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MV ESTONIA ACCIDENT INVESTIGATION

Stability calculations

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Stability calculations

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Abstract

The static and dynamic stability of MV Estonia were calculated. The current most accurate estimates of the real loading condition in the night of accident was used in the calculations. This report replaces the technical report no. VALC110 released in December 1995 with the same title. Some additions and amendments have been made to the previous version.

In the calculation case where the side of the ship effectively contributes to the righting moment, the static heel angles were 23, 39 and 49 degrees when there was respectively 1000, 2000 and 3000 tons of water on the cardeck. When the side above the 4th deck is not included in the calculations, the ship capsizes with more than 2000 tons of water on the cardeck. The lower corner of the bow ramp descended gradually near the calm water level. When there was about 2000 tons of water on the cardeck, the freeboard at the ramp corner was 0.4 m. As more water flooded in the freeboard remained almost constant until the amount of water was about 3500 ton after which the ramp corner began to sink reaching finally the calm water level.

The effect of cargo shifting on static and dynamic stability was investigated. The static heel angles in the case of cargo not shifted were about 0, 10 and 20 degrees when there was 0, 400 and 1000 ton water on cardeck. In the case of cargo shifted an unrealistically large displacement, the corresponding heel angles were about 10, 20 and 30 degrees.

The vessel was built to satisfy the two compartment stability regulations according to the 1974 Solas Convention. The stability was checked also according to the alternative regulations of IMO Resolution A.265 on subdivision and stability of passenger ships. Neither the metacentric height nor subdivision index of MV Estonia meet the requirements of A.265.

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1 INTRODUCTION

The static and dynamic stability of MV Estonia have been calculated using the current most accurate estimates of the real loading condition in the night of accident. This report replaces the technical report no. VALC110 released in December 1995 with the same title. Some additions and amendments have been made to the previous version.

The calculations of static righting arm h_ϕ or GZ and dynamic stability in terms of area below the static stability curve were carried out for cases with different amounts of water on the cardeck. The static and dynamic heel angles are presented as functions of water weight on cardeck. The calculations were first made assuming that the side above the 4th deck (roof of the cardeck) is included i.e. the whole hull volume above the 4th deck is effective and contributes to righting moment. The same calculations were then made for the case in which the side above the 4th deck is not included representing situation where water can freely flow inside the hull above the 4th deck. The static heel angle, draught and trim were calculated also for the case where the hull side between 4th and 6th decks at the aft part of the ship was not included. This corresponds an assumed condition that the large restaurant windows on decks 4 and 5 broke as they sank under the water being the first openings besides the ramp through which water flooded inside the superstructure.

Also the effect of cargo shifting on the cardeck was investigated. The static and dynamic stability were compared to the case where the cargo was assumed not shifted. The calculations were made with the amount of water on cardeck as parameter. The side above the 4th deck was not included in these calculations.

The damage analysis was accomplished for MV Estonia. The static stability was calculated for cases where water tight hull volume above the cardeck gradually decreases as the ship heels and more water flows inside through openings. Also the freeboard of some critical openings was calculated as function of water weight on the cardeck.

The vessel was built to satisfy the two compartment stability regulations according to the 1974 Solas Convention. The imaginary damage in the 1974 SOLAS regulations is limited to the compartments under the cardeck. The kind of damage which occurred to MV Estonia where water enters the cardeck is not taken into account in these regulations. The stability was also checked according to the IMO Resolution A.265. The overall GM-requirement in accordance with regulation 5 and the subdivision index of regulation 6 were calculated according to the A.265 regulations on subdivision and stability of passenger ships.

2 COMPUTATION METHOD

The program package NAPA was used in the stability calculations and damage analysis. NAPA (the Naval Architectural Package) is a computer-aided engineering system used in the basic design work for a ship project and in naval architectural calculations. The package comprises the definition of hull form, superstructures, bulkheads, decks and compartments. Besides stability and damage analysis NAPA can be used when calculating hydrostatics, tank volumes, capacities, loading conditions, inclining test results etc.

The NAPA program package is used world wide by shipyards, consultants, navies etc. In Finland, NAPA has been a long time the standard method by which the shipyards have made hydrostatic calculations.

The hull form of MV Estonia was defined in the NAPA program already before the accident for a new stability booklet. This hull form definition has been used in the stability calculations which were actually made by Mr Junnila at Ship Consulting Ltd. in Turku. Mr Junnila had also made the former valid stability booklet of the vessel dating from 20 January 1991. The stability booklet was made after an inclination test made 11 January 1991 at Masa Yards in Turku. The present stability calculations are based on the results of the same inclination tests.

The report containing the damage stability calculations according to the IMO MSC/Circ. 574 was also made by Mr. Junnila at Ship Consulting Ltd. in July 1994. These calculations are part of the IMO Resolution MSC. 26(60) which came into force at 1. October 1994.

3 LOADING CONDITION

The main particulars of MV ESTONIA are presented in Table 3.1. The lines drawing is shown in Figure 3.1. The lines drawing does not show the ducktail attached to the transom which, however, is included in the stability calculations.

Table 3.1 Main particulars of MV Estonia.

	Symbol	Dimension	Actual values	Actual values without visor	Preliminary values
Length over all	L_{oa}	m	155.4	150.7	155.4
Waterline length	L_{wl}	m	144.8	144.8	144.8
Length btw. perp.	L_{pp}	m	137.4	137.4	137.4
Beam mld, A deck	B	m	24.2	24.2	24.2
Waterline beam	B_{wl}	m	23.6	23.6	23.6
Draught mean	T	m	5.389	5.356	5.500
Draught at aft. perp.	T_a	m	5.607	5.665	5.750
Draught at forw. perp.	T_f	m	5.172	5.047	5.250
Trim, positive by stern		m	0.435	0.618	0.500
Displacement	∇	m^3	11931	11872	12243
Volume of whole hull		m^3	74730	-	74730
Length of cardeck		m	136.0	136.0	136.0
Breadth of cardeck		m	24.20	24.20	24.20
Volume of cardeck		m^3	18543	18543	18543
Longitudinal CG from aft. perp.	LCG	m	63.85	63.48	63.70
Vertical CG from keel	KG	m	10.62	10.62	10.50
Transverse metacentric height	GM_T	m	1.17	1.26	1.28

The calculations of static and dynamic stability for the case with side above the 4th deck is not included as well as the investigation of cargo shifting effects were carried out in such an early stage that only the preliminary estimates of main particulars were available. In all the other cases, the actual values were used. They are also estimates but based on more accurate information of vessel's loading condition. The difference between the actual and the preliminary loading conditiohs has some effects on the results mainly due to the change of transverse metacentric height GM_T.

