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OPERATION OF DREDGERS AT REDUCED FREEBOARD

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Abstract

For the "Sub-Committee on Stability and Load Lines and on Fishing Vessels Safety" of IMO, a ship motions computer program based on the strip theory has been developed. This program is used in a study for a revision of the technical regulations of the 1966 International Convention on Load Lines (1966 ICLL).
On behalf of the Directorate General of Shipping and Maritime Affairs in the Netherlands, this computer program has been adapted for carrying out relative vertical motion calculations for the "Working Group on Dredgers Operating at Reduced Freeboards" of IMO. Bow deck wetness calculations at reduced freeboards have been carried for three series of dredging vessels with systematic varied hull forms and principal dimensions, operating in coastal sea areas.
In this report, the results of this study are presented.

1 Introduction

The "Sub-Committee on Stability and Load Lines and on Fishing Vessels Safety" of IMO studies a revision of the technical regulations of the 1966 International Convention on Load Lines (1966 ICLL).
Recently, comprehensive research on freeboard requirements, based on calculated vertical relative ship motions, has been carried out in several countries. In the Dutch study of Journée et al. (1997), the strip theory computer code SEAWAY of the Delft University of Technology has been adapted for this purpose. The resulting new computer program SEAWAY-R

includes the regulations of the 1966 ICLL and the theoretical approaches of several countries. Journée (1997) has showed the validity of the calculated motions by this program.
For an assumed safe and seaworthy ship, freeboard and bow height have been determined according to the rules of the 1966 ICLL. For this ship, the probabilities on shipping water at deck and at the bow have been calculated from the vertical relative motions of this ship and long term weather information as used in the theoretical approaches of the different countries, like for instance wave scatter diagrams. Using this approach, these probabilities have been kept constant for a large number of ships with a wide range of ship dimensions. This results in required freeboards and bow heights, by which the ship motions and the weather are accounted for.

On behalf of the Directorate General of Shipping and Maritime Affairs in the Netherlands, computer program SEAWAY-R has been adapted for carrying out relative vertical motion calculations for the "Working Group on Dredgers Operating at Reduced Freeboards" of IMO.
Bow deck wetness calculations at reduced freeboards have been carried out here for three hull forms of Type-B ships with different block coefficients C_B at 85 per cent of the depth D: $C_B =$ 0.68, 0.78 and 0.88. The ratio $L_{0.85D} / D$ has been kept constant at a value being 15.0.
These three parent ships have been scaled linear to a range of ships with a length between perpendiculars L_{pp} being 60, 80, 100, 120, 140, 160, 180 and 200 meters, respectively. The ships have no sheer, a poop over $0.14 \cdot L_{pp}$ with standard height and a forecastle over $0.07 \cdot L_{pp}$ with standard height. The forward ship speed in head waves coincides with $Fn = 0.10$.
The definitions of the freeboards and bow heights as used here are given in Figure 1.

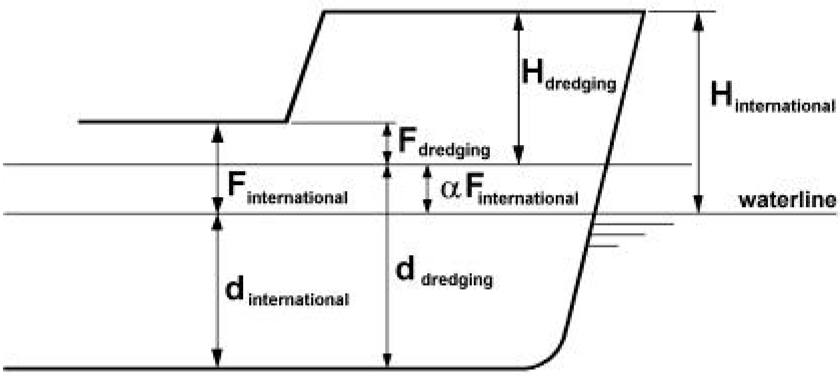

Figure 1 Definition of Freeboards and Bow Heights

Starting point of the calculations are the long term wave statistics described by the Mean Annual Wave Scatter Diagrams for the coastal zones 10, 11 and 17, as given in Global Wave

Statistics. These diagrams consist of tables with rows of significant wave heights $H_{1/3}$ and columns of zero up-crossing wave periods T_2. At each combination $(H_{1/3}, T_2)$ the probability of occurrence of a sea state, described by this combination, is given.

A new wave scatter diagram will be obtained in this study by replacing the probabilities of occurrence at the last row (highest $H_{11/3}$) by zero values. Then the probabilities will be normalized, in such a manner that the sum of the probabilities remains 1.0. This procedure will be repeated for the other rows, until the last wave scatter diagram will contain zeros only. This means that a range of wave scatter diagrams with decreasing maximum significant wave heights has been created. For ships sailing in an upcoming storm with seas defined by this range of wave scatter diagrams, this procedure means that they are supposed to escape to safe still water at an increasing earlier moment.

For the series of ships, characterized by the three block coefficients and the range of ship lengths, will be calculated:

- Freeboard and bow height, according to the rules of the 1966 International Convention on Load Lines;
- At this freeboard, the probability of shipping water at the bow in the original Mean Annual Wave Scatter Diagram;
- For this value of the probability of shipping water the maximum allowable significant wave height, obtained with the "reduced" wave scatter diagrams, at a range of freeboard reductions.

The principle of this calculation routine in computer program SEAWAY-R has been shown in Figure 2 and will be discussed in more detail in Chapter 4.

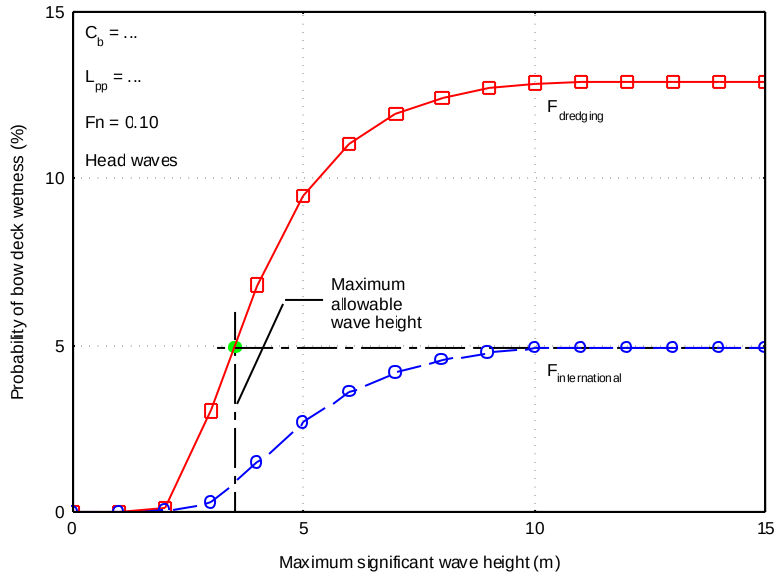

Figure 2 Principle of Calculation Method

2 Parent Hull Forms

Three different standard hull forms of Type-B ships have been used here during the calculations of the vertical ship motions relative to the waves, the freeboard and the bow height:

- a vessel with $C_B = 0.68$ at $0.85 \cdot D$
- a vessel with $C_B = 0.78$ at $0.85 \cdot D$
- a vessel with $C_B = 0.88$ at $0.85 \cdot D$

with main dimensions as tabled below.

