage fore and aft can also be calculated by means of model test based empiric formulae that also take account of the lateral channel dimensions (Eloot et al, 2008).

The probability of bottom touch is calculated in a way that is customary for seakeeping problems, and which is based on a Rayleigh distribution of peak-to-peak values of responses of a ship to irregular waves. However, the probability calculation also accounts for a number of additional uncertainties. Due to the uncertainty of the bottom level, the still water draft, the tidal level, the squat estimation, the net UKC is not exactly known; for this reason, a standard deviation on this value is taken into account. Other types of uncertainty that are taken into consideration concern the quality of wave climate predictions, errors on response amplitude operators, effects of unknown parameters such as weight distributions and initial stability; the effect of such deviations is accounted for by introducing a standard deviation on the significant wave height.

3 APPLICATIONS

3.1 *Use of ProToel as a short term planning tool for shipping traffic to Zeebrugge*

3.1.1 *Criteria*

Presently deep-drafted ships arriving at or departing from Zeebrugge need to take account of following tidal restrictions (see Figure 4):

– in the *Scheur West* and *Pas van het Zand* channels, a gross UKC of at least 15% and 12.5% of draft, respectively, is required;
– in the outer harbour of Zeebrugge, i.e. within the breakwaters, the minimum gross UKC is reduced to 10%;
– in areas subject to sedimentation where the bottom of the navigation areas is covered with fluid mud, a penetration of 7% of draft in the mud layer is considered as acceptable in case sufficient tug assistance is available;
– passage of the breakwaters is subject to a current window limited by a value for the cross current of 2 knots.

For LNG-carriers, however, stricter criteria are maintained. The required UKC in the sea channels *Scheur West* and *Pas van het Zand* is increased to 20% of draft, and to 15% in the harbour area, while the acceptable cross current at the breakwaters is reduced to 1.5 knots.

According to a probabilistic approach, a tidal window should be determined in such a way that the probability of undesired phenomena – such as bottom touch – does not exceed a selected value. More important than the probability, however, is the risk, defined as the probability of occurrence multiplied by the financial and impact consequences. The latter depend on the channel bed (rock, sand, mud, …), the type of vessel (tanker, general cargo, container, …) and environmental sensitivity of the area. Considerations on acceptable risk and probability have been formulated by Savenije (1996), PIANC (1997) and others, and is usually related to an acceptable number of groundings during the lifetime of a channel. The acceptable overall probability of bottom touch is of the order of magnitude of 10^{-4}, while 10^{-2} may be considered as a maximum value for any ship transit.

Examples.As a (fictitious, but realistic) example, the results of ProToel are given for a container carrier (W100) with a length of 397.7 m, a beam of 56.4 m and a draft of 15.5 m departing from and arriving at the harbour of Zeebrugge in favourable wave conditions (significant wave height 0.9 m). The speed over ground is assumed to be 12 knots in the *Scheur West* channel, 10 knots in the *Pas van het Zand*, and 4 knots in the harbour area. Following a deterministic approach based on gross UKC, the tidal window for the departing ship (Figure 5) opens at 11:30 and closes at 17:30; however, between 13:30 and 15:45 no traffic is possible due to the tidal currents. From a probabilistic point of view, the probability of bottom touch is acceptable between 9:15 and 19:30, but the limiting criterion will be the penetration in the mud layer, which only takes acceptable values between 11:15 and 19:15. While the effect on the opening time of the tidal window is only marginal, the departure time can be postponed by 1.75 hours if a reduced gross UKC were accepted and a probabilistic approach were followed in this particular case. For the arriving ship (Figure 6), no advantage is obtained by introducing a probabilistic criterion in this particular case: the opening time of the window remains unchanged, while the closing time is determined by the acceptable penetration into the fluid mud layer. Also here, the tidal window is interrupted due to exceedance of the allowable cross current.

3.1.2 *Present status*

Actually (January 2009) *ProToel* can be used within the intranet of the Department of Mobility and Public Works of the Flemish Government. Forecasts for waves, tidal elevations and tidal currents are updated continuously by the Flemish Hydrography on the server of Flanders Hydraulics Research. In a next phase, the program will be validated and the probabilistic approach will be evaluated.