4 RESULTS

4.1 Definitions

Static stability is expressed in terms of static righting arm h_ϕ or GZ as a function of heel angle. The righting arm is defined as the horizontal distance from the centre of gravity G to the vertical line through the centre of buoyancy B. The definitions are shown in Figure 4.1. The static stability is often illustrated as a curve of righting arm vs. heel angle. A typical static stability curve is presented in Figure 4.2. The heel angle at which the curve first intersects the horizontal axis represents equilibrium position when the righting and heeling moments are equal. This angle is referred as static heel angle.

Dynamic stability is the integral of static stability i.e. the area under the righting arm curve. This integral is denoted as e_ϕ and it is expressed as a function of heel angle. It is proportional to the work needed to heel the ship to a certain angle. The heel angle at which the dynamic stability curve intersects the horizontal axis (dynamic heel angle) represents the angle to which the ship heels from equilibrium position after a sudden heeling moment. At that heel angle the work done by heeling moment equals the work done by righting moment. The roll damping is assumed to have no effect on the dynamic heel angle though in reality some damping exist.

4.2 Static and dynamic stability (side included)

The static and dynamic stability for the case with side above the 4th deck included were calculated with 0, 200, 400, 600, 1000, 1400, 2000, 3000 and 4000 tons of water on cardeck. The draught and trim of the ship and the water level on the cardeck assuming neither heel nor trim angle, are shown in Figure 4.3 as functions of water amount on the cardeck. The effect of cargo on water level was not taken into account. Draught is defined at midships as in Figure 4.1. Trim is the difference of draughts at after and fore perpendiculars. In Figure 4.4 the static (solid line) and dynamic heel angles are shown as functions of water amount on cardeck. The actual values of ship main particulars excluding the visor were used. The h_ϕ and e_ϕ values as functions of heel angle are shown in Figures 4.5 and 4.6, respectively. The static heel angle and the inflooded water for four cases is visualised in Figure 4.7 corresponding 1000, 2000, 3000 and 4000 ton water on cardeck. The frames drawn in each case are #6, #80.5 and #156 with x-coordinates of 3.6, 69.0 and 134.8 m from AP, respectively. These drawings as well as the h_ϕ and e_ϕ values were calculated using the actual values with the visor but the influence of the visor on the results is insignificant.

4.3 Static and dynamic stability (side not included)

The stability for the case with side above the 4th deck not included was calculated with 0, 200, 400, 600, 1000, 1400 and 2000 tons of water on cardeck. The h_ϕ and e_ϕ values as functions of heel angle are presented in Figures 4.8 and 4.9, respectively. The static and dynamic heel angles as functions of water amount on cardeck are shown in Figure 4.10 where the last dynamic heel angle corresponding to 1350 ton water is interpolated using the adjacent values. The preliminary values of ship main particulars were used.

Assuming that some of the large windows on the 4th and 5th deck broke being the first openings through which the water flooded on these decks, a damage case where a large space between the 4th and 6th deck in the aft part of the ship was excluded from the watertight hull volume was also analysed. On the 4th deck, the hull volume from the aft bulkhead to the cabin department, i.e. to the frame no. 44, was disregarded. On the 5th deck, the disregarded space extended from the aft bulkhead to the frame V just aft from the main stairway. The static heel angle in the case when these spaces do not contribute any more to the stability is shown in Figure 4.4 (dotted line). The draught and trim compared to the intact hull case are shown in Figure 4.11. These calculations were done using the actual values of ship main particulars but without the visor.

4.4 Effect of cargo shifting

The h_ϕ and e_ϕ values for the case where the cargo on the cardeck was assumed to be shifted were calculated in cases with 0, 400 and 1000 tons water on the cardeck. The side above the cardeck was not included in the righting moment calculations. The weight of cargo in both sides of the cardeck was 300 tons. The transverse locations of the centre of gravity for shifted cargo were conservatively estimated as 11.0 m on starboard side and -3.0 m on port side measured from ship centreline. These values are somewhat conservative because in reality the cargo could not move that much. It has been estimated that during the MV Estonia accident the cargo was able to move only about 1 m sideways. The static and dynamic heel angles are shown in Figure 4.12. The h_ϕ and e_ϕ values together with the corresponding results of unshifted case are presented as functions of heel angle in Figures 4.13 and 4.14, respectively. The preliminary values of ship main particulars were used.

4.5 Damage analysis

The freeboard from the calm water level to selected openings through which the progressive flooding may have started was predicted for different amounts of water on the cardeck. The openings considered were the door to foredeck from 5th deck aft, large side windows aft on 4th and 5th deck, a weathertight door to foredeck and the lower corner of the ramp opening. In addition, there were ventilation fans on the 4th deck along the front bulkhead, under the weathertight door. Similar fans were near to the side on the 4th deck aft. Water had access to the cardeck through these fans if they were not closed which is probable. A summary of the critical openings is given in Table 4.1.

Table 4.1 Critical openings.

Opening	Deck/Height from baseline (m)	Dist. from after perp. (m)	Transv. dist. from CL (m)	Area (m^2)	Number on SB side
Door to cafeteria aft	5th/16.2	2.4	9.7	3	1
Large side windows aft	4th/13.8	3.6	12.1	0.9	15
Large side window aft	5th/16.7	3.6	12.1	0.9	37
Door to foredeck	5th/16.2	123.6	8.4	1.5	1
Ramp opening (corner)	3rd/7.65	134.8	2.75	30	1
Fans to CD on aft deck	4th/14.2	-3.6	10.9	0.8	4
Fans to CD on fore deck	4th/14.2	124.3	10.9	0.8	4

The calculated freeboard values at the first five openings as functions of water on cardeck are drawn in Figure 4.15. It shows that the first openings which go under the calm water level are the side windows on the 4th deck. This occurs when there is about 2000 tons of water on the cardeck and the heel angle is about 40 degrees. At this stage, the lowest corner of the ramp opening is about 0.4 m above the calm water surface and it remains slightly above the water level until there is over 5000 tons of water on the cardeck.

Though it is impossible to predict how the flooding of the vessel hull and the superstructure developed, some simplified flooding cases have been analysed. The h_ϕ and e_ϕ values as functions of heel angle for different damage stages are presented in Figures 4.16 and 4.17, respectively. The static stability was calculated for cases where watertight hull volume above the cardeck gradually decreases as the ship heels and more water flows inside through openings. The notation of first damage stage 'cardeck out' in the figures means that water can flood in to the cardeck through the lower corner of the opened bow ramp. The second stage 'cardeck & decks 5-6 out' means that water can flow in also to the 5th deck through the openings on that deck with the result that the hull volume between decks 5 and 6 does not contribute any more to the righting moment. In the next stage 'cardeck & decks 4-6 out' water has flowed down also between decks 4 and 5. After this stage openings on the upper decks gradually remain under the water level representing the last three damage stages. The actual values of ship main particulars including the visor have been used.