Standard Type-B Ships					
Block coefficient at $0.85 \cdot D$	$C_B(0.85 \cdot D)$	(-)	0.680	0.780	0.880
Length between perpendiculars	L_{pp}	(m)	100.00	100.00	100.0
Length over depth ratio	$L_{0.85 \cdot D} / D$	(-)	15.00	15.00	15.00
Length over breadth ratio	L_{pp} / B	(-)	8.00	7.00	6.00
Nominal breadth over draught ratio	$(B/d)_n$	(-)	2.50	3.00	3.50

The three ships have no sheer, a poop over $0.14 \cdot L_{pp}$ with a height of 2.35 meter and a forecastle over $0.07 \cdot L_{pp}$ with a height of 2.35 meter.
These standard ships have been scaled linear to a range of ships with a length between perpendiculars L_{pp} being 60, 80, 100, 120, 140, 160, 180 and 200 meter, respectively.

Here after, a short description of each of the three standard ships will be given.

2.1 Block Coefficient $C_B(0.85 \cdot D)$ = 0.68 Ship

This ship has been derived from an existing Ro-Ro vessel, Parent Form 37 of Versluis (1995), with the following principal dimensions:

Parent Form 37 of Versluis (1995)			
Length between perpendiculars	L_{pp}	(m)	198.80
Breadth	B	(m)	32.24
Draught	d	(m)	9.00
Block coefficient	C_B	(-)	0.644
Amidships section coefficient	C_M	(-)	0.979
Center of buoyancy, forward of $L_{pp}/2$	L_{CB}/L_{pp}	(-)	-0.012
Length over breadth ratio	L_{pp}/B	(-)	6.17
Breadth over draught ratio	B/d	(-)	3.58

This ship has been transformed to a block coefficient $C_B = 0.68$ at 85% of a depth D equal to $L_{0.85 \cdot D}/15.0$. Then, a 3-D linear scaling to $L_{pp} = 100$ meter, a breadth equal to $L_{pp}/8.0$ and the ICLL-1966 draught following from a depth equal to $L_{0.85 \cdot D}/15.0$ gives the standard $C_B(0.85 \cdot D) = 0.68$ ship, as used in the calculations.

Standard $C_B(0.85 \cdot D) = 0.68$ Ship			
Length at $0.85 \cdot D$	$L_{0.85 \cdot D}$	(m)	100.27
Length between perpendiculars	L_{pp}	(m)	100.00
Breadth	B	(m)	12.50
Depth	D	(m)	6.68
Draught	d	(m)	5.00
Block coefficient at $0.85 \cdot D$	$C_B(0.85 \cdot D)$	(-)	0.680
Block coefficient at d	C_B	(-)	0.662
Amidships section coefficient	C_M	(-)	0.979
Center of buoyancy, forward of $L_{pp}/2$	L_{CB}/L_{pp}	(-)	-0.012
Length over depth ratio	$L_{0.85 \cdot D}/B$	(-)	15.00
Length over breadth ratio	L_{pp}/B	(-)	8.00
Breadth over draught ratio	B/d	(-)	2.50
Initial metacentric height	$\overline{GM}$	(m)	1.00
Radius if inertia for pitch	k_{yy}	(m)	25.00

The body plan of the $C_B(0.85 \cdot D) = 0.68$ ship is presented below.

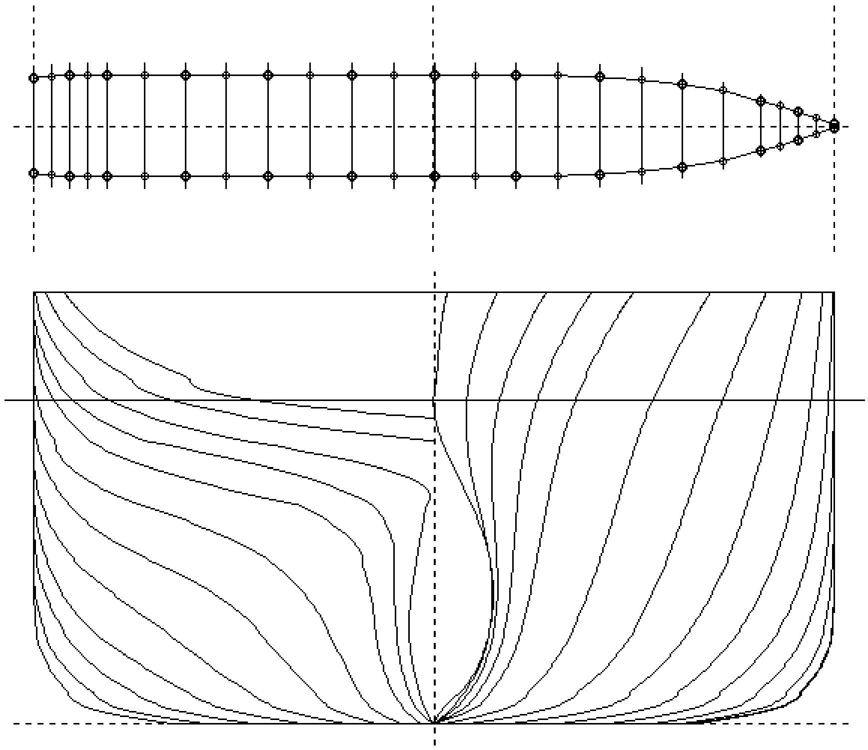

Figure 3 Hull Form of $C_B(0.85 \cdot D) = 0.68$ Ship

A 3-D linear scaling is used to obtain from this parent hull form a range of ship sizes with a constant ratio $L_{0.85 \cdot D} / D = 15.0$. The main dimensions of these ships are tabled below.