3.2 *Use of ProToel for long-term accessibility predictions*

In order to perform a long term accessibility analysis with *ProToel*, the program was extended to allow the execution of batch computations. In this way, the length of tidal windows can be calculated for all tidal cycles within a longer period, e.g. a year. For such a long term prediction, only astronomical tide data can be used, so that only deterministic criteria based on gross UKC can be applied for determining the tidal windows. For the statistical post-processing of the resulting tidal windows, additional tools have been developed.

This type of application was performed for a container carrier arriving at and departing from the harbour of Antwerp. An example of the output is given in Figure 7, and can be interpreted as follows: for both the arriving and departing ships with the considered draft values, a tidal window of at least 60 minutes is expected in more than 92% of the cases. It should be mentioned that in the example the arriving ship has a larger draft than the departing ship.

The computations appeared to be in good agreement with an existing analysis, but also revealed that the results may be very sensitive to the detailed depth profile and the assumptions used for interpolation of the tidal curves along the trajectory.

location		limit	9:00	9:15	9:30	9:45	10:00	10:15	10:30	10:45	11:00	11:15	11:30	11:45	12:00
Zeebrugge_Kaai	min gross UKC to nautical bottom [%]	10	4.85	4.82	5.29	5.8	7.23	8.04	9.51	10.06	10.89	11.29	12.29	12.83	13.93
	min gross UKC to top mud [%]	-7	-13.21	-13.24	-12.78	-12.27	-10.84	-10.03	-8.56	-8	-7.17	-6.77	-5.78	-5.23	-4.14
Zeebrugge	min gross UKC to nautical bottom [%]	10	4.82	4.82	5.29	5.8	7.23	8.04	9.51	10.06	10.89	11.29	12.29	12.83	13.93
	min gross UKC to top mud [%]	-7	-13.24	-13.24	-12.78	-12.27	-10.84	-10.03	-8.56	-8	-7.17	-6.77	-5.78	-5.23	-4.14
Zeebrugge_Ingang	min gross UKC to nautical bottom [%]	12.5	4.82	5.29	5.8	7.23	8.04	9.51	10.06	10.89	11.29	12.29	12.83	13.93	14.51
	min gross UKC to top mud [%]	-7	-6.79	-6.33	-5.82	-4.38	-3.57	-2.11	-1.55	-0.72	-0.32	0.67	1.22	2.31	2.9
	max current speed [knts]	2	1.88	1.82	1.79	1.71	1.67	1.55	1.49	1.37	1.3	1.13	1.01	0.77	0.66
Pas_van_het_Zand	min gross UKC to nautical bottom [%]	12.5	9.36	9.8	10.61	11.75	12.96	14.02	14.83	15.41	16.02	16.8	17.62	18.44	19.33
	min gross UKC to top mud [%]	-7	9.36	9.8	10.61	11.75	12.96	14.02	14.83	15.41	16.02	16.8	17.62	18.44	19.33
Scheur_West	min gross UKC to nautical bottom [%]	15	10.37	11.27	12.34	13.4	14.34	15.09	15.77	16.47	17.23	18.05	18.88	19.81	20.86
Kwintebank-Scheur	min gross UKC to nautical bottom [%]	15	11.27	11.97	13.4	14.04	15.09	15.55	16.47	16.97	18.05	18.6	19.81	20.5	22.15
probability of bottom touch		1.0E-02	1.4E-01	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00