The allowed trim/draught combinations with regard to three stability criteria of 1974 Solas Convention have also been calculated. The criteria which the ship has to meet in the final flooded condition are:

- minimum GM = 0.05 m
- maximum heel angle = 12 degrees
- marginline not submerged

The allowed and not allowed trim/draught combinations for MV Estonia are shown in Figure 4.18. In Figure 4.19 the equilibrium floating position of the ship is shown for the case when the cardeck and decks between 4-6 are out. The cross-section is at the longitudinal coordinate x=79.4 m from the after perpendicular.

4.6 Stability check according to IMO Resolution A.265

The results of stability check according to IMO Resolution A.265 are presented in NAPA output format in Tables 4.2 and 4.3. The former table shows the minimum required intact GM in the final stage of flooding for the draughts of 5.02, 5.28 and 5.42 m and stern trim of 0.6 m in accordance with regulation 5 of A.265.

Regulation 5 states that in the final stage of flooding there shall be a positive metacentric height GM_T, calculated by the constant displacement method and for the ship in upright condition, of at least

$$GM_T = 0.003\frac{B_2^2(N_1 + N_2)}{\Delta F_1} \quad \text{or}$$

$$GM_T = 0.015\frac{B_2}{F_1} \quad \text{or}$$

$GM_T = 0.05$ m whichever is greater,

where B_2 = is the extreme moulded breadth of the ship at midlength at the relevant bulkhead deck.
Δ = displacement of the ship in the undamaged condition.
F_1 = the effective mean damaged freeboard as defined in the regulation 1 of A.265.
N_1 = number of persons for whom life-boats are provided
N_2 = number of persons (including officers and crew) that the ship is permitted to carry in excess of N_1.

In two compartment flooding the heel angle shall not exceed 12 degrees either.

The table shows also the summary of calculation for regulation 6 using the minimum required intact GM values and thus attained subdivision index A and the required subdivision index R. The attained subdivision index A in regulation 6 is calculated as:

$$A = \sum aps$$

where 'a' accounts for the probability of damage as related to the position of the compartment in the ship's length
'p' evaluates the effect of the variation in longitudinal extent of damage on the probability that only the compartment or group of compartments under consideration may be flooded
's' evaluates the effect of freeboard, stability and heel in the final flooded condition for the compartment or group of compartments under consideration.

The required subdivision index R is determined as:

$$R = 1 - \frac{1000}{4L_s + N + 1500}$$

where L_s = subdivision length of ship = 143.158 m
N = $N_1 + 2N_2$ = 3308

The value of N which gives the required index equal to the attained one is also presented in the table.

The latter table shows the attained subdivision index calculated using minimum intact GM of 1.0, 1.3 and 1.6 m for the corresponding draughts expressed above. These GM values represent typical cases for the draughts in question. The actual values of ship main particulars were used.

The damage stability calculations were made in 1994 according to the IMO MSC/Circ. 574 which is a simplified method based upon resolution A.265. It is a calculation procedure to assess the survivability characteristics of existing Ro-Ro passenger ships. The following intact loading condition has been used in this investigation: mean moulded draught 5.55 m, trim 0.5 m by stern and GM 1.544 m. Cross-flooding has been assumed between fresh water tank 4A and 4B as well as heeling tanks 13 and 14. The filling of heeling tanks is about 50%. The side casings after and forward on deck A have been assumed weathertight.

The attained subdivision index A = 0.6531 when GM = 1.544 m. The required subdivision index A_{max} = 0.6873. Ro-Ro passenger ships constructed before 1 July 1997 shall comply with regulation 8, as amended by resolution MSC. 12(56), not later than the date of first periodical survey after the date of compliance which depends on the ratio A/A_{max}. In the case of MV Estonia the ratio A/A_{max} was 0.9502. For the ships having the ratio 0.95 or more but less than 0.975 the date of compliance is 1 October 2004.

5. DISCUSSION

Both the static and dynamic heel angles for the case of side included are larger than those for the case of sides not included when there is less than 2000 tons of water on the cardeck. This ambiguous result is a consequence of the fact that the actual transverse metacentric height used in the case of side included was smaller than the preliminary assumption used in the calculations for the other case. When the amount of water on the cardeck increases and the heel angle grows over 40 degrees, the effect of intact hull side is emphasised. The static righting arm increases when the ship heels to the maximum calculation angle of 90 degrees. The dynamic heel angle remains under 90 degrees even in the worst calculation case when there is 4000 tons of water on the cardeck. If the effect of side is not included, the ship capsizes when the amount of water on the cardeck is more than 2000 tons.

In the case of side not included the static righting arm starts to decrease right after the heel angle of 40 degrees and becomes rapidly negative. The dynamic heel angle cannot even be calculated when the amount of water on the cardeck is more than about 1350 tons.

The steady heel angle due to the ship's turn back to the opposite heading was not significant. If a steady turning circle diameter of $3L_{pp}$ and speed of 15 kn are assumed the heel angle was about 3 degrees when there was 400 - 1000 tons of water on the cardeck. Using speed of 10 kn the corresponding heel angle was about 1.5 degrees. The effect of roll damping fins which were active at the time of the accident, has been neglected in this simplified consideration.

With the heel angles of nearly 90 degrees the ship had not much dynamic stability left. Because the ship did not turn upside down, it could not have rolled much in the final stage of flooding but the situation must have been quite static.

The static heel angles in the case of cargo not shifted were about 0, 10 and 20 degrees when there was 0, 400 and 1000 tons of water on the cardeck. In the case of cargo shifted, the corresponding heel angles were about 10, 20 and 30 degrees. The cargo shifting reduces the static righting arm about 0.4 m in the heel angle range of 0 - 40 degrees. The distance of cargo shifting was, however, unrealistically large in the calculations.

A ship does not have to satisfy both the 1974 Solas regulations and A.265 Resolution but if the ship satisfy the A.265 regulations, the collision bulkhead need not to be extended weathertight to the deck next above the relevant bulkhead deck. The damage stability of a ship is considered sufficient according to the IMO Resolution A.265 if the metacentric height of the ship in damaged condition meets the requirements of regulation 5 and the attained subdivision index according to the regulation 6 is not less than the required subdivision index.

MV Estonia satisfies the damage stability criteria of 1974 Solas Convention but the damage stability cannot be considered sufficient with regard to the regulations in the resolution A.265. The actual GM was less than 1.3 m whereas the required GM should have been more than 2 m for the draught in question. Moreover, if the GM had been sufficient, the attained subdivision index would in any case have been too small. The required index was 0.8141 when the attained one was only 0.7090. This attained value would, however, have been sufficient if N ($=N_1 + 2N_2$) had been less than 1364.