$C_B(0.85 \cdot D) = 0.68$ Ships										
Length	L_{pp}	m	60.00	80.00	**100.00**	120.00	140.00	160.00	180.00	200.00
Breadth	B	M	7.50	10.00	**12.50**	15.00	17.50	20.00	22.50	25.00
Draught	d	m	3.05	4.06	**5.00**	5.86	6.71	7.57	8.45	9.38
Length at $0.85 \cdot D$	L	m	60.16	80.22	**100.27**	120.33	140.38	160.44	180.49	200.55
Depth	D	m	4.01	5.35	**6.68**	8.02	9.36	10.70	12.03	13.37
Freeboard	F	m	0.96	1.29	**1.68**	2.17	2.65	3.12	3.58	3.99
Bow height	H	m	2.96	3.77	**4.49**	5.12	5.65	6.10	6.46	6.73

2.2 Block Coefficient $C_B(0.85 \cdot D)$ = 0.78 Ship

This ship has been derived from an existing Ro-Ro vessel, Parent Form 16 of Versluis (1995), with the following principal dimensions:

Parent Form 16 of Versluis (1995)			
Length between perpendiculars	L_{pp}	(m)	132.00
Breadth	B	(m)	21.00
Draught	d	(m)	8.53
Block coefficient	C_B	(-)	0.760
Amidships section coefficient	C_M	(-)	0.996
Center of buoyancy, forward of $L_{pp}/2$	L_{CB}/L_{pp}	(-)	+0.012
Length over breadth ratio	L_{pp}/B	(-)	6.29
Breadth over draught ratio	B/d	(-)	2.46

This ship has been transformed to a block coefficient $C_B = 0.78$ at 85% of a depth D equal to $L_{0.85 \cdot D}/15.0$. Then, a 3-D linear scaling to $L_{pp} = 100$ meter, a breadth equal to $L_{pp}/7.0$ and the ICLL-1966 draught following from a depth equal to $L_{0.85 \cdot D}/15.0$ gives the standard $C_B(0.85 \cdot D) = 0.78$ ship, as used in the calculations.

Standard $C_B(0.85 \cdot D) = 0.78$ Ship			
Length at $0.85 \cdot D$	$L_{0.85 \cdot D}$	(m)	100.11
Length between perpendiculars	L_{pp}	(m)	100.00
Breadth	B	(m)	14.29
Depth	D	(m)	6.67
Draught	d	(m)	4.90
Block coefficient at $0.85 \cdot D$	$C_B(0.85 \cdot D)$	(-)	0.780
Block coefficient at d	C_B	(-)	0.760
Amidships section coefficient	C_M	(-)	0.996
Center of buoyancy, forward of $L_{pp}/2$	L_{CB}/L_{pp}	(-)	+0.012
Length over depth ratio	$L_{0.85 \cdot D}/B$	(-)	15.00
Length over breadth ratio	L_{pp}/B	(-)	7.00
Breadth over draught ratio	B/d	(-)	2.92
Initial metacentric height	$\overline{GM}$	(m)	1.00
Radius if inertia for pitch	k_{yy}	(m)	25.00

The body plan of the $C_B(0.85 \cdot D) = 0.78$ ship is presented below.

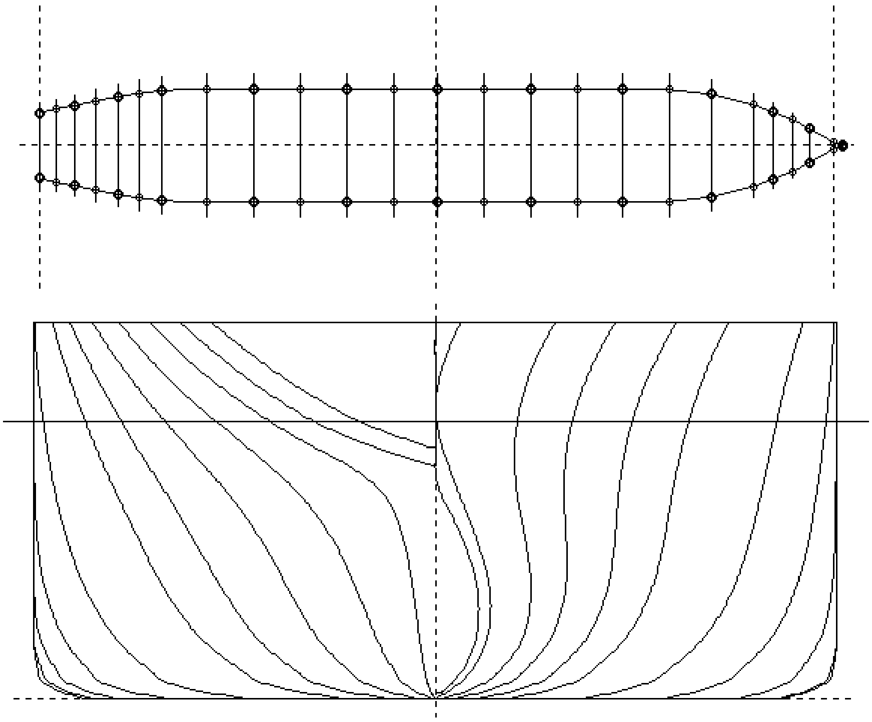

Figure 4 Hull Form of $C_B(0.85 \cdot D) = 0.78$ Ship

A 3-D linear scaling is used to obtain from this parent hull form a range of ship sizes with a constant ratio $L_{0.85 \cdot D} / D = 15.0$. The main dimensions of these ships are tabled below.

$C_B(0.85 \cdot D) = 0.78$ Ships										
Length	L_{pp}	m	60.00	80.00	**100.00**	120.00	140.00	160.00	180.00	200.00
Breadth	B	M	8.75	11.43	**14.29**	17.15	20.01	22.86	25.72	28.88
Draught	d	m	2.99	3.99	**4.90**	5.72	6.54	7.38	8.22	9.12
Length at $0.85 \cdot D$	L	m	60.07	80.09	**100.11**	120.13	140.15	160.18	180.20	200.22
Depth	D	m	4.00	5.34	**6.67**	8.01	9.34	10.68	12.01	13.35
Freeboard	F	m	1.01	1.35	**1.77**	2.29	2.80	3.30	3.79	4.23
Bow height	H	m	2.76	3.51	**4.18**	4.76	5.26	5.68	6.01	6.26

2.3 Block Coefficient $C_B(0.85 \cdot D)$ = 0.88 Ship

This ship has been derived from an existing Ro-Ro vessel, Parent Form 49 of Versluis (1995), with the following principal dimensions:

Parent Form 49 of Versluis (1995)			
Length between perpendiculars	L_{pp}	(m)	277.90
Breadth	B	(m)	44.80
Draught	d	(m)	16.60
Block coefficient	C_B	(-)	0.842
Amidships section coefficient	C_M	(-)	0.995
Center of buoyancy, forward of $L_{pp}/2$	L_{CB}/L_{pp}	(-)	+0.023
Length over breadth ratio	L_{pp}/B	(-)	6.20
Breadth over draught ratio	B/d	(-)	2.70

This ship has been transformed to a block coefficient $C_B = 0.88$ at 85% of a depth D equal to $L_{0.85 \cdot D}/15.0$. Then, a 3-D linear scaling to $L_{pp} = 100$ meter, a breadth equal to $L_{pp}/6.0$ and the ICLL-1966 draught following from a depth equal to $L_{0.85 \cdot D}/15.0$ gives the standard $C_B(0.85 \cdot D) = 0.88$ ship, as used in the calculations.