12:00	12:15	12:30	12:45	13:00	13:15	13:30	13:45	14:00	14:15	14:30	14:45	15:00	15:15	15:30	15:45	16:00	16:15	16:30
13.93	14.51	15.81	16.58	18.45	19.57	22.32	23.93	27.38	28.97	31.35	32.04	32.44	32.29	31.64	31.24	30.26	29.65	28.25
-4.14	-3.55	-2.25	-1.49	0.38	1.51	4.25	5.87	9.32	10.91	13.29	13.98	14.38	14.22	13.58	13.17	12.2	11.59	10.18
13.93	14.51	15.81	16.58	18.45	19.57	22.32	23.93	27.38	28.97	31.35	32.04	32.29	32	31.24	30.78	29.65	28.97	27.49
-4.14	-3.55	-2.25	-1.49	0.38	1.51	4.25	5.87	9.32	10.91	13.29	13.98	14.22	13.94	13.17	12.72	11.59	10.91	9.43
14.51	15.81	16.58	18.45	19.57	22.32	23.93	27.38	28.97	31.35	32.04	32.44	32.29	31.64	31.24	30.26	29.65	28.25	27.49
2.9	4.2	4.96	6.84	7.96	10.71	12.32	15.77	17.36	19.74	20.43	20.83	20.67	20.03	19.63	18.65	18.04	16.63	15.88
0.66	0.49	0.48	0.72	0.97	1.68	2.1	2.89	3.18	3.45	3.44	3.17	2.98	2.58	2.4	2.1	1.98	1.76	1.65
19.33	20.33	21.5	22.96	24.69	26.84	29.29	31.9	34.23	35.87	36.61	36.44	36.12	35.31	34.8	33.55	32.84	31.37	30.63
19.33	20.33	21.5	22.96	24.69	26.84	29.29	31.9	34.23	35.87	36.61	36.44	36.12	35.31	34.8	33.55	32.84	31.37	30.63
20.86	22.15	23.67	25.58	27.77	30.18	32.51	34.37	35.67	36.21	36.06	35.6	35.02	34.28	33.4	32.35	31.25	30.08	28.88
22.15	23.14	25.58	27.02	30.18	31.75	34.37	34.63	34.15	33.01	32.36	30.91	30.1	28.37	27.47	25.63	24.69	22.82	21.86
0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00

16:30	16:45	17:00	17:15	17:30	17:45	18:00	18:15	18:30	18:45	19:00	19:15	19:30	19:45	20:00	20:15	20:30	20:45	21:00
28.25	27.49	25.95	25.16	23.48	22.62	20.85	19.86	17.59	16.34	13.91	12.79	10.77	9.82	8.08	7.3	5.94	5.35	4.33
10.18	9.43	7.89	7.09	5.42	4.56	2.78	1.8	-0.47	-1.72	-4.16	-5.27	-7.3	-8.24	-9.99	-10.76	-12.13	-12.72	-13.73
27.49	26.73	25.16	24.34	22.62	21.75	19.86	18.78	16.34	15.1	12.79	11.75	9.82	8.92	7.3	6.59	5.35	4.81	3.91
9.43	8.66	7.09	6.27	4.56	3.69	1.8	0.71	-1.72	-2.97	-5.27	-6.31	-8.24	-9.14	-10.76	-11.48	-12.72	-13.25	-14.16
27.49	25.95	25.16	23.48	22.62	20.85	19.86	17.59	16.34	13.91	12.79	10.77	9.82	8.08	7.3	5.94	5.35	4.33	3.91
15.88	14.34	13.55	11.87	11.01	9.23	8.25	5.98	4.73	2.29	1.18	-0.85	-1.79	-3.54	-4.31	-5.68	-6.27	-7.28	-7.71
1.65	1.41	1.27	0.94	0.76	0.57	0.61	0.8	0.9	1.09	1.2	1.41	1.49	1.62	1.66	1.71	1.72	1.75	1.75
30.63	29.08	28.28	26.62	25.72	23.63	22.45	20.01	18.84	16.69	15.69	13.85	13	11.5	10.85	9.72	9.24	8.46	8.07
30.63	29.08	28.28	26.62	25.72	23.63	22.45	20.01	18.84	16.69	15.69	13.85	13	11.5	10.85	9.72	9.24	8.46	8.07
28.88	27.64	26.36	25.02	23.56	21.88	20.09	18.34	16.71	15.23	13.85	12.61	11.49	10.51	9.65	8.94	8.35	8.01	7.92
21.86	19.93	18.93	16.91	15.95	14.21	13.43	12.03	11.4	10.31	9.87	9.25	9.1	8.94	8.22	8.01	8.01	7.93	8.01
0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	7.0E-11	1.6E-14	1.0E+00	1.0E+00	1.0E+00	1.0E+00	1.0E+00	1.0E+00