6. CONCLUSIONS

The final situation before the ship sank was probably quite static without significant roll motion because the ship did not turn upside down though it had not much dynamic stability left.

The relatively small water amount of 1000 tons on the cardeck caused the static heel angle of about 20 degrees. The ramp corner remained above the calm water level until there was about 5000 tons of water on the cardeck. The progressive flooding started earlier probably on the 4th deck through the windows broken by the water pressure.

An unrealistically large cargo shift would increase the heel angle by about 10 degrees.

ACKNOWLEDGEMENTS

Special thanks to Mr Veli-Matti Junnila from Ship Consulting Ltd. and Associate Professor Jerzy Matusiak from the Technical University of Helsinki for proof-reading and valuable comments on this report.

Table 4.2 Results of stability check according to the IMO Resolution A.265. Subdivision index calculated using actual minimum intact GM values according to the regulation 5 of A.265.

```
Overall GM-requirement in accordance with regulation 5
------------------------------------------------------

  Initial condition    Minimum
     Draught    Trim    intact GM

     5.020   -0.600    1.465
     5.280   -0.600    2.447
     5.420   -0.600   32.315


Summary of a-calculation for Regulation 6
=========================================

 1-compartment groups sum a*p= 0.2782     sum a*p*s= 0.2782
 2-compartment groups sum a*p= 0.4091     sum a*p*s= 0.3792
 3-compartment groups sum a*p= 0.2248     sum a*p*s= 0.0516
 4-compartment groups sum a*p= 0.0808     sum a*p*s= 0.0000
------------------------------------------------------------

Attained subdivision index A =                      0.7090
Required subdivision index R calc. for N= 3308      0.8141
Attained index A = 0.7090 corresponds to
required index R for N= 1364
```

Table 4.3 Results of stability check according to the IMO Resolution A.265. Subdivision index calculated using typical intact GM values for the respective draughts.

```
Overall GM-requirement in accordance with regulation 5
------------------------------------------------------

  Initial condition    Minimum
     Draught    Trim    intact GM

     5.020   -0.600    1.000
     5.280   -0.600    1.300
     5.420   -0.600    1.600


Summary of a-calculation for Regulation 6
=========================================

 1-compartment groups sum a*p= 0.2782     sum a*p*s= 0.2782
 2-compartment groups sum a*p= 0.4091     sum a*p*s= 0.2683
 3-compartment groups sum a*p= 0.2248     sum a*p*s= 0.0328
 4-compartment groups sum a*p= 0.0808     sum a*p*s= 0.0000
------------------------------------------------------------

Attained subdivision index A =                      0.5793
Required subdivision index R calc. for N= 3308      0.8141
Attained index A = 0.5793 corresponds to
required index R for N=  304
```

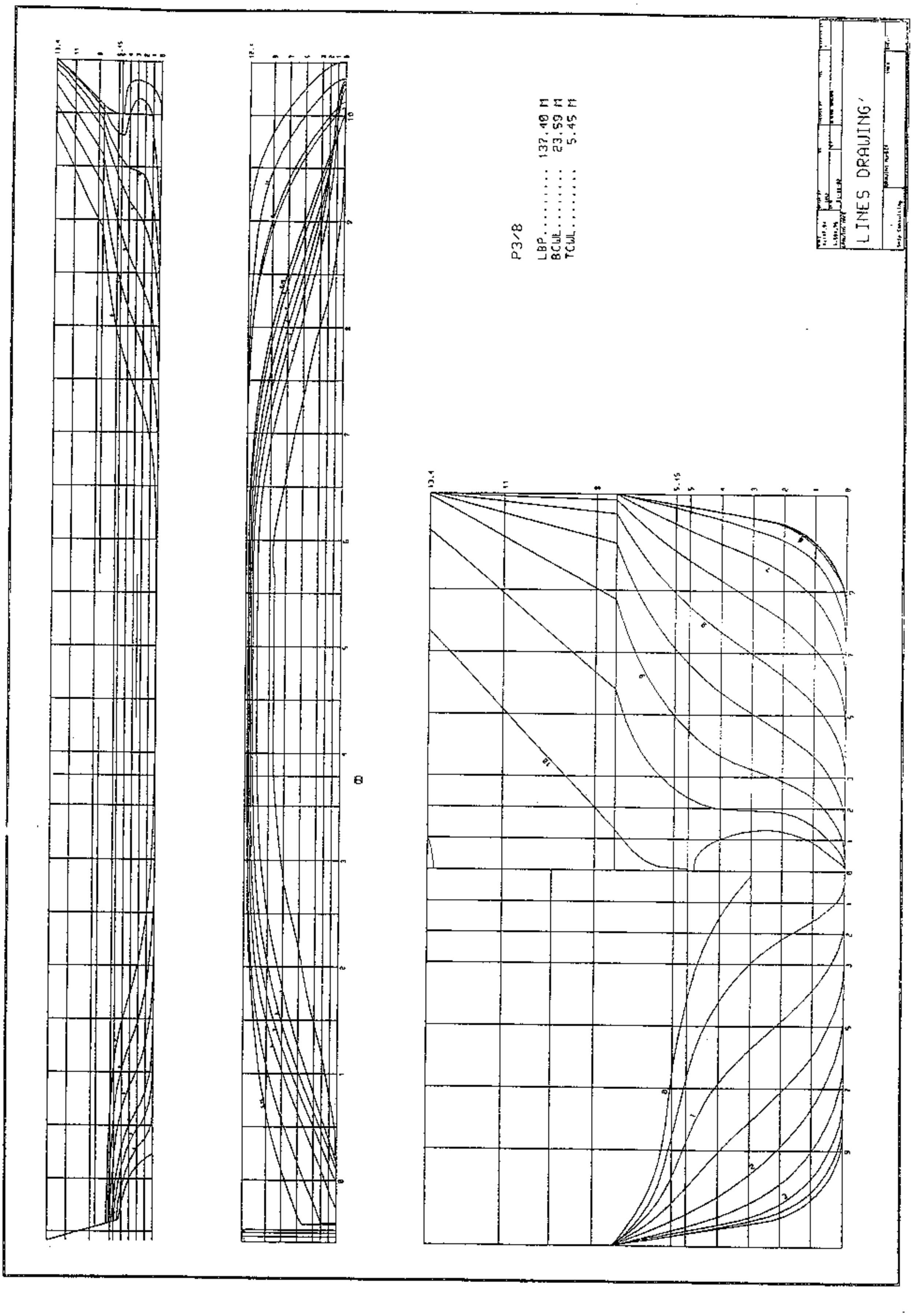

Figure 3.1 Lines drawing of MV Estonia.

