SUPPLEMENT No. 523

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MV ESTONIA Accident Investigation. Numerical predictions of the water inflow to the car deck.

Technical Report VALC174.

VTT Manufacturing Technology.

Espoo 1996.

MV ESTONIA ACCIDENT INVESTIGATION

Numerical prediction of the water inflow to the car deck

CONFIDENTAL

TECHNICAL REPORT VALC174

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Espoo, February 1996

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Projekti/työ - Project identification	Sivuja - Pages	Päiväys - Date	Raportin nro - Report No.
VAL435401	20	12.02.1996	VALC174

Otsikko ja tekijä - Title and author

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Numerical prediction of the water inflow to the car deck

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Päivitys raporttiin nro - Update to report no.	Hyväksynyt - Approved by

Julkisuus - Availability statement
[] B (Julkinen - Public) [x] C (Luottamuksellinen - Confidential) [] C (Salainen - Secret)
Määräpäivä - Until date

Abstrakti, sisällysluettelo, tms. - Abstract, list of contents etc.

ABSTRACT

Water inflow to the car deck of MV Estonia have been simulated in irregular seas at different headings and different forward speeds by applying a non-linear numerical method. Conclusions are based on the present estimate of the sea state, speed and heading at the time of the accident. The numerical predictions indicate that the amount of the water inflow was so great that MV Estonia could not run the ramp slightly open very long without anybody noticing it. It is also clear that the ship could not run the ramp fully open very long in head or oblique seas. Otherwise the turn to the opposite heading would not have been possible. The evaluation of water inflow during the turn is very difficult, because several disturbances may take place. Moreover, the wave-induced motions of the ship near beam seas depend on the heel of the ship and the water inflow is very sensitive for the freeboard.

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1.INTRODUCTION

As a part of the accident investigation water inflow to the car deck of MV Estonia on her accident voyage have been estimated by a numerical method. The method and the results of the predictions are presented in this report. The water inflow simulation is based on the simulation of the wave-induced motions of the vessel in irregular seas. However, seakeeping characteristics of MV Estonia from the point-of-view of wave-induced motions and calculation of the relative motion are discussed in other technical reports VTT VALC53 and VTT VALC106, respectively. An estimate of the sea condition used in the calculations are the same as reported in VTT VALC106.

2. SIMULATION METHOD

The target of the simulation was to determine the velocity of water inflow to the car deck at different time steps and then to integrate the velocity of water inflow with respect to time. The simulation method of water inflow is based on the method presented in a technical report VTT VALC106. In the present method, it is important to know the values of the relative motion at the ramp opening during the simulation. All the other quantities can be calculated, when the variables such as forward speed, heel and bow wave height of the ship together with the dimensions of the ramp opening are known. Only heave and pitch motions of the ship are considered. Thus, the effect of roll on the vertical relative motion at the ramp has been ignored. When determining the motions of the ship, the heel was taken into account by calculating the transfer functions and their phases for the inclined ship. This was done using MOT35-program (McCreight,1976), which is able to handle asymmetric hull shapes.

2.1. THE FORMULAE OF THE WATER INFLOW

Irregular waves and ship motions were simulated as reported in VTT VALC106. The formulae of the elevation of a long-crested wave surface, the wave-induced motions of the ship and the relative motion of the ship are presented by Formulae 1, 4 and 5 of VTT VALC106, respectively. The formula of the water inflow can be divided into three separate parts i.e. water inflow due to wave particles, water inflow due to the static pressure and water inflow due to the ship speed. In the following, these components of the water inflow will be treated more detailed.

<u>**The water inflow due to wave particles**</u>

Velocity potential of the plane waves for deep water, when the situation is considered with respect to the steady moving ship, can be written in the form:

$$\phi = \Sigma \frac{ga_i}{\omega_i} e^{k_i z} \sin(k_i x \cos\mu + k_i y \sin\mu - \omega_{ei} t + \varepsilon_i) \quad , \quad (1)$$

where

a_i = Amplitude of the ith harmonic wave component

ω_i = Circular frequency of the ith harmonic wave component

ω_{ei} = Encounter frequency of the ith harmonic wave component

g = Acceleration due to gravity

k_i = Wave number of the ith wave component

xyz = Cartesian co-ordinate system moving at the mean forward speed of the vessel with origin on the mean free surface defined by z=0. The positive direction of z points upwards and the centre of gravity of the ship is on the z-axis and x-axis points in the direction of the moving ship

μ = Heading of the ship

ε_i = Random phase angle of the ith wave component

The velocity of the wave particles in the direction of the x-axis can be derived by differentiating the velocity potential with respect to x. Thus the velocity of water particles gets the form

$$V_{wp}(t) = \frac{\partial\phi}{\partial x} = \Sigma \omega_i a_i \cos\mu e^{k_i z} \cos(k_i x \cos\mu + k_i y \sin\mu - \omega_{ei} t + \varepsilon_i) \qquad (2)$$

In the linearized wave theory, the free surface is defined as the plane z=0. Using this approximation in (2) and by assuming that the y-coordinate is small, the velocity of water particles gets the form

$$V_{wp}(t) = \Sigma \omega_i a_i \cos\mu \cos(k_i x \cos\mu - \omega_{ei} t + \varepsilon_i) , \qquad (3)$$

Mass inflow of water particles can be calculated from the formula

$$\dot{M}_{wp}(t) = -\rho V_{wp}(t) A(t) , \qquad (4)$$

where

ρ = Density of water

$A(t)$ = Area of the opening.

A(t) can be calculated using the definitions of Fig. 1 from the formula

$$A(t) = \int_0^{Z_r(t)-C} b(\bar{z})d\bar{z} \,. \qquad (5)$$

Thus, the vertical variation of the fluid particle velocity in the wave is disregarded. Formula (5) is valid only when the relative motion $Z_r(t)$ is greater than C, which is the freeboard to the lowest corner of the opening.

The water inflow due to the static pressure

Water velocity due to static pressure can be written in the area of the opening in the form

$$V_{st}(t) = \sqrt{2g(Z_r(t) - \bar{z} - C)} \qquad (6)$$

and the corresponding water inflow in the form

$$\dot{M}_{st}(t) = \rho \int_0^{Z_r(t)-C} b(\bar{z})V_{st}(t)d\bar{z} = \rho \int_0^{Z_r(t)-C} b(\bar{z})\sqrt{2g(Z_r(t) - \bar{z} - C)}d\bar{z} \qquad (7)$$

The water inflow due to the ship speed

Mass inflow of water due to the ship speed can be written in the form

$$\dot{M}_{sp}(t) = \rho \bar{V} A(t) \,, \qquad (8)$$

where

$\bar{V}$ = Ship speed

Total mass of water on the car deck

Total mass of water on the car deck can be obtained by integrating the components of water inflow with respect to time

$$M_A = \int_0^t (\dot{M}_{wp}(t) + \dot{M}_{st}(t) + \dot{M}_{sp}(t))dt \qquad (9)$$

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Besides above mentioned variable dependencies, also heading and heel of the ship are time dependent, if the total sequence of events is considered. Moreover the water inflow is of great deal probabilistic in nature because of irregular waves. Therefore the whole inflow phenomenon is factorized so that the certain variables are considered as constants and the so obtained subphenomena are simulated in the time domain and treated in the probabilistic way. In this way, it is easier to judge the importance of each variable on the calculated result.