Figure 5. ProToel results for a container vessel departing from Zeebrugge (fictitious example)

location		limit	8:15	8:30	8:45	9:00	9:15	9:30	9:45	10:00	10:15	10:30	10:45	11:00	11:15
Kwintebank-Scheur	min gross UKC to nautical bottom [%]	15	11.77	12.07	12.71	13.16	14.23	14.81	15.98	16.59	17.79	18.37	19.49	20.07	21.35
Scheur_West	min gross UKC to nautical bottom [%]	15	12.96	13.95	14.85	15.63	16.28	16.93	17.64	18.41	19.26	20.16	21.23	22.5	24.08
Pas_van_het_Zand	min gross UKC to nautical bottom [%]	12.5	14.12	15.07	15.83	16.42	16.99	17.67	18.43	19.25	20.13	21.15	22.34	23.84	25.61
	min gross UKC to top mud [%]	-7	14.12	15.07	15.83	16.42	16.99	17.67	18.43	19.25	20.13	21.15	22.34	23.84	25.61
Zeebrugge_Ingang	min gross UKC to nautical bottom [%]	12.5	14.84	15.61	16.18	16.75	17.49	18.29	19.13	20.03	21.08	22.34	23.92	25.8	28.04
	min gross UKC to top mud [%]	-7	14.84	15.61	16.18	16.75	17.49	18.29	19.13	20.03	21.08	22.34	23.92	25.8	28.04
	max current speed [knts]	2	1.41	1.31	1.22	1.12	0.98	0.82	0.64	0.49	0.45	0.58	0.92	1.4	1.99
Zeebrugge	min gross UKC to nautical bottom [%]	10	10.86	11.29	12.04	12.47	13.5	14.05	15.2	15.85	17.38	18.33	20.63	22.01	25.12
	min gross UKC to top mud [%]	-7	-7.21	-6.4	-6.02	-5.09	-4.56	-3.45	-2.86	-1.5	-0.68	1.34	2.57	5.46	7.06
Zeebrugge_Kaai	min gross UKC to nautical bottom [%]	10	11.29	11.67	12.47	12.97	14.05	14.61	15.85	16.56	18.33	19.41	22.01	23.52	26.73
	min gross UKC to top mud [%]	-7	-6.77	-6.4	-5.59	-5.09	-4.02	-3.45	-2.22	-1.5	0.26	1.34	3.95	5.46	8.66
probability of bottom touch		1.0E-02	1.0E+00	1.0E+00	1.0E+00	1.0E+00	1.0E+00	1.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00

11:15	11:30	11:45	12:00	12:15	12:30	12:45	13:00	13:15	13:30	13:45	14:00	14:15	14:30	14:45	15:00	15:15	15:30	15:45
21.35	22.08	23.78	24.79	27.12	28.43	31.09	32.31	34.22	34.85	35	34.62	33.63	33.02	31.63	30.89	29.35	28.55	26.9
24.08	25.96	28.13	30.39	32.48	34.19	35.23	35.72	35.56	35	34.62	33.63	33.02	31.63	30.89	29.35	28.55	26.9	26.04
25.61	27.74	30.05	32.31	34.24	35.49	36.15	36.06	35.54	35.13	34.12	33.48	32.04	31.28	29.74	28.94	27.26	26.4	24.55
25.61	27.74	30.05	32.31	34.24	35.49	36.15	36.06	35.54	35.13	34.12	33.48	32.04	31.28	29.74	28.94	27.26	26.4	24.55
28.04	30.45	32.76	34.68	35.85	36.41	36.36	36.03	35.54	34.93	34.12	33.14	32.04	30.9	29.74	28.53	27.26	25.96	24.55
28.04	30.45	32.76	34.68	35.85	36.41	36.36	36.03	35.54	34.93	34.12	33.14	32.04	30.9	29.74	28.53	27.26	25.96	24.55
1.99	2.58	3.04	3.33	3.35	3.21	2.96	2.69	2.43	2.21	2.03	1.86	1.7	1.52	1.31	1.07	0.82	0.6	0.58
25.12	26.73	29.56	30.61	31.75	31.85	31.36	31.02	30.16	29.6	28.26	27.52	26	25.22	23.59	22.75	20.99	20.03	17.86
7.06	10.18	11.5	13.27	13.68	13.78	13.29	12.95	12.09	11.54	10.2	9.45	7.93	7.15	5.53	4.68	2.92	1.97	-0.2
26.73	28.25	30.61	31.33	31.91	31.85	31.36	31.02	30.16	29.6	28.26	27.52	26	25.22	23.59	22.75	20.99	20.03	17.86
8.66	10.18	12.55	13.27	13.84	13.78	13.29	12.95	12.09	11.54	10.2	9.45	7.93	7.15	5.53	4.68	2.92	1.97	-0.2
0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00