Standard $C_B(0.85 \cdot D) = 0.88$ Ship			
Length at $0.85 \cdot D$	$L_{0.85 \cdot D}$	(m)	100.54
Length between perpendiculars	L_{pp}	(m)	100.00
Breadth	B	(m)	16.67
Depth	D	(m)	6.70
Draught	d	(m)	4.82
Block coefficient at $0.85 \cdot D$	$C_B(0.85 \cdot D)$	(-)	0.880
Block coefficient at d	C_B	(-)	0.859
Amidships section coefficient	C_M	(-)	0.905
Center of buoyancy, forward of $L_{pp}/2$	L_{CB}/L_{pp}	(-)	+0.023
Length over depth ratio	$L_{0.85 \cdot D}/B$	(-)	15.00
Length over breadth ratio	L_{pp}/B	(-)	6.00
Breadth over draught ratio	B/d	(-)	3.46
Initial metacentric height	$\overline{GM}$	(m)	1.00
Radius if inertia for pitch	k_{yy}	(m)	25.00

The body plan of the $C_B(0.85 \cdot D) = 0.88$ ship is presented below.

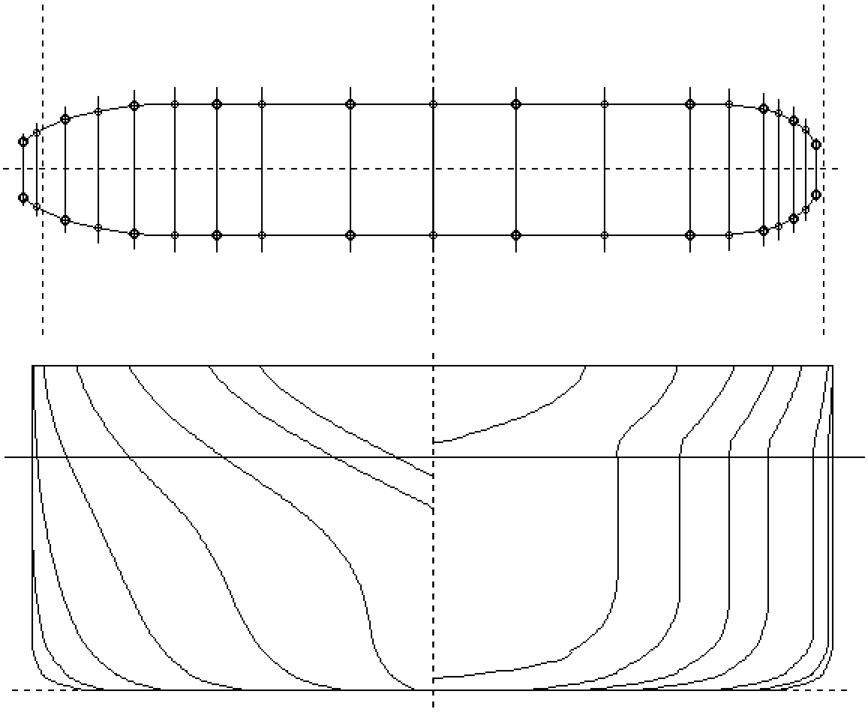

Figure 5 Hull Form of $C_B(0.85 \cdot D) = 0.88$ Ship

A 3-D linear scaling is used to obtain from this parent hull form a range of ship sizes with a constant ratio $L_{0.85 \cdot D} / D = 15.0$. The main dimensions of these ships are tabled below.

$C_B(0.85 \cdot D) = 0.88$ Ships										
Length	L_{pp}	m	60.00	80.00	**100.00**	120.00	140.00	160.00	180.00	200.00
Breadth	B	M	10.00	13.34	**16.67**	20.00	23.34	26.67	30.01	33.34
Draught	d	m	2.96	3.93	**4.82**	5.62	6.41	7.22	8.04	8.92
Length at $0.85 \cdot D$	L	m	60.32	80.43	**100.54**	120.65	140.76	160.87	180.98	201.01
Depth	D	m	4.02	5.36	**6.70**	8.04	9.38	10.72	12.07	13.41
Freeboard	F	m	1.06	1.43	**1.88**	2.42	2.97	3.51	4.02	4.49
Bow height	H	m	2.59	3.30	**3.92**	4.47	4.94	5.33	5.64	5.87

3 Wave Scatter Diagrams

For the sea area under consideration, the long-term ocean wave statistics are presented in wave scatter diagrams.
The wave scatter diagrams of three coastal areas in Western Europe, as used in this report, are tabled below.

Global Wave Statistics, Irish Sea, Zone 10, Mean Annual, All Directions													
	T_2 (s)												
$H_{1/3}$ (m)	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5
0.5	0	0	0	6	44	71	44	14	3	0	0	0	0
1.5	0	0	0	1	22	91	144	64	21	5	1	0	0
2.5	0	0	0	0	7	46	85	67	30	9	2	0	0
3.5	0	0	0	0	2	17	42	42	23	8	2	0	0
4.5	0	0	0	0	1	6	18	21	13	6	2	0	0
5.5	0	0	0	0	0	2	7	9	7	3	1	0	0
6.5	0	0	0	0	0	1	3	4	3	2	1	0	0
7.5	0	0	0	0	0	0	1	2	2	1	0	0	0
8.5	0	0	0	0	0	0	1	1	1	1	0	0	0
9.5	0	0	0	0	0	0	0	1	1	0	0	0	0
10.5	0	0	0	0	0	0	0	0	0	0	0	0	0
11.5	0	0	0	0	0	0	0	0	0	0	0	0	0
12.5	0	0	0	0	0	0	0	0	0	0	0	0	0