3. THE TURNING CIRCLE OF MV ESTONIA

Turning circles of different car and passenger ferries built in the beginning of 80's are reported in Table 1. The length of the ship L, the velocity of the ship during the turn V, the diameter of the turning circle D and the ratio of D/L are shown in the table. Common for these ships is that they have the propulsion system with two propellers and the rudders are situated behind the propellers.

Table 1. Diameters of the turning circle for different car and passenger ferries

	L/[m]	V/[knots]	D/[m]	D/L
Ship 1	127.4	19.5	374	2.9
		18.2	341	2.6
		10.6	416	3.3
Ship 2	166.0	20.0	515	3.1
		20.0	560	3.4
		15.0	480	2.8
		15.0	560	3.4
Ship 3	166.0	20.0	533	3.2
		22.0	557	3.3
Ship 4	121.2	20.6	339	2.8
		21.0	338	2.8
Ship 5	157.3	20.0	481	3.1
		20.0	491	3.1
		15.0	482	3.1
		15.0	505	3.2

As can be seen in Table 1 the diameter of the turning circle D is proportional to the ship length and the ratio of D/L is almost constant for all ships. It is remarkable to notice that the diameter of the turning circle for each ship seems to be independent on the ship speed.

When the average value of D/L is used, the diameter of the turning circle for MV Estonia D=3.1*L=3.1*155 m=480 m and the length of the circle arc during the turn $P=\pi*240$ m =754 m. The duration times of the turn at different speeds are shown in Table 2.

Table 2. The duration times of the turn at different speeds

V/[knots]	T/[min.]
15	1.6
10	2.5
5	4.9
3	8.2

The duration times of the turn in Table 2 can be considered to represent quite rough estimates, because several disturbances may take place during the turn. Such factors of the disturbance are high wind speed, rough sea and heel of the ship, which may slow the turn or help the turning vessel depending on the phase of the turn. It is also probable that the ship speed was not constant during the turn. The duration times of the turn in Table 2 are, however, quite short. Thus, due to the short turning time it seems not possible that very large quantities of water came to the car deck during the turn.

4. RESULTS

Main results of the simulations are curves presenting probabilities at which water inflow exceeds different levels in terms of water in tons per one minute. Figures 2-10 show curves of exceedance probabilities. The exceedance probabilities are plotted on a logarithmic scale while water inflow is on a linear scale.

Water inflow is non-linear with regard to the relative motion at the visor and the statistical distribution of water inflow is not known. Therefore the simulated sequences have been one hour in which time the vessel encountered about 800 waves. Thus all together 60 one minute long samples were obtained during the simulation time and the highest value of water inflow represents an exceedance probability level of about 0.017. The time step of 0.1 s and the significant wave height of 4.0 m were used in each simulation sequence.

The transfer functions of the vessel at different headings and speeds were determined for the heel values of 0°, 22° and 35° which correspond to the cases of 0 ton, 950 tons and 1800 tons water on the car deck, respectively. Effects of these transfer functions on the water inflow are shown in the figures, too.

5. DISCUSSION

Figure 2 shows an exceedance probability of water inflow when the breadth of the opening changes and the other variables are as follows: the significant wave height Hs=4.0 m, the heading of the ship HEAD=150°, the heel of the ship HEEL=0°, the velocity of the ship V=15 knots, the distance from the mean free surface of the water to the lowest corner of the opening C=1.4 m and the bow wave BW=1.0 m. The purpose of the different opening breadths is to simulate the different clearances between the ramp and ship hull. Thus the values of the opening breadth B of 0.5 and 0.1 m correspond to the clearance values of 0.25 m and 0.05 m between the ramp and the ship hull, respectively. As can be seen in Fig. 2 the mass inflow of water is directly proportional to the value of the clearance. At the exceedance probability level of 0.5 the water inflow values of 18 tons/minute and 90 tons/minute are obtained, when the breadth of the opening B is 0.1 and 0.5, respectively.

Figure 3 presents results of the calculations for the speed of 15 knots when the heading and the heel of the ship are changing. The change in the heel has also an effect on the variable C so that for the heel value of 35° the variable C gets even a negative value i.e. the lowest corner of the opening is below the mean free surface of water. Here the freeboard C has been reduced by 1 m due to the bow wave. The effect of the bow wave on the freeboard in this dynamic case is difficult to estimate. This is unfortunate since the freeboard has a very significant effect on the water inflow. The bow wave height has been estimated by numerical predictions of the SHIPFLOW-program. The effect of the open ramp laying on the forepeak deck on the water inflow has not been considered. The mass inflow of water seems to be larger in the bow seas (HEAD=150°) than in the head seas (HEAD=180°). This is probably due to the larger wave-induced motions of the ship in bow seas. The mass inflow of water with the heel value of 22° is only slightly greater than in the case the ship floating upright although the freeboard C is considerable smaller in the former case. The mass inflow of water is largest in the case where the heel angle of the ship is 35°. This case is perhaps irrelevant, because the main engines of the ship were hardly functioning with so great value of the heel.

The effects of the transfer functions on water inflow with different values of the heel are investigated in Figure 4. The water inflow was calculated in head seas when the velocity of

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the ship V=15 knots and the effect of the heel on the freeboard C was not taken into account i.e. it is constant. Only the transfer functions and their phases were changed and in this way the influence of the wave-induced motions on the mass inflow of water was obtained. C=1.4 m was used in the predictions. The slowest inflow of water was obtained with the transfer functions corresponding to the heel value of 22° while the wave-induced motions at the opening are largest when the transfer functions of the heel value 35° are used. An exceedance probability curve of water inflow is between these two cases when transfer functions of the upright ship are employed. The exceedance probability curves for the upright ship are almost identical in the cases when the transfer functions obtained from SCORES- and MOT35-programs are used. The general trend of the wave-induced motions can be noticed in Fig. 4: the wave-induced motions decrease when the ship begins to incline and after a certain value of the heel the wave-induced motions of the ship begin dramatically to increase. The water plane area of the ship seems to behave vice versa: it firstly increases and secondly after a certain value of the heel it decreases when the ship is gradually inclining.

Figure 5 shows the results of the calculations in head seas when the significant wave height is 4.0 m and the velocity of the ship 10 knots. The exceedance probability curves are plotted for three different values of the heel angle. The curves for the two lowest values of heel are almost one on the other. The greatest values of water inflow were obtained for the heel angle of 35°. Effects of the ship velocity on water inflow can be seen when Figures 3 and 5 are compared. The trends of the probability curves are quite similar although amounts of water inflow are smaller when the ship speed is 10 knots. This is partly due to the smaller bow wave. The similar conclusions can be made when Figures 5 and 6 are compared with each other. Figure 6 shows the case where the ship is moving in head seas at the velocity of 5 knots.