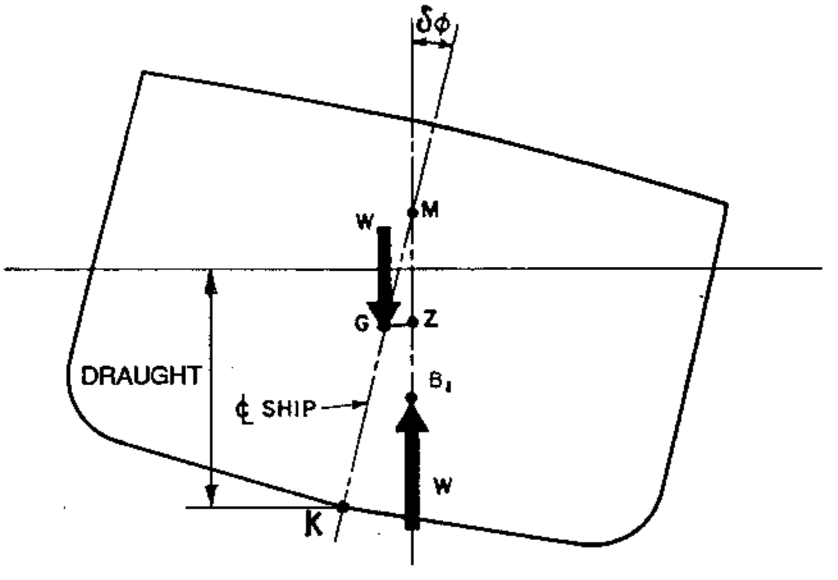

Figure 4.1 Definition of symbols.

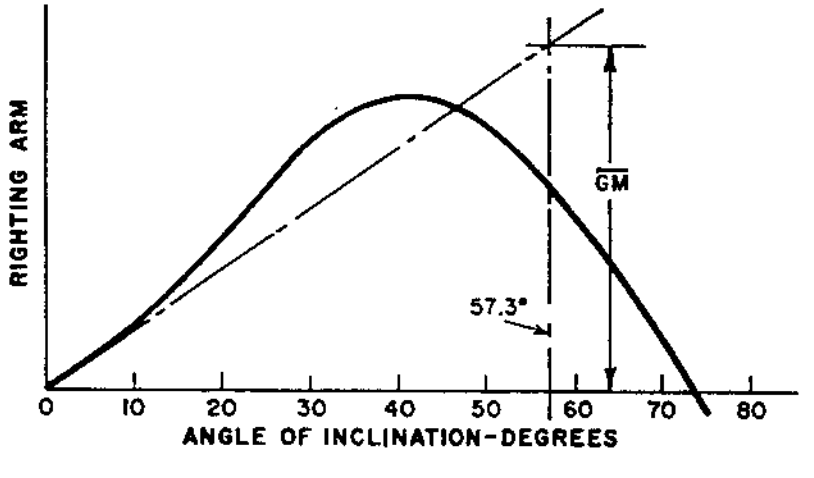

Figure 4.2 Typical righting arm (GZ) curve.

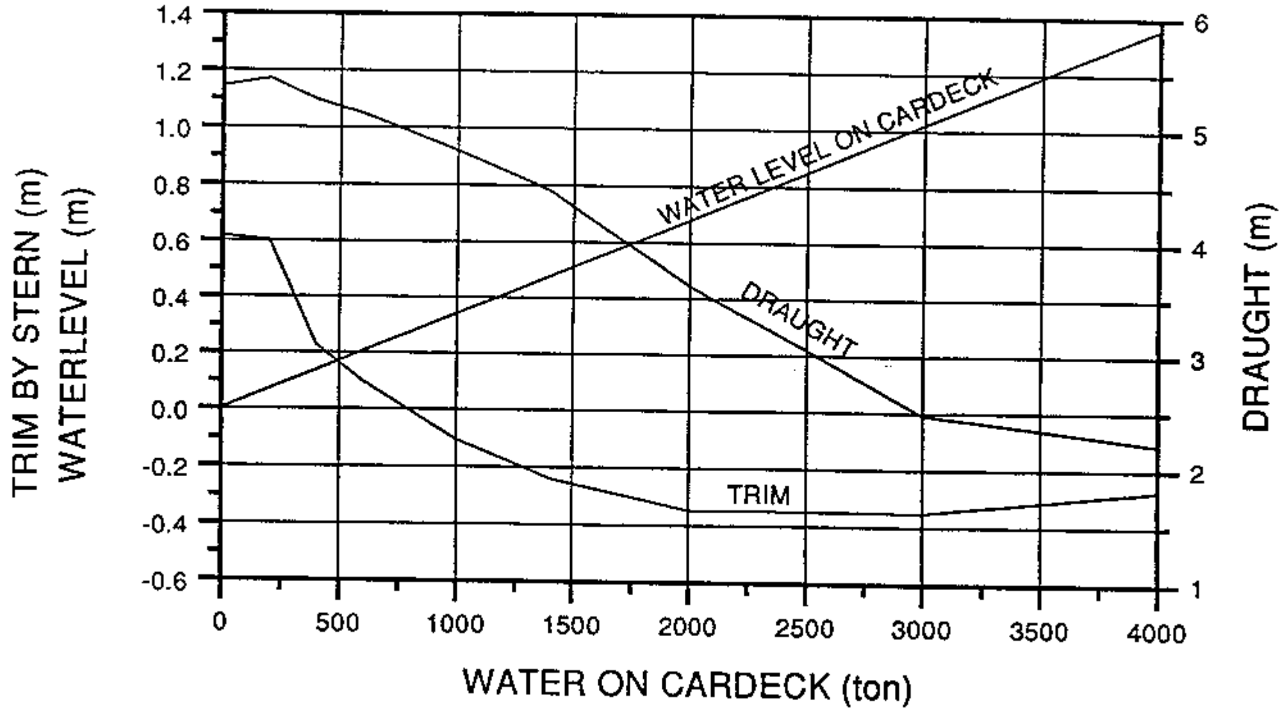

Figure 4.3 The water level on the cardeck, draught and trim as functions of water amount on the cardeck, side included.