Global Wave Statistics, North Sea, Zone 11, Mean Annual, All Directions													
	T_2 (s)												
$H_{1/3}$ (m)	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5
0.5	0	0	0	19	86	94	41	10	2	0	0	0	0
1.5	0	0	0	3	49	121	99	40	10	2	0	0	0
2.5	0	0	0	1	17	63	73	40	13	3	1	0	0
3.5	0	0	0	0	6	27	39	26	10	3	1	0	0
4.5	0	0	0	0	2	11	19	14	6	2	1	0	0
5.5	0	0	0	0	1	4	9	7	4	1	0	0	0
6.5	0	0	0	0	0	2	4	4	2	1	0	0	0
7.5	0	0	0	0	0	1	2	2	1	1	0	0	0
8.5	0	0	0	0	0	0	1	1	1	0	0	0	0
9.5	0	0	0	0	0	0	1	1	0	0	0	0	0
10.5	0	0	0	0	0	0	0	0	0	0	0	0	0
11.5	0	0	0	0	0	0	0	0	0	0	0	0	0
12.5	0	0	0	0	0	0	0	0	0	0	0	0	0

Global Wave Statistics, Gulf of Biscay, Zone 17, Mean Annual, All Directions													
	T_2 (s)												
$H_{1/3}$ (m)	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5
0.5	0	0	0	1	9	34	43	25	8	2	0	0	0
1.5	0	0	0	0	2	29	85	93	52	18	5	1	0
2.5	0	0	0	0	0	11	59	82	66	31	10	3	1
3.5	0	0	0	0	0	3	21	46	47	28	11	3	1
4.5	0	0	0	0	0	1	8	21	26	19	9	3	1
5.5	0	0	0	0	0	0	3	9	13	11	6	2	1
6.5	0	0	0	0	0	0	1	4	6	6	3	1	1
7.5	0	0	0	0	0	0	1	2	3	3	2	1	0
8.5	0	0	0	0	0	0	0	1	2	2	1	1	0
9.5	0	0	0	0	0	0	0	0	1	1	1	0	0
10.5	0	0	0	0	0	0	0	0	0	1	0	0	0
11.5	0	0	0	0	0	0	0	0	0	0	0	0	0
12.5	0	0	0	0	0	0	0	0	0	0	0	0	0

These three tables have been normalized and added with an equal weight, as given in the table below.

Global Wave Statistics, Zones 10, 11 and 17, Mean Annual, All Directions													
	T_2 (s)												
$H_{1/3}$ (m)	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5
0.5	0	0	0	26	139	199	128	49	13	2	0	0	0
1.5	0	0	0	4	73	241	298	197	83	25	6	1	0
2.5	0	0	0	1	24	120	207	189	109	43	13	3	1
3.5	0	0	0	0	8	47	102	114	80	39	14	3	1
4.5	0	0	0	0	3	18	45	56	45	27	12	3	1
5.5	0	0	0	0	1	6	19	25	24	15	7	2	1
6.5	0	0	0	0	0	3	8	12	11	9	4	1	1
7.5	0	0	0	0	0	1	4	6	6	5	2	1	0
8.5	0	0	0	0	0	0	2	3	4	3	1	1	0
9.5	0	0	0	0	0	0	1	2	2	1	1	0	0
10.5	0	0	0	0	0	0	0	0	0	1	0	0	0
11.5	0	0	0	0	0	0	0	0	0	0	0	0	0
12.5	0	0	0	0	0	0	0	0	0	0	0	0	0

All data in this table have to be normalized, so to be divided by the total number of observations. Then, each number $q_{i,j}$ in the table represents the frequency of occurrence of a sea state defined by the parameter combination $\left(H_i, T_j\right)$.

A series of new wave scatter diagram has been obtained by replacing the probabilities of occurrence at the last row (highest $H_{1/3}$) by zero values. Then all probabilities in the new wave scatter diagram will be normalized, in such a manner that the sum of the probabilities remains 1.0. This procedure will be repeated for the other rows, until the last wave scatter diagram will contain zeros only.

This means that a range of wave scatter diagrams with decreasing maximum significant wave heights has been created. For ships sailing in an upcoming storm with seas defined by this range of wave scatter diagrams, this procedure means that they are supposed to escape to safe still water at an increasing earlier moment.

4 Calculation Procedure

The computer code SEAWAY of the Delft University of Technology was basis for the creation of a new computer program, named SEAWAY-R, to calculate relative motions, using wave scatter diagrams.

SEAWAY (see Journee (1992, 1996)) is a frequency domain ship motions PC program, based on both the ordinary and the modified strip theory, to calculate among others the wave-induced loads and motions with six degrees of freedom of mono-hull ships and barges in a seaway. When not accounting for interaction effects between the two individual hulls, these calculations can also be carried out for twin-hull ships, such as semi-submersibles or catamarans. The program is suitable for deep and shallow water.
The program requires two separate input data files: hull form data file and a variable input data file. The offsets of the cross sections of the fully loaded ship are input and have to be stored in the hull form data file. At any actual loading of the ship, new offsets will be calculated by the program from these data by the actual amidships draught and trim, given in the variable input data file. A linear transformation of the hull form can be carried out by three independent scale factors. A control program displays the body plan of the ship, as stored in the hull form data file, on the screen and an input-editor can be used to create the input data file.
At choice, the Lewis or the N-parameter close-fit conformal mapping method and the potential theory of Ursell-Tasai can calculate the two-dimensional hydrodynamic deep-water coefficients. Also the 2-D diffraction pulsating source theory of Frank can be used. Shallow water coefficients can be determined with the Lewis conformal mapping method and the potential theory given by Keil.
Special attention is paid to submerged sections and to the surge coefficients. The wave potentials will be defined for the actual water depth. Linear and non-linear roll damping coefficients are determined by the Ikeda method, but they can be input too. The program will carry out the linearisation.
At choice, input spectra and various ideal spectra, such as Bretschneider and JONSWAP spectra can define the uni-directional wave spectra. Either the spectral centroid period T_1 or the zero-upcrossing period T_2 can define these spectra.

This computer code SEAWAY has been rewritten for load line calculation purposes. Several calculation procedures with respect to deck and bow wetness have been included. Journee (1997) has showed the validity of the calculated motions by this program. Also, the rules of the 1966 International Convention on Load Lines (1966 ICLL) have been incorporated in the program SEAWAY-R.

The vertical relative motions between the ship and the water surface are generally the largest at the forward end of the ship. In high waves these motions may be so large that the deck and/or the bow ships water. This occurs most frequently at high ship speeds in head waves although it is not unknown in other conditions.
The effective freeboard in fully dynamic conditions will be different from the results obtained from the geometric freeboard at zero forward speed in still water and the calculated vertical relative motions of a sailing ship in undisturbed waves.