Figures 7, 8 and 9 represent the results of the calculations when the heading of the ship is 110° and speeds of the ship are 10 knots, 5 knots and 0 knot, respectively. Because of the symmetry the curves in the figures correspond to the case of the 250° heading, too. The effect of roll motion on the vertical relative motion at the ramp opening has not been considered. When the vessel had forward speed the roll damping fins reduced roll motion and later it seems on the basis of witness accounts that the roll motion was not very significant. Due to the relatively small width of the ramp opening the vertical motion of the ramp corner due to roll is not very large. The heel value of 22° gives the smallest and the heel value of 35° the greatest values of the water inflow. The exceedance probability curve for the ship without heel is located between the above mentioned cases. The ship speed seems to have a very significant effect on the water inflow.

Figure 9 shows also results of a comparison when the ship speed is 0 knot, the heel angle is 35° and the freeboard C is changing. The freeboard C has really a significant effect on the

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water inflow. The changes of the water inflow in this case are only due to the water inflow caused by the static pressure.

Figure 10 shows the exceedance probability curves in the following seas for two speed values of the ship upright.

The numerical predictions show that if the ramp is fully open the water flow into the car deck at 15 knots speed in head or oblique seas with the significant wave height of 4 m is rapid. The water inflow easily exceeds 500 tons in one minute and flow rates of about 2000 ton per minute seem possible if the ship has a heel angle of 35°. Forward speed has a strong effect on the water inflow which drops to about 300 tons/minute in head seas at 10 knots speed when the heel angle is less than 22°. In this case there is a chance of 1 to 10 that the flow rate exceeds 400 tons/minute, i.e. once in ten minutes. At a heel angle of 35°, the inflow may exceed 800 tons/minute at a probability of 50 % in head seas at 10 knots speed. In the following seas with 4 m significant wave height for the ship upright at 5 knots speed the inflow of water exceeds 50 tons/minute at a probability of about 30 % and 100 tons/minute at a probability of 20 %.

Because the phenomenon of the water inflow is so complicated and unstable, it is impossible to exactly simulate the sequence of the events on the basis of the water inflow calculations only. Also stability calculations (Report VTT VALC110) and interpretations of the witness accounts are needed when the sequence of the events is considered.

6. CONCLUSIONS

The water inflow to the car deck of MV Estonia has been simulated for different headings, heel angles and speeds of the vessel by a numerical method. Each simulation sequence took one hour and an exceedance probability curve of the water inflow rate was determined for each case. Only heave and pitch motions of the ship were considered when the relative motion at the ramp opening was defined in different time steps of the simulation.

Because the phenomenon of the water inflow is so complicated and unstable, it is impossible to exactly simulate the sequence of the events on the basis of the water inflow calculations only. Also stability calculations of the ship and interpretations of the witness accounts are needed when the sequence of the events is considered. However, some conclusions can be made on the basis of the water inflow calculations.

MV Estonia run some time in oblique seas at about 15 knots speed so that the visor pressed the ramp which was slightly open and water flowed to the car deck through the narrow gaps at the sides of the ramp. If the width of the openings on both sides in total was 0.1 m or 0.5 m, the inflow of water to the car deck may have been near 20 tons/minute or about 80 tons/minute, respectively. The amount of the water inflow was so great that MV Estonia could not run the ramp slightly open very long without anybody noticing it.

The numerical predictions show that if the ramp is fully open the flow of water to the car deck at 15 knots speed in head or oblique seas with the significant wave height of 4 m is rapid. The water inflow easily exceeds 500 tons or even more in one minute. The ship could not run the ramp fully open very long in head and oblique seas. Otherwise the turn to the opposite heading would not have been possible.

The turn to the opposite heading at the speed of 10 knots takes about 2.5 minutes. The evaluation of the water inflow during the turn is very difficult, because several disturbances may take place. Such factors of the disturbance are high wind speed, rough sea and heel of the ship. It is also probable that the ship speed was not constant during the turn. Moreover, the wave induced motions of the ship (i.e. the water inflow) near beam seas depend on the heel of the ship and the water inflow is very sensitive for the freeboard.

For the ship floating upright, the water inflow may exceed 30 tons/minute at a probability of 10 % in the following seas at 0 knot speed. Forward speed of the ship has a strong effect on the water inflow.

7. REFERENCES

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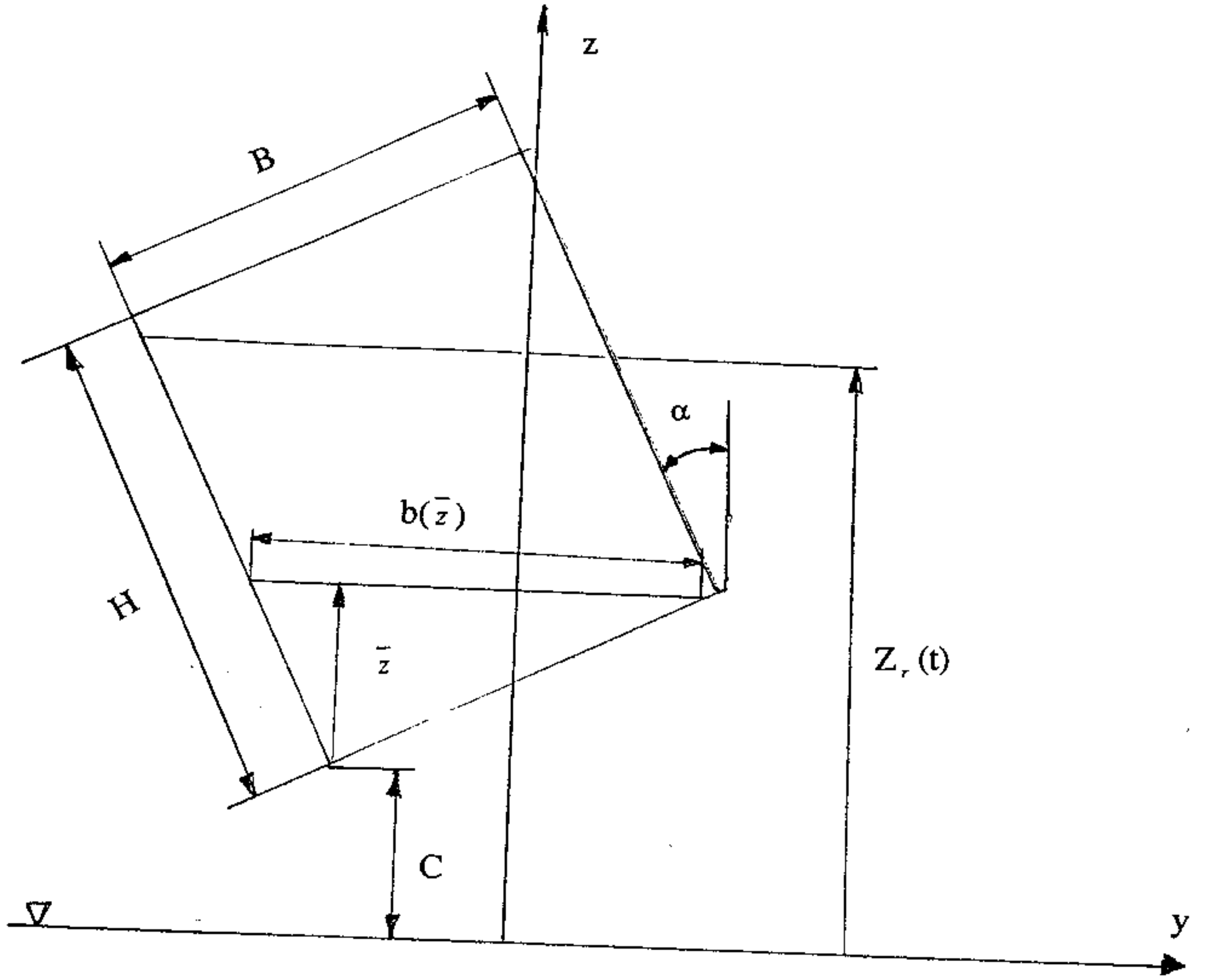