15:45	16:00	16:15	16:30	16:45	17:00	17:15	17:30	17:45	18:00	18:15	18:30	18:45	19:00	19:15	19:30	19:45	20:00	20:15
26.9	26.04	24.22	23.22	21.01	19.85	17.63	16.59	14.69	13.81	12.21	11.5	10.23	9.68	8.75	8.37	7.9	7.85	7.85
26.04	24.22	23.22	21.01	19.85	17.63	16.59	14.69	13.81	12.21	11.5	10.23	9.68	8.75	8.37	7.9	7.84	7.86	8.23
24.55	23.51	21.19	19.98	17.71	16.67	14.74	13.83	12.19	11.46	10.18	9.62	8.65	8.25	7.7	7.59	7.72	8.28	8.95
24.55	23.51	21.19	19.98	17.71	16.67	14.74	13.83	12.19	11.46	10.18	9.62	8.65	8.25	7.7	7.59	7.72	8.28	8.95
24.55	22.96	21.19	19.39	17.71	16.17	14.74	13.39	12.19	11.11	10.18	9.35	8.65	8.07	7.7	7.58	7.89	8.59	9.69
24.55	22.96	21.19	19.39	17.71	16.17	14.74	13.39	12.19	11.11	10.18	9.35	8.65	8.07	7.7	7.58	7.89	8.59	9.69
0.58	0.7	0.83	0.97	1.12	1.28	1.42	1.53	1.61	1.66	1.69	1.71	1.72	1.72	1.7	1.69	1.66	1.64	1.6
17.86	16.67	14.3	13.19	11.17	10.22	8.47	7.68	6.27	5.66	4.6	4.14	3.41	3.18	3.06	3.14	3.81	4.43	6.01
-0.2	-1.39	-3.76	-4.87	-6.9	-7.85	-9.6	-10.39	-11.79	-12.4	-13.47	-13.93	-14.65	-14.88	-15	-14.69	-14.25	-12.89	-12.05
17.86	16.67	14.3	13.19	11.17	10.22	8.47	7.68	6.27	5.66	4.6	4.14	3.41	3.18	3.14	3.38	4.43	5.18	6.85
-0.2	-1.39	-3.76	-4.87	-6.9	-7.85	-9.6	-10.39	-11.79	-12.4	-13.47	-13.93	-14.65	-14.88	-14.93	-14.69	-13.64	-12.89	-11.21
0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	1.0E+00	1.0E+00	1.0E+00	1.0E+00	1.0E+00	1.0E+00	1.0E+00	1.0E+00	1.0E+00

Figure 6. ProToel results for a container vessel arriving at Zeebrugge (fictitious example)

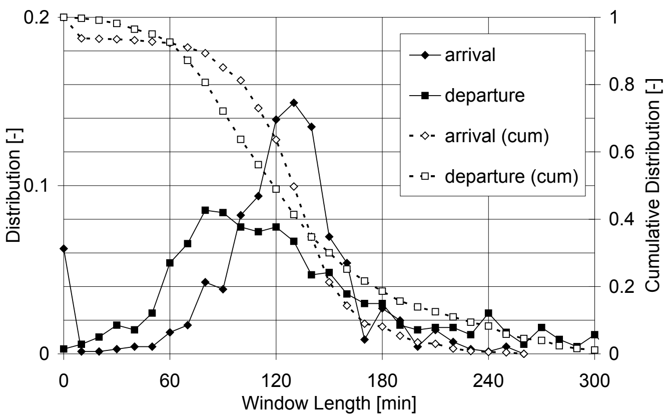


Figure 7. Distribution of length of tidal windows for container vessels arriving at / departing from Antwerp with given drafts (different for arrival and departure, values not communicated), based on a one-year period. The cumulative distribution shows the fraction of the tides offering a window with a length of at least the abscissa value. Note that a percentage of tides (especially for arriving vessels) does not result into a tidal window for the given draft, yielding a nonzero distribution value for a window length equal to zero.

4 TOWARDS A GENERALISED PROBABILISTIC METHODOLOGY

4.1 *Introduction*

Although the present tool can be applied to a wide range of access channels, the development of a general methodology for a probabilistic approach requires a number of extensions.

In the first place, squat not only depends on the ship characteristics and speed through water, but is also affected by the channel characteristics (water depth, lateral limitations), the proximity of banks and interaction with meeting and overtaking or overtaken ships.