When sailing in still water, sinkage, trim and the ship's wave system will effect the local geometric freeboard. Static swell-up h_s should be taken into account.
Then, the effective freeboard f_e follows from the geometric freeboard f and the static swell-up h_s by:

$$f_e = f - h_s$$

The amplitude s_a of the relative motion of an oscillating ship in undisturbed regular waves can be calculated from the heave, pitch and wave motions. But, an oscillating ship will produce waves and these dynamic phenomena will influence the amplitude of the relative motion.
A dynamic swell-up Δz_a should be taken into account and the actual amplitude of the relative motions becomes:

$$s_a^* = s_a + \Delta z_a$$

Then, shipping of water is defined by:

$$s_a^* > f_e$$

The spectral density of the vertical relative motion is given by:

$$S_{s^*z}(w) = \left(\frac{s_a^*}{z_a} \right)^2 \cdot S_z(w)$$

in which w is the circular wave frequency.

The spectral moments are given by:

$$m_{ns^*} = \int_0^\infty S_{s^*z}(w) \cdot w_e^{\,n} \cdot dw \quad \text{with: } n = 0, 1, 2, \ldots$$

in which w is the frequency of encounter.

When using the Rayleigh distribution, the probability of shipping water is given by:

$$P\left\{ s_a^* > f_e \right\} = e^{\frac{-f_e^2}{2 m_{0s^*}}}$$

The program SEAWAY-R includes methods to obtain the static and dynamic swell-up from the diffracted and radiated waves. However, in the study presented here, the static and dynamic swell-up have not been taken into account.
So, it is assumed in this study:

$$h_s = 0 \text{ and } \Delta z_a = 0$$

For the theoretical determination of the vertical relative motions in head waves at an infinite water depth, the ordinary strip theory has been used here. To minimize computing time during this study, the potential coefficients have been calculated by conformal mapping of the cross sections to the unit circle by means of a Lewis transformation. The differences with other more accurate methods, which are included in the program SEAWAY-R but will take much more computing time, appeared to be very small.
In a sea state defined by $(H_{1/3}, T_2)$, the short term probability of bow deck wetness P_{ST} follows from the bow height H with:

$$P_{ST} = P\{s_a > H\} = e^{\frac{-H^2}{2m_{0s}}}$$

Reversed, for a pre-defined probability of bow deck wetness P_{ST}, the bow height H follows from:

$$H = \sqrt{-2m_{0s} \cdot \ln(P_{ST})}$$

The long term probability of bow deck wetness follows from a multiplication of the short term probability P_{ST} in a certain sea state with the probability $P_{WSD} = P\{H_{1/3}, T_2\} = q_{i,j}$ on the occurrence of this sea state in a certain sailing area during a certain period, obtained by a wave scatter diagram.
The total long-term probability of deck wetness P_{LT} in this sailing area can be found by summing up these individual long-term probabilities:

$$P_{LT} = \sum \{P_{ST} \cdot P_{WSD}\}$$

For the previously defined ships, the freeboards and bow heights have been determined according to the rules of the 1966 ICLL. The table freeboards and the standard bow heights of the 1966 ICLL are presented in Figure 6 as a function of the ship length at 85% of the depth.

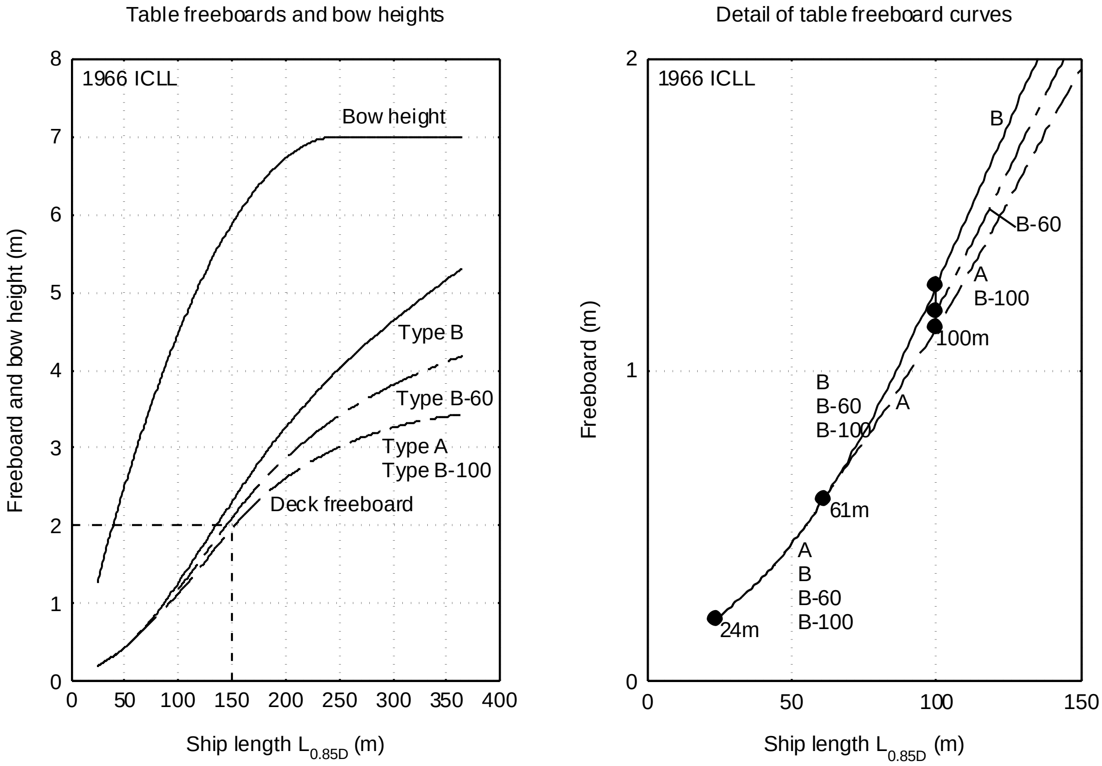

Figure 6 Table Freeboards and Standard Bow Heights of the 1966 ICLL

Corrections on these table freeboards and standard bow heights due to a deviating block coefficient, the dimensions of the superstructures, etc. have been accounted for. Given the required depth D of each ship ($L_{0.85 \cdot D} / D = 0.15$), these 1966 ICLL rules deliver the freeboard F (and from this also the draught d) and the bow height H of the ship.

Then, the long term probability of shipping water at the bow deck (forecastle deck at forward perpendicular) P_{LT} has been calculated from the vertical relative motions of the ship and the long term weather information, obtained from the original wave scatter diagram for coastal areas.