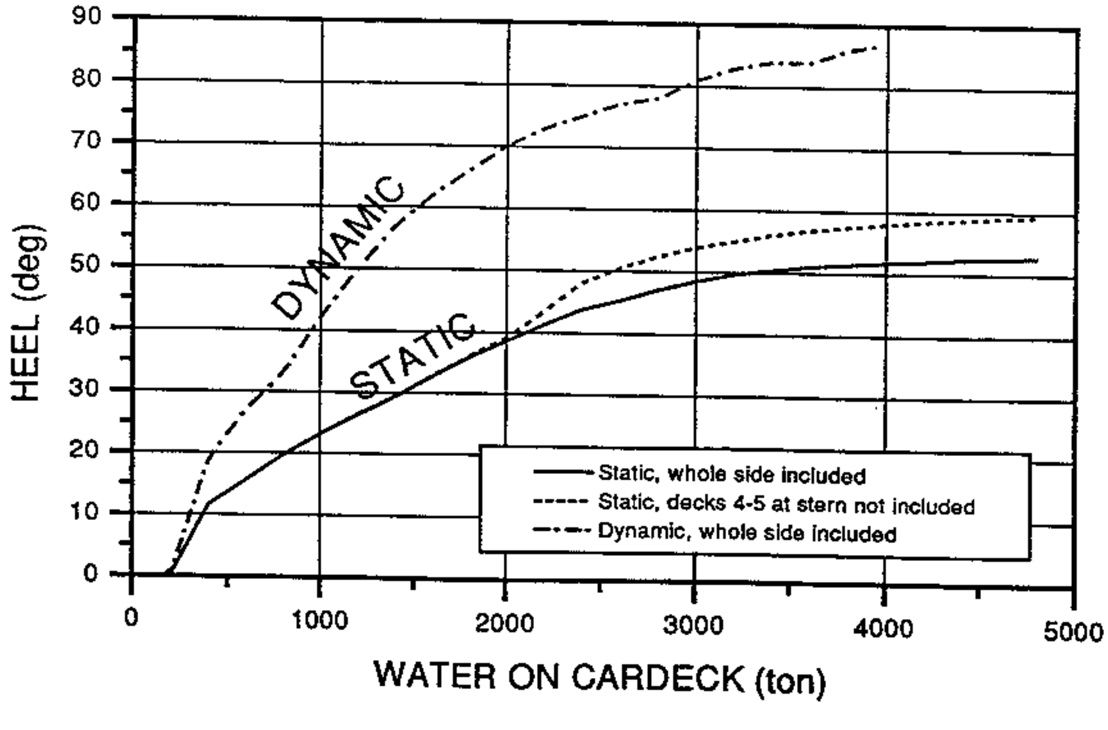

Figure 4.4 Static and dynamic heel angles.

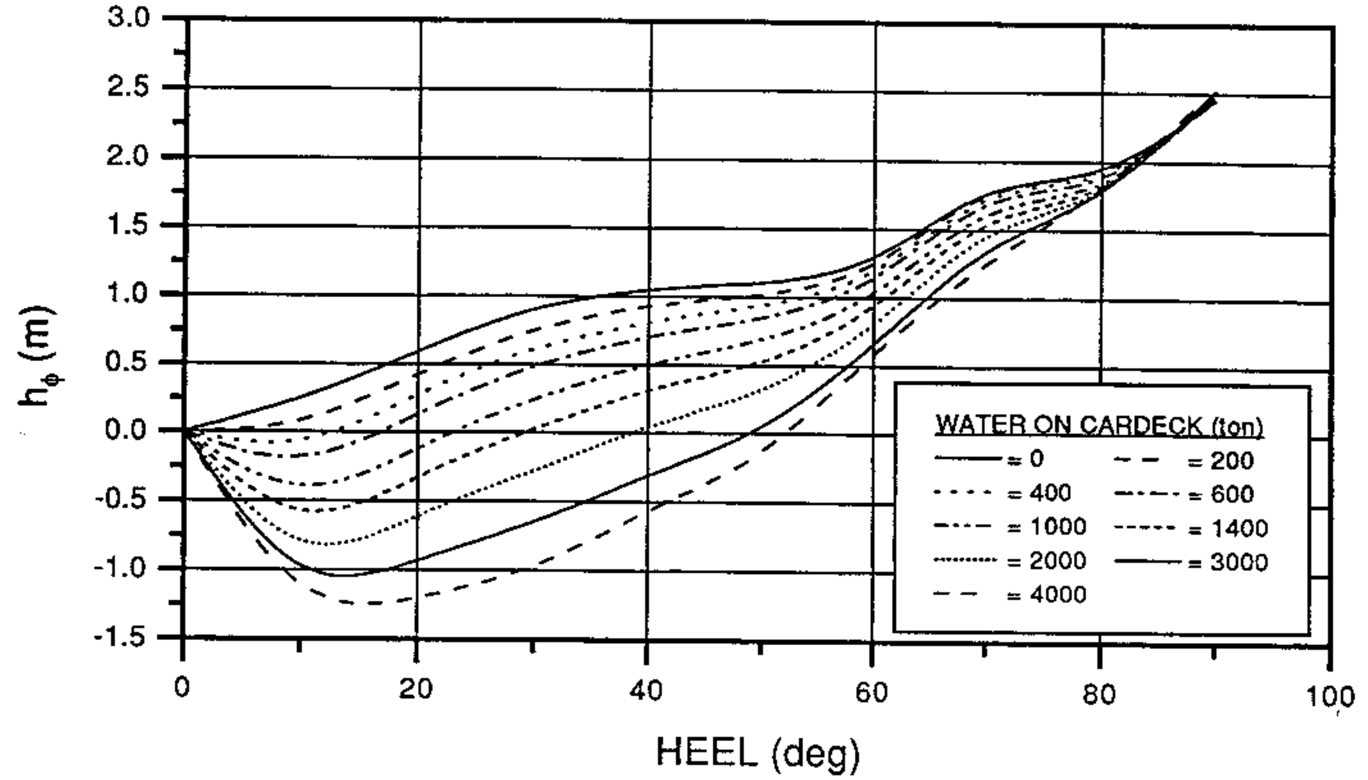

Figure 4.5 Static stability curves, side included.