B = Breadth of the ramp opening
H = Height of the ramp opening
C = Distance from the free surface of water to the lowest corner of the opening
$\bar{z}$ = Coordinate from the lowest corner of the opening
b($\bar{z}$) = Local breadth of the opening parallel to the free surface of water
Z_r (t) = Relative motion of the ship at the opening
α = Heel of the ship

Fig. 1. Geometric definitions of the ramp opening used in the calculations

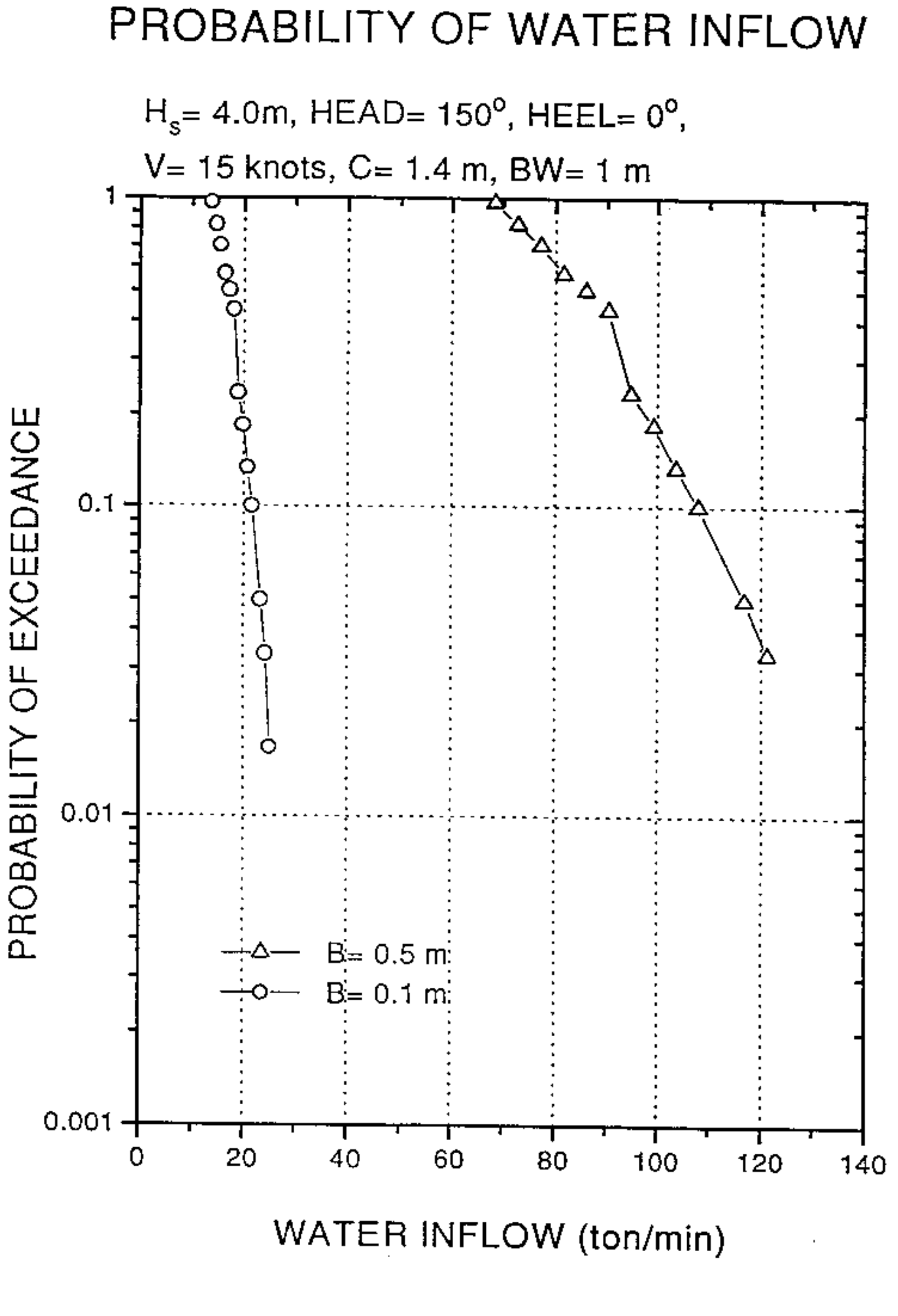

Fig. 2. Water inflow to the car deck in the bow oblique seas with Hs = 4.0 m

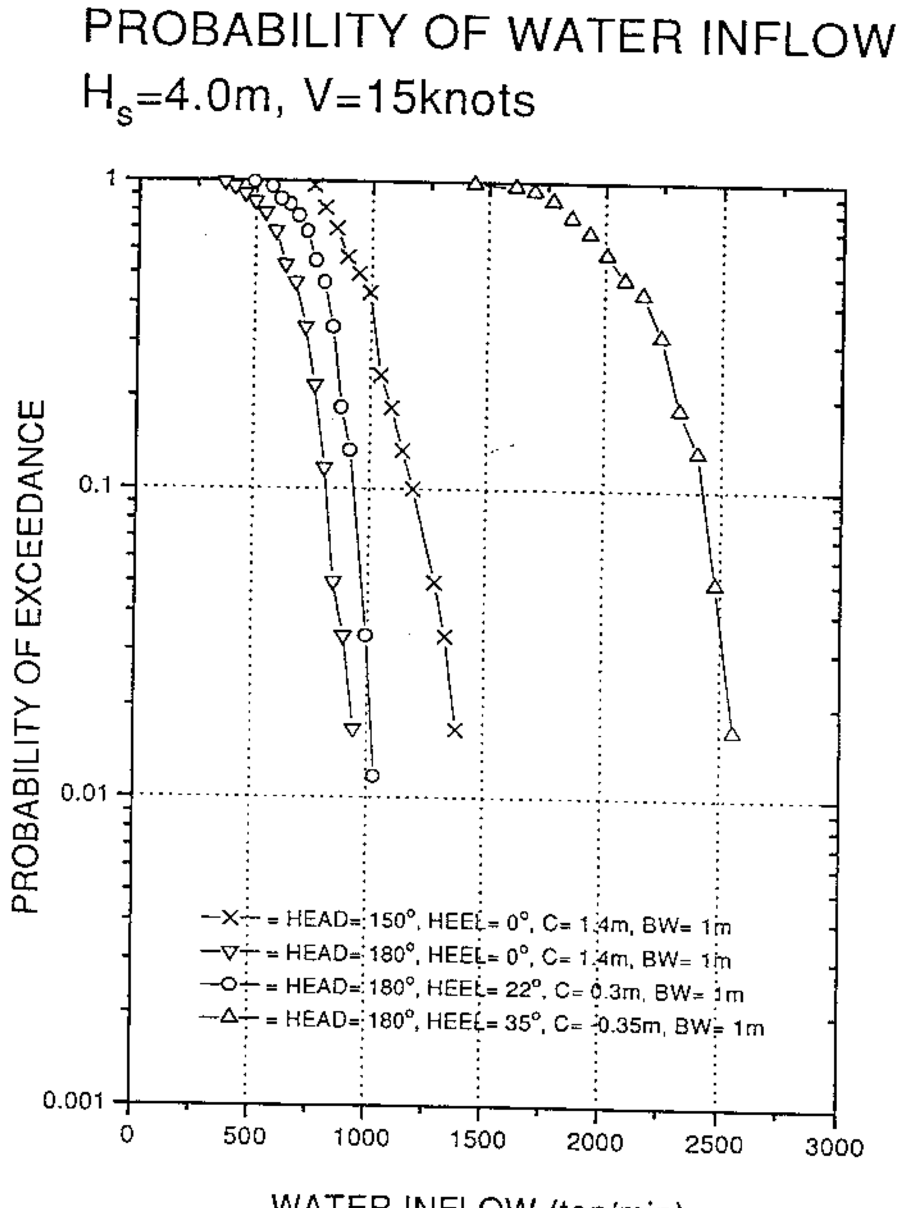

Fig. 3. Water inflow to the car deck in the oblique and head seas

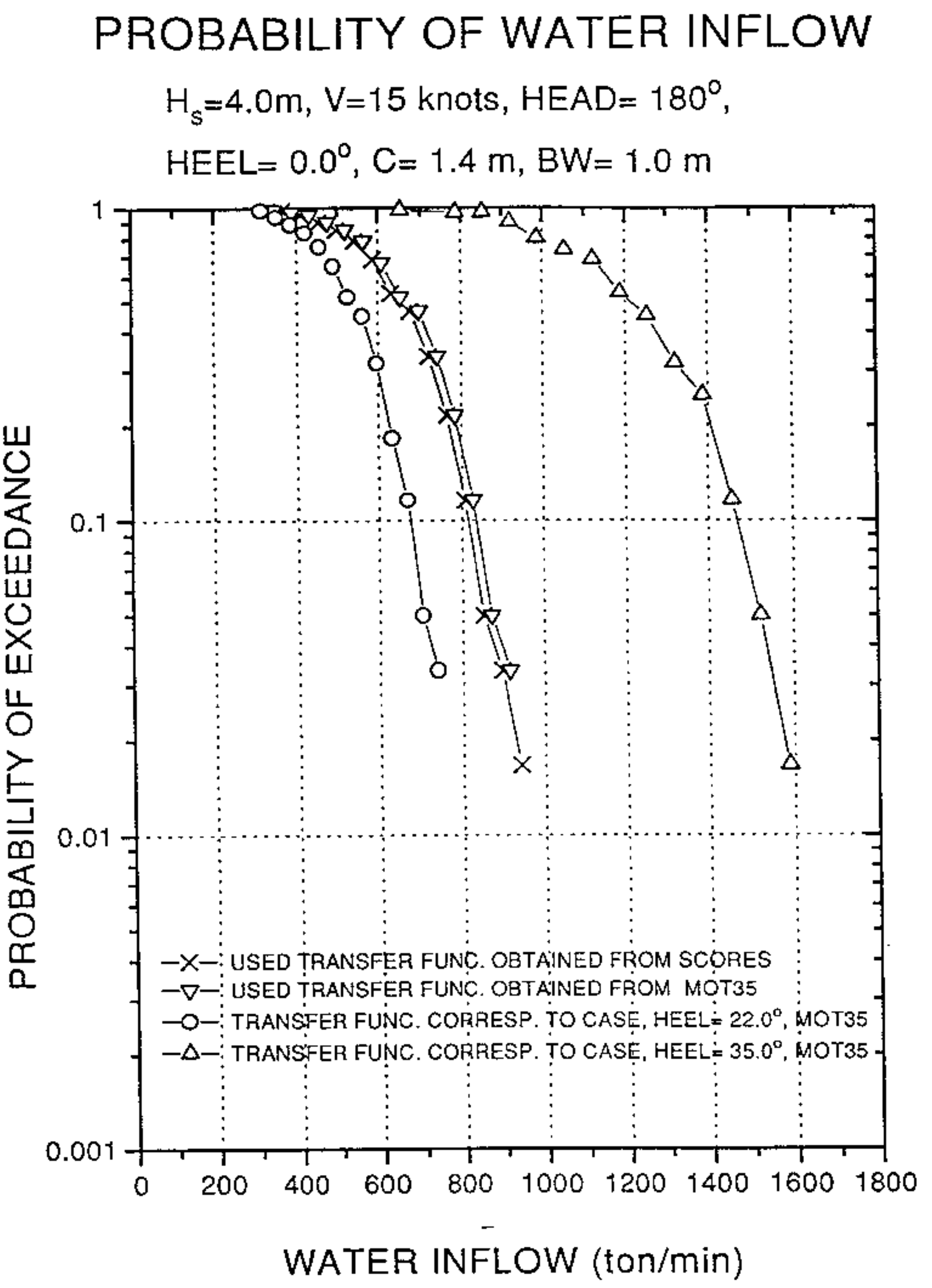

Fig. 4. Water inflow to the car deck calculated with different kinds of the transfer functions.