Furthermore, the probability of bottom touch does not only depend on squat and the response to the local wave climate, but other effects may be of importance as well (e.g. wind, heel in bends). In some cases, even the basic principle for determining the probability of undesired events might have to be reconsidered. This is especially the case if the response to waves is not the main cause of bottom touch.

Finally, it should always be born in mind that not only contact with the bottom due to vertical motions should be taken into account, but that all undesired events (groundings, collisions with fixed structures or with other ships) are of importance in order to assess the total safety of shipping traffic.

4.2 *Practical case: access to Antwerp for large container vessels*

The importance of additional effects on squat can be illustrated by the results of real-time simulations that have been executed on the ship manoeuvring simulators of Flanders Hydraulics Research (SIM225 and SIM360+) to evaluate the accessibility of the West Scheldt for large containerships with a length over all of 366 – 380 – 400 m. Both simulators were coupled so that with two operating bridges the encounters are as realistic as possible.

During the simulations the sinkage fore and aft was calculated taking into account ship dependent parameters (draft, displacement, block coefficient, midship section area); environmental parameters (water depth, distance to banks); operational parameters (forward and lateral velocities and accelerations, yaw rate and acceleration, propeller rate) and other shipping traffic (draft of target ship, displacement of target ship, block coefficient of target ship, lateral distance between ships, longitudinal velocity of target ship) (Eloot et al. 2008).

As an example, Figure 8 shows a particular encounter of a departing containership (366 m x 48.8 m x 13.1 m) with a larger ship (400 m x 56.4 m x 14.5 m) in the bend of Bath on the river Scheldt (maximum flood current, wind SW 5Bf). The encounter occurred with a lateral distance equal to 56m and a relative speed through the water for both ships of approximate3ly 12 knots. The velocity parameters and sinkages of the downstream ship can be studied based on the graphs in Figure 8. The lowest obtained static UKC along the whole trajectory is approximately 50% while the maximum sinkage occurs at the stern with a maximum UKC reduction of approximately 10% of the ship’s draft.

4.3 *Requirements*

At least the following investigations are required to develop a generalised probabilistic admittance policy for deep-drafted ships:

- Redefinition of the probability of bottom touch in navigation channels that are not exposed to wave action. The present method for calculating this probability is based on a Rayleigh distribution of the peak-to-peak values for the vertical motion of a number of critical points. Hence, the overall probability during a transit requires the availability of a value for the average encounter period, which cannot be defined in absence of waves. Therefore, there is a need for an alternative methodology resulting into a probability of bottom contact that is not merely dependent on the characteristics of the wave spectrum.
- Integration of the influence of wind on net UKC. This effect may be caused in several ways: the lateral force and yawing moment caused by non-longitudinal relative wind directions result into the occurrence of both heel, which directly reduc-

es the UKC, and drift, which may lead to increased squat, but also to reduced speed.

- Integration of the effect of cross currents and waves on drift and, eventually, on squat;
- Integration of the effect of bends in the fairway, which may cause speed reduction, but also heel and increased squat due to yawing and drift.
- Integration of the effect of interaction with other shipping traffic, particularly on squat;
- Integration of the effect of interaction with banks, particularly on squat;
- Link with occurrence of other undesired effects.

5 CONCLUSIONS

A software tool for supporting operational and strategic decisions concerning accessibility of harbours for (deep-drafted) vessels subject to tidal windows has been presented. For short-term planning the tool has been implemented for the approach to the harbour of Zeebrugge, where multiple criteria (gross UKC, probability of bottom touch, keel penetration into fluid mud layers, cross currents) are of importance. An example is also given of a long-term statistical analysis of the length of tidal windows. Finally, requirements are formulated that have to be fulfilled to develop a generalised probabilistic admittance policy for deep-drafted ships.