This probability P_{LT} has been kept constant for new calculations with the same ship at a range of increased draughts (or decreased freeboards and bow heights) for the generated series of "reduced" wave scatter diagrams, each characterized by a maximum significant wave height. For each ship, the draught d of the ship has been increased by 50, 60, 66.7, 70 and 80 per cent of the international freeboard F, respectively. It is obvious that for each ship the draught d and the bow height H will be decreased with the same amount.

For each of these draughts, the long term probability of shipping water at the bow deck has been obtained for each "reduced" wave scatter diagram, so as a function of the maximum wave height in the diagrams. Then, the probability P_{LT} delivers the maximum allowable significant wave height at this draught. The principle of the calculation method has been given in Figure 2, already.

5 Results of Computations

Here, the computational results are given for a range of reduced freeboards for each of the three series of ships with a constant block coefficient and a range of ship dimensions. The probabilities of exceeding the bow freeboard, determined by the ICLL 1966 freeboard rules and the Mean Annual Wave Scatter Diagram, are given as a function of the ship length. These probabilities have been kept constant for each combination of ship length, reduced freeboard and allowable maximum wave height.

The allowable maximum wave heights are presented in the figures as a function of the ship length for a range of reduced freeboards.

For three decrease of freeboard factors a and three block coefficients C_B, a survey of the calculated maximum allowable wave heights as a function of the ship length L_{pp} are given in Figure 7, Figure 8 and Figure 9.