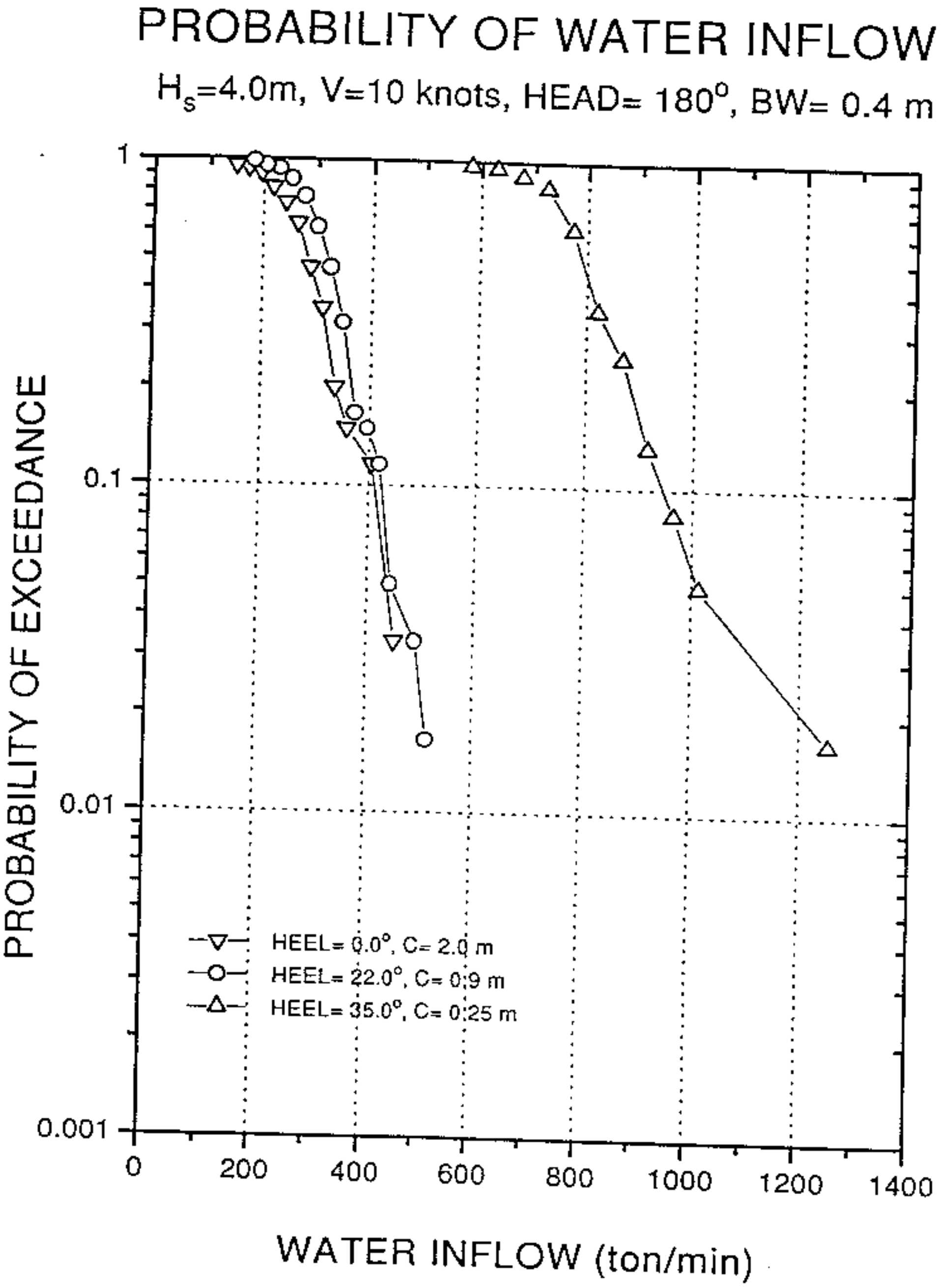

Fig. 5. Water inflow to the car deck in the head seas

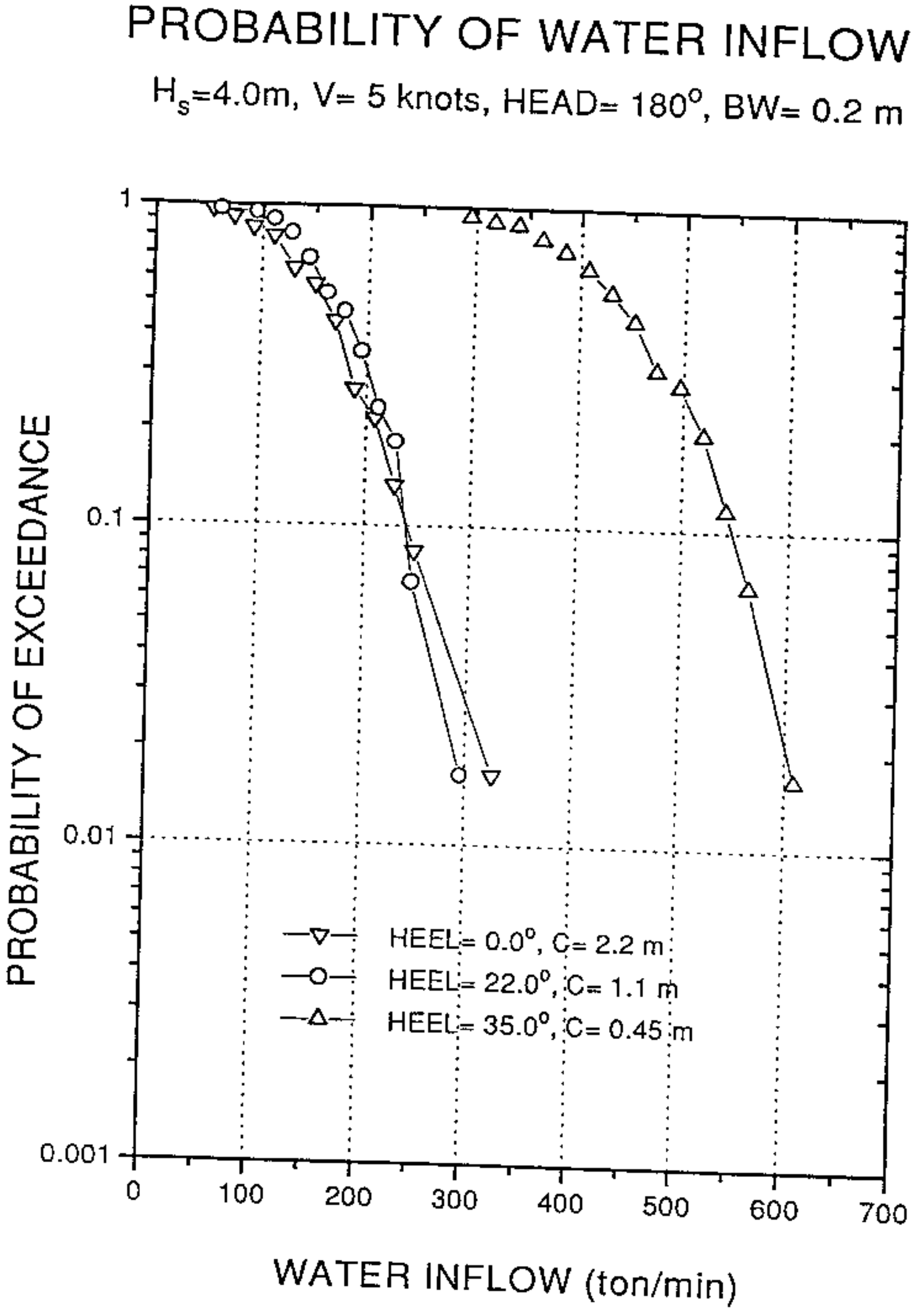

Fig. 6. Water inflow to the car deck in the head seas