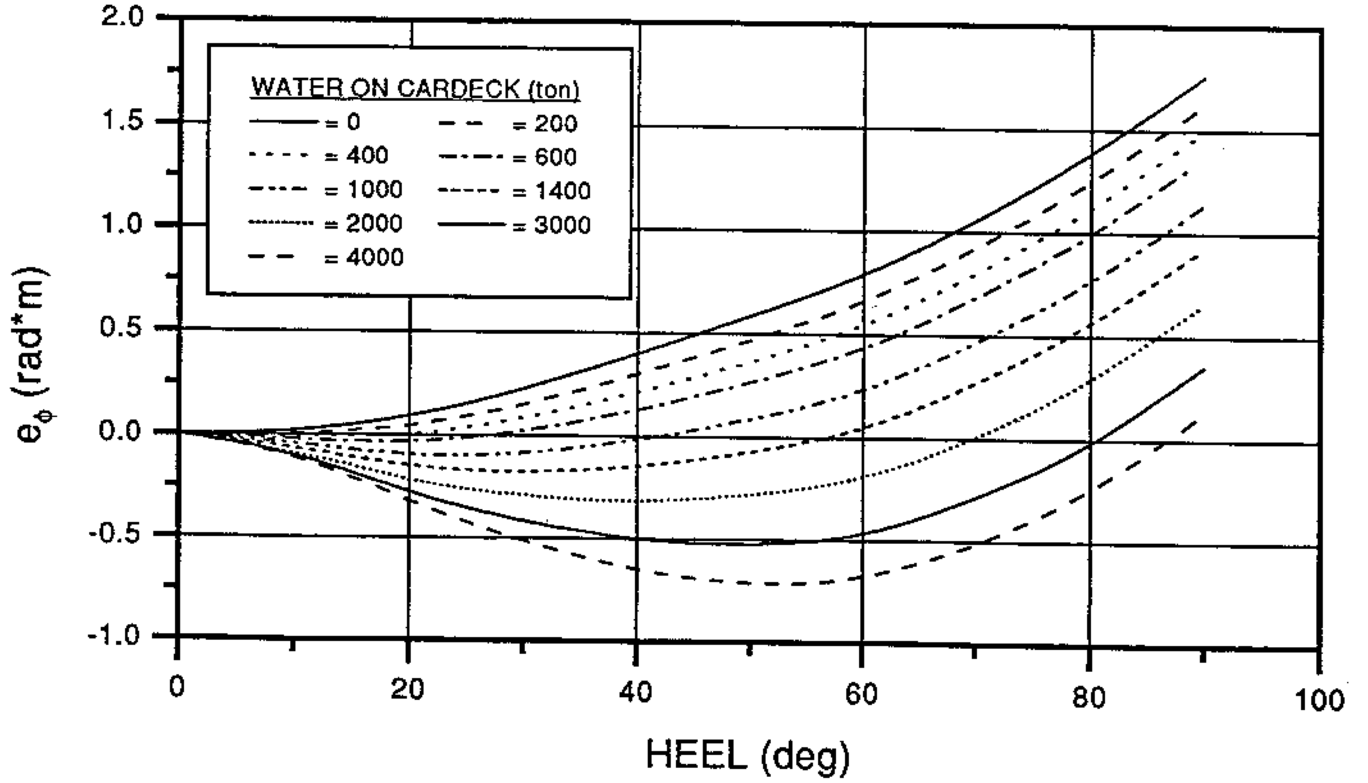

Figure 4.6 Dynamic stability curves, side included.

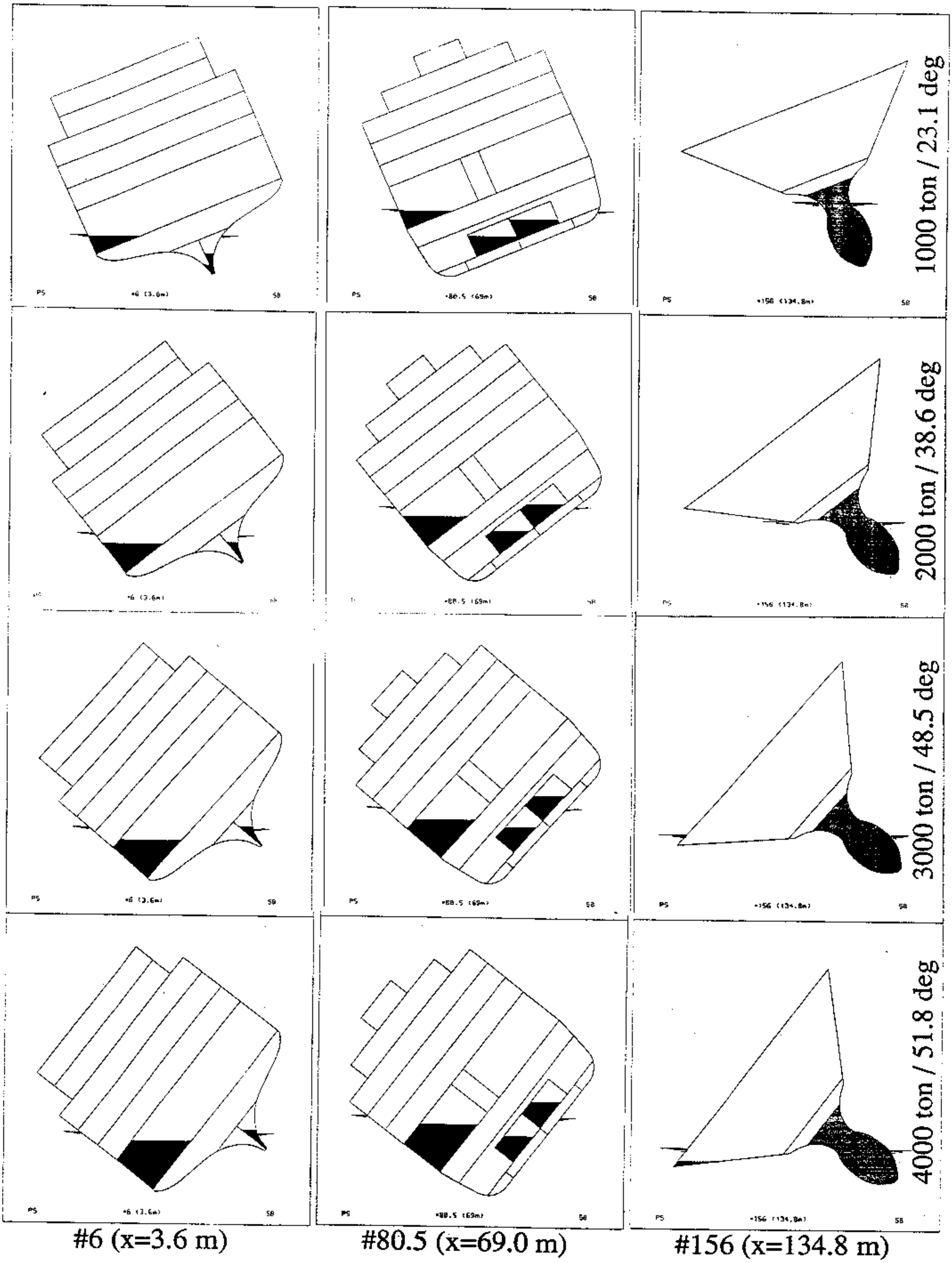

Figure 4.7 Cross-sections at frames #6, #80.5 and #156. The amount of inflooded water 1000, 2000, 3000 and 4000 ton.