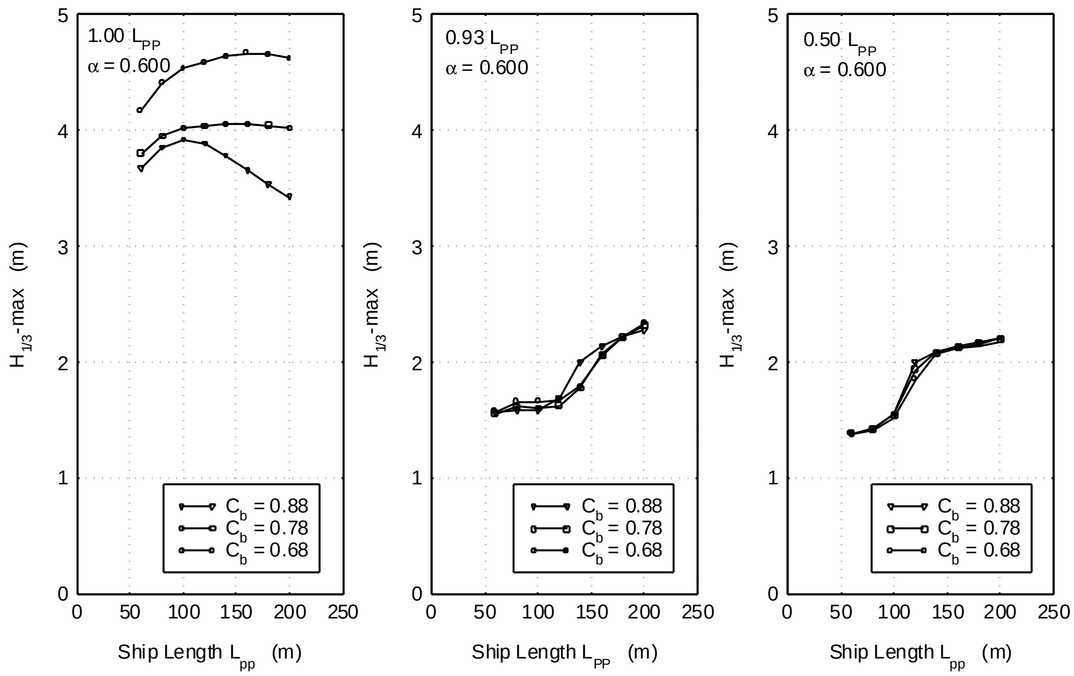

Figure 7 Maximum Allowable Wave Heights for a = 0.600

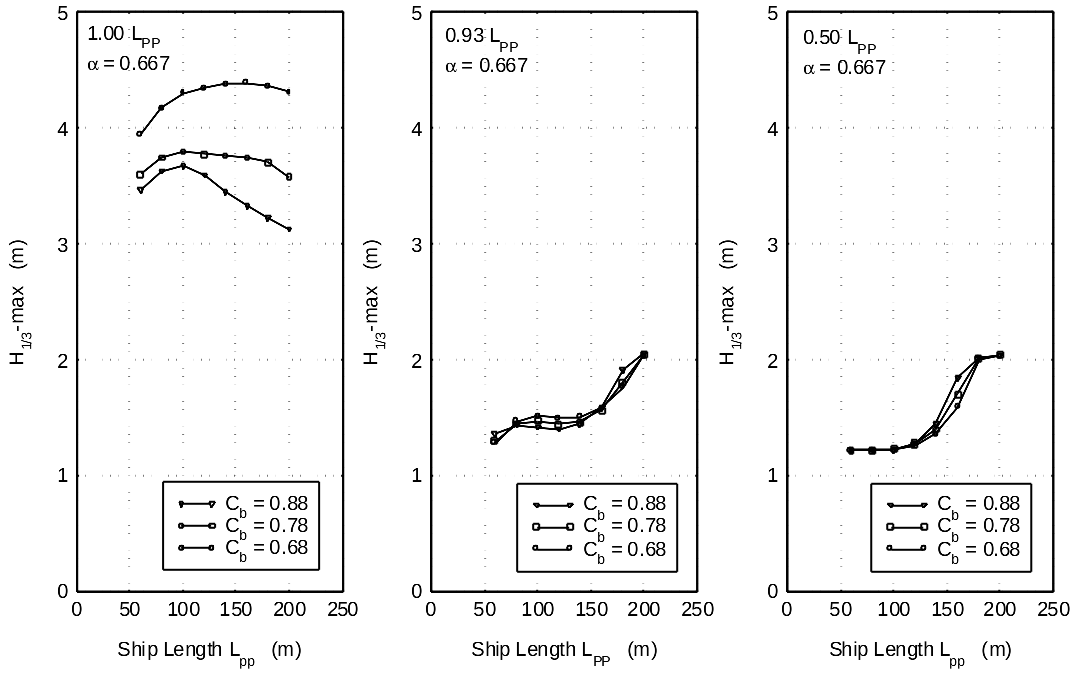

Figure 8 Maximum Allowable Wave Heights for *a* = 0.667

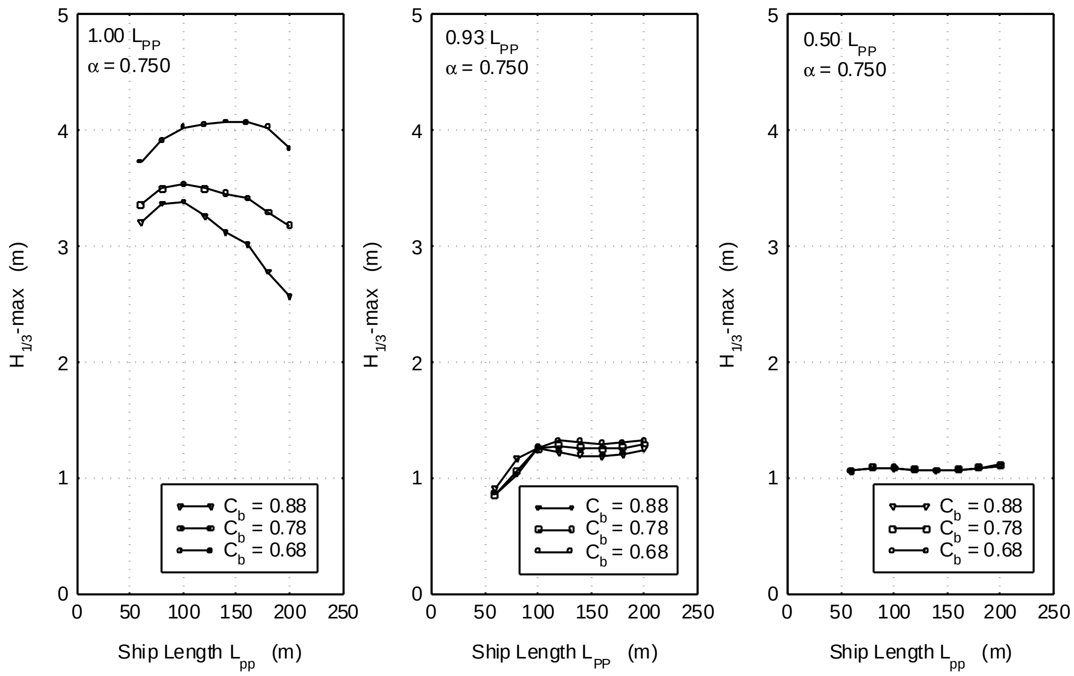

Figure 9 Maximum Allowable Wave Heights for *a* = 0.750

Because of the very restricted size of this study, some critical remarks have to be kept in mind when judging the results presented in Figure 7, Figure 8 and Figure 9:

- The effect of sheer, dimensions of poop and forecastle, L/B ratio and B/d ratio on the maximum allowable wave heights has not been investigated.
- The results in Figure 7, Figure 8 and Figure 9 are based on three wave scatter diagrams, averaged over the whole year. Modified probabilities due to "forced" staying in calm waters during severe weather have not been taken into account. The use of other wave scatter diagrams than the average mean annual diagram for the coastal areas 10, 11 and 17 could also effect the results that are obtained in these figures.
- The effect of the static swell-up has not been taken into account. The height of the bow wave is approximately proportional to the ship speed-squared and to the ship size. This last dependency could influence the results in Figure 7, Figure 8 and Figure 9 somewhat.
- Also, the effect of the dynamic swell-up has not been taken into account. It is expected however, that this effect on the results in Figure 7, Figure 8 and Figure 9 can almost be ignored due the relatives of this study.
- One Froude number is not representative for the entire range of ship lengths. For instance, $Fn = 0.10$ corresponds with 8.6 knots for $L_{pp} = 200$ meter and only with 4.7 knots for $L_{pp} = 60$ meter. The effect of other speeds than those corresponding to this Froude number, other headings than head waves and, as a consequence of other headings, the inclusion of roll motions were not objectives of this study.

6 Addition for ships without a Forecastle

This study has been repeated now for the previously defined ships without a forecastle. The international freeboard, $F_{\text{international}}$, as well as the bow height, $H_{\text{international}}$, are determined by the bow height required by the rules of the of the 1966 International Convention on Load Lines.

In this additional study, the freeboard has been decreased with a factor 2/3, thus $a = 0.667$, and the calculations have been performed at the forward perpendicular of the series of ships. The final results are presented in Figure 10.

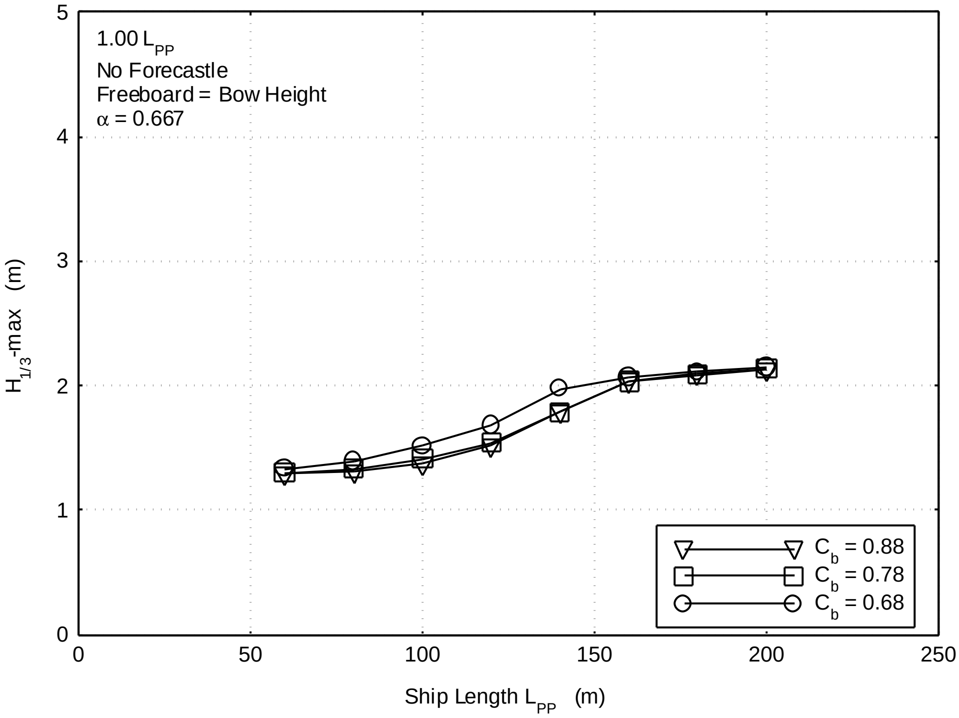

Figure 10 Maximum Allowable Wave Heights (no forecastle ships)

7 References

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