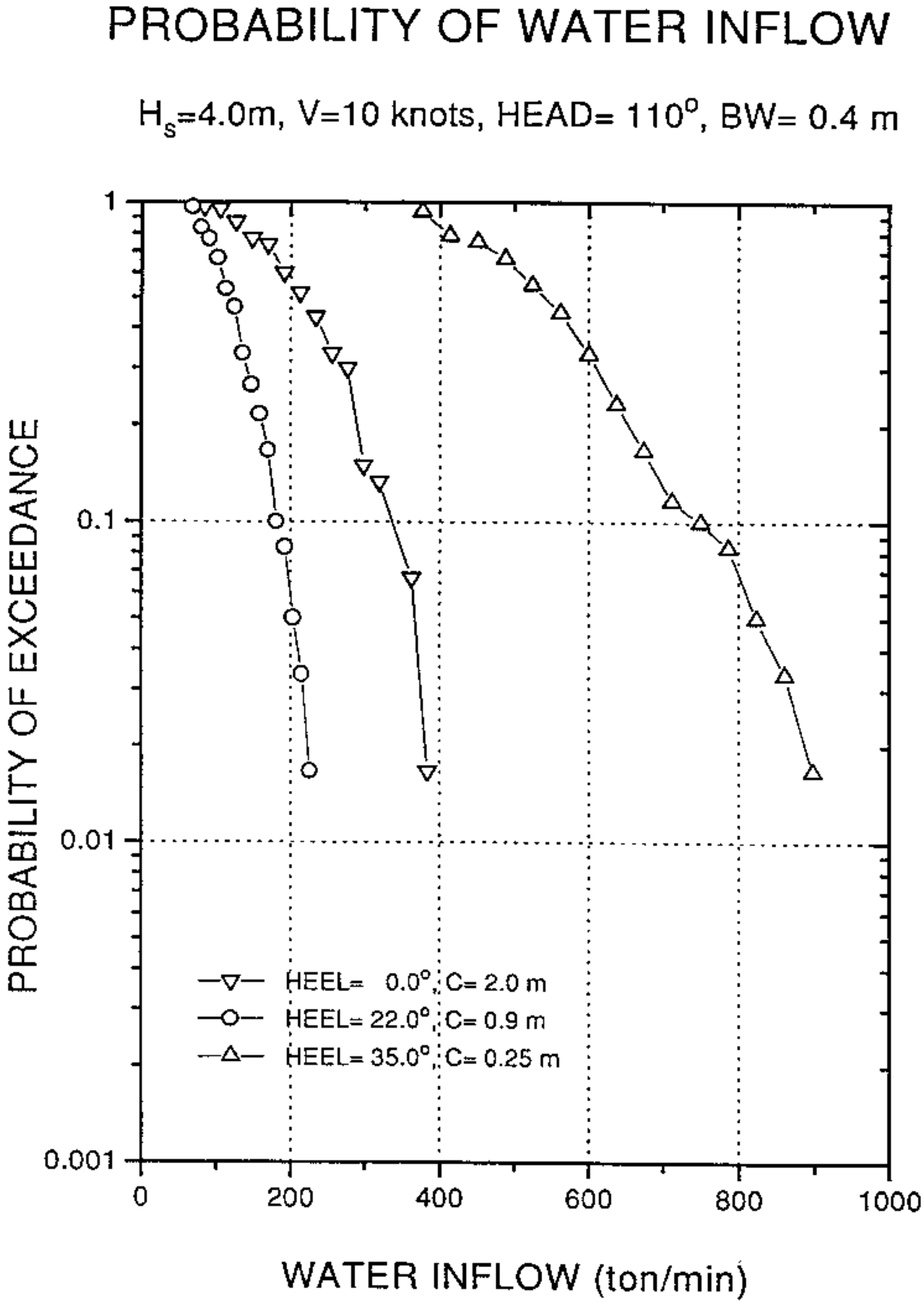

Fig. 7. Water inflow to the car deck in the beam seas

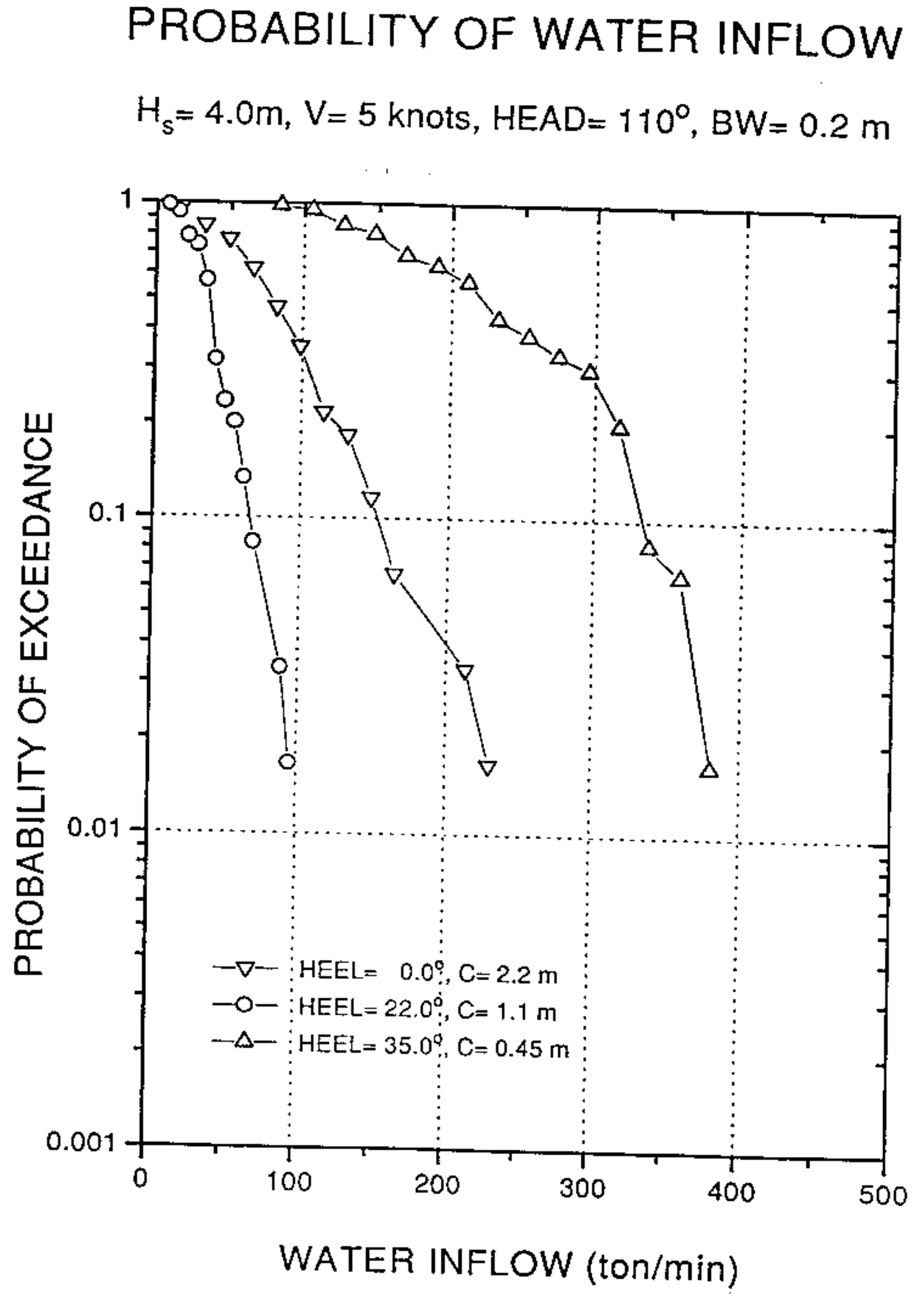

Fig. 8. Water inflow to the car deck in the beam seas