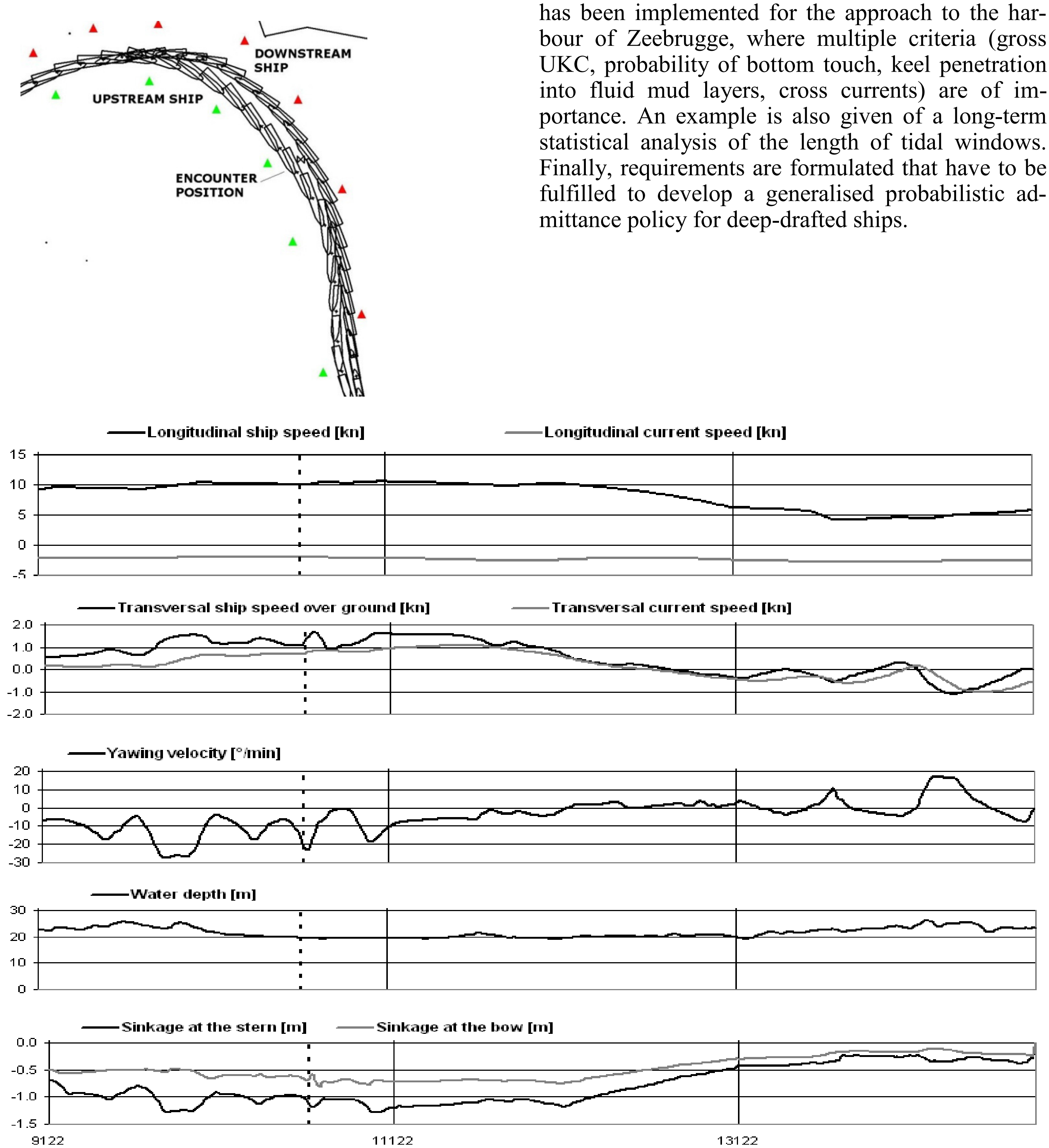


Figure 8. Real-time simulation of an encounter at the bend of Bath during flood tide: trajectories of both ships during the total manoeuvre and parameters of the ship sailing downstream with the encounter position indicated with a dashed vertical line.

REFERENCES

Eloot, K.; Verwilligen, J.; Vantorre, M. 2008. An overview of squat measurements for container vessels in restricted water. International conference on safety and operations in canals and waterways SOCW 2008, Glasgow, 19-20 September 2008.

PIANC. 1997. Approach Channels: A Guide for Design, Final Report of the Joint PIANC-IAPH Working Group II-30 in cooperation with IMPA and IALA, Supplement to PIANC Bulletin, No. 95.

Savenije, P. 1996. Probabilistic admittance policy deep draught vessels. PIANC Bulletin, No. 91, June 1996.

Vantorre, M.; Laforce, E.; Eloot, K.; Richter, J.; Verwilligen, J.; Lataire, E. 2008. Ship motions in shallow water as the base for a probabilistic approach policy. Proceedings of the ASME 27th International Conference on Offshore Mechanics and Arctic Engineering OMAE2008, Estoril, 15-20 June 2008

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