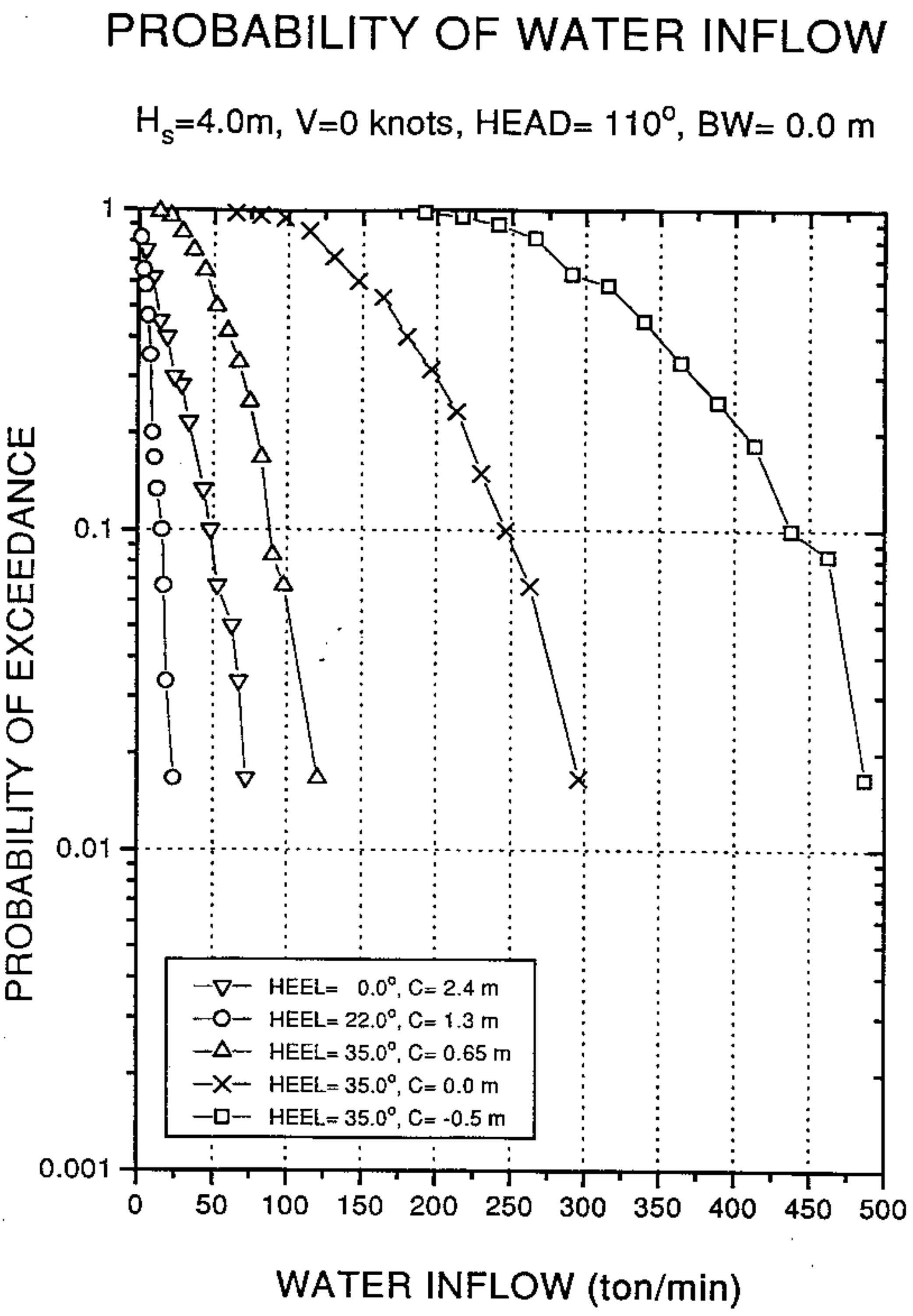

Fig. 9. Water inflow to the car deck in the beam seas

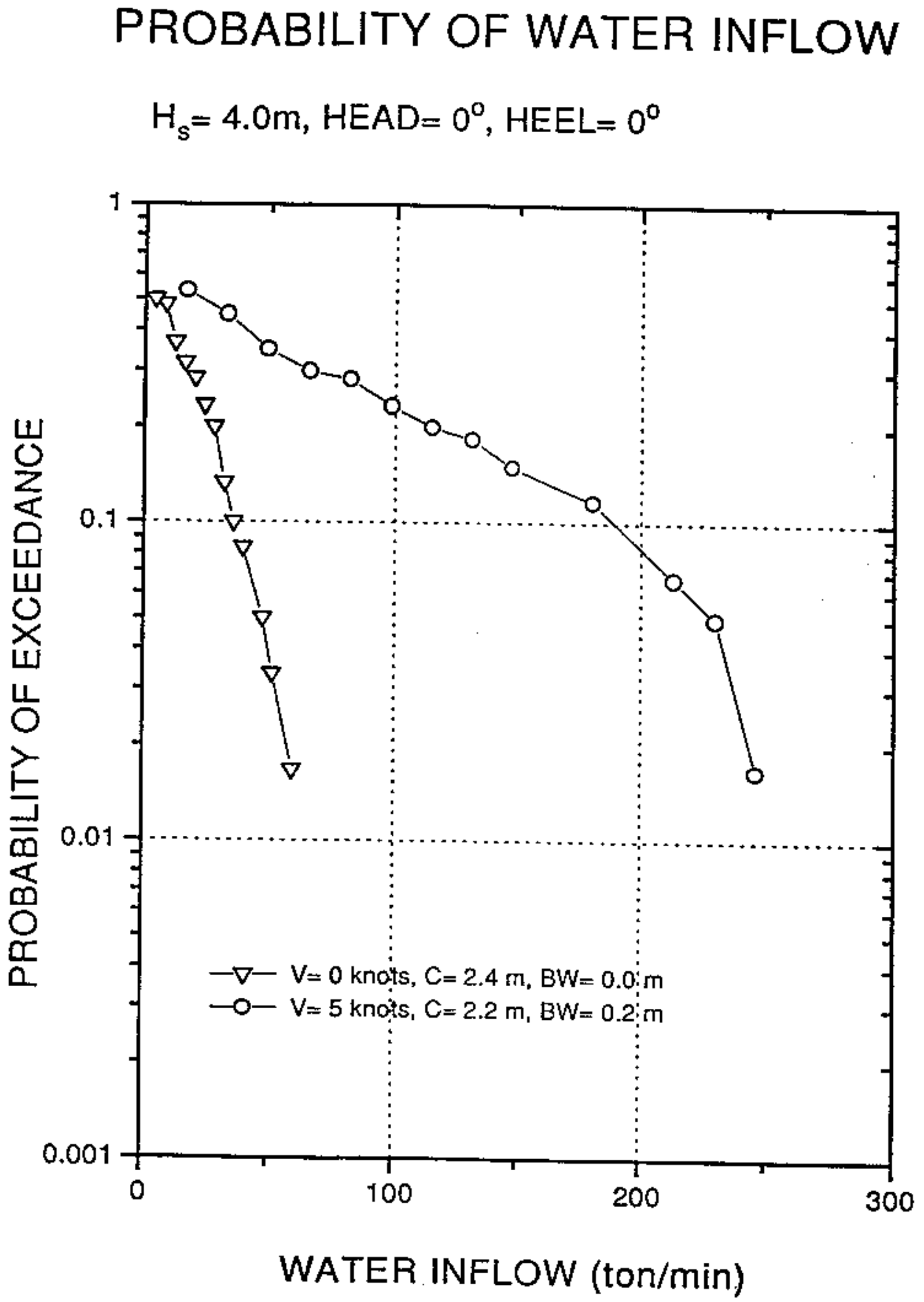

Fig. 10. Water inflow to the car deck in the following seas