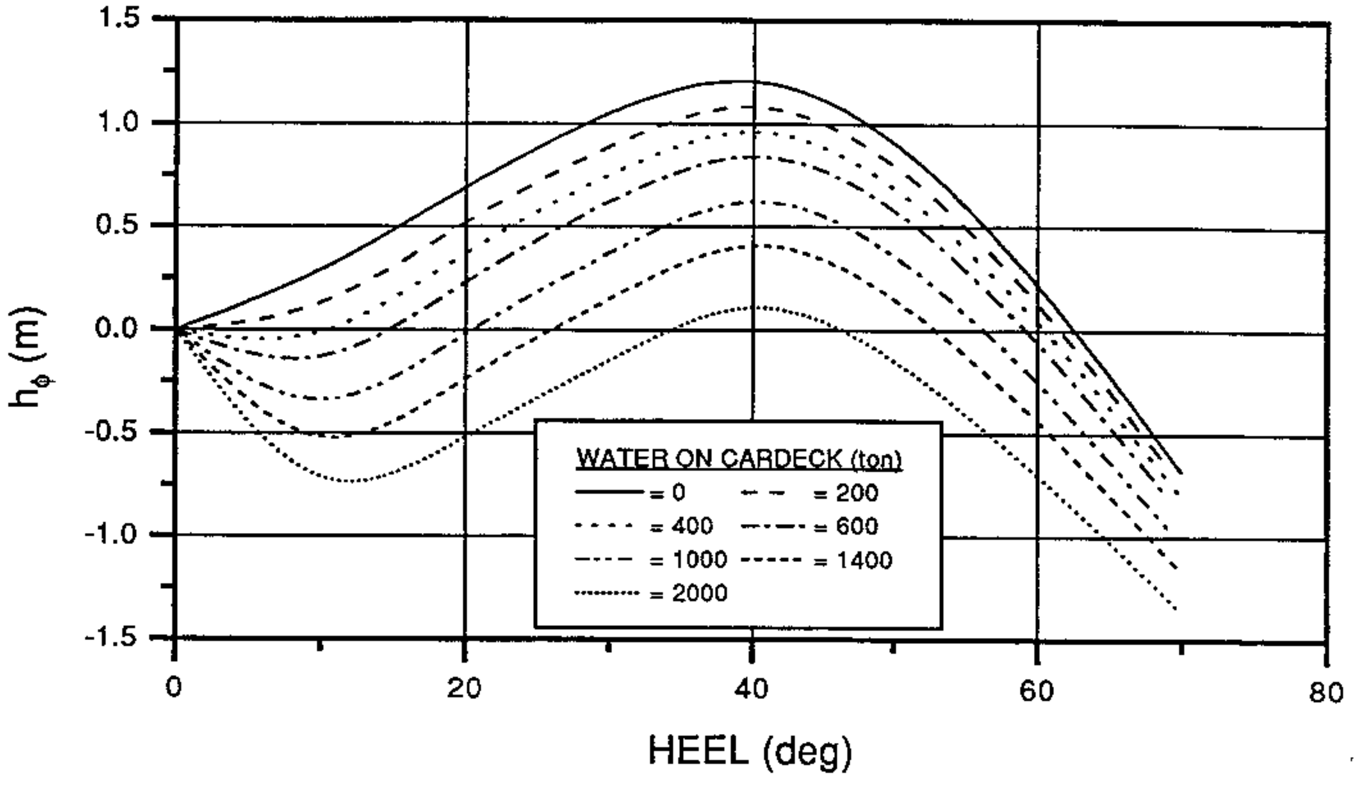

Figure 4.8 *Static stability curves. Side above 4th deck not included, preliminary load condition.*

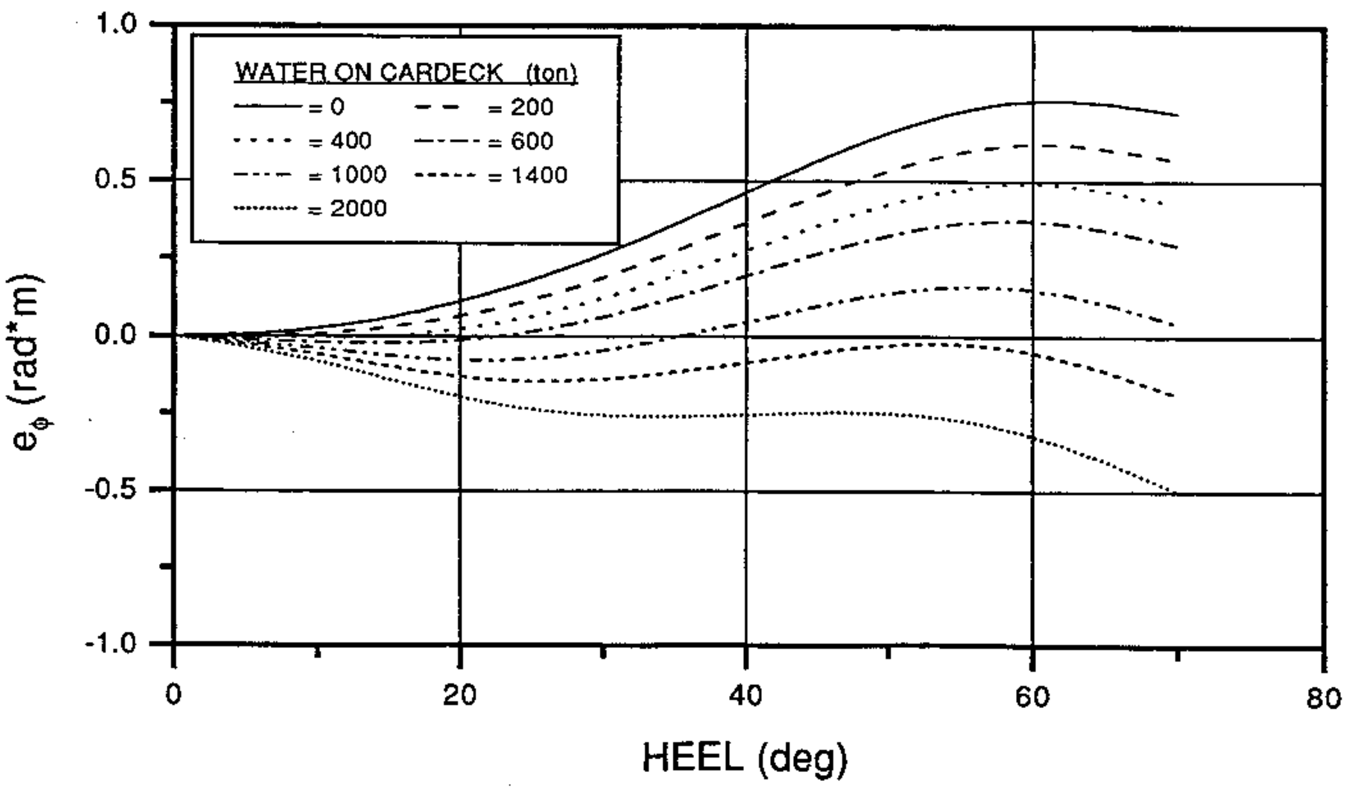

Figure 4.9 *Dynamic stability curves. Side above 4th deck not included, preliminary load condition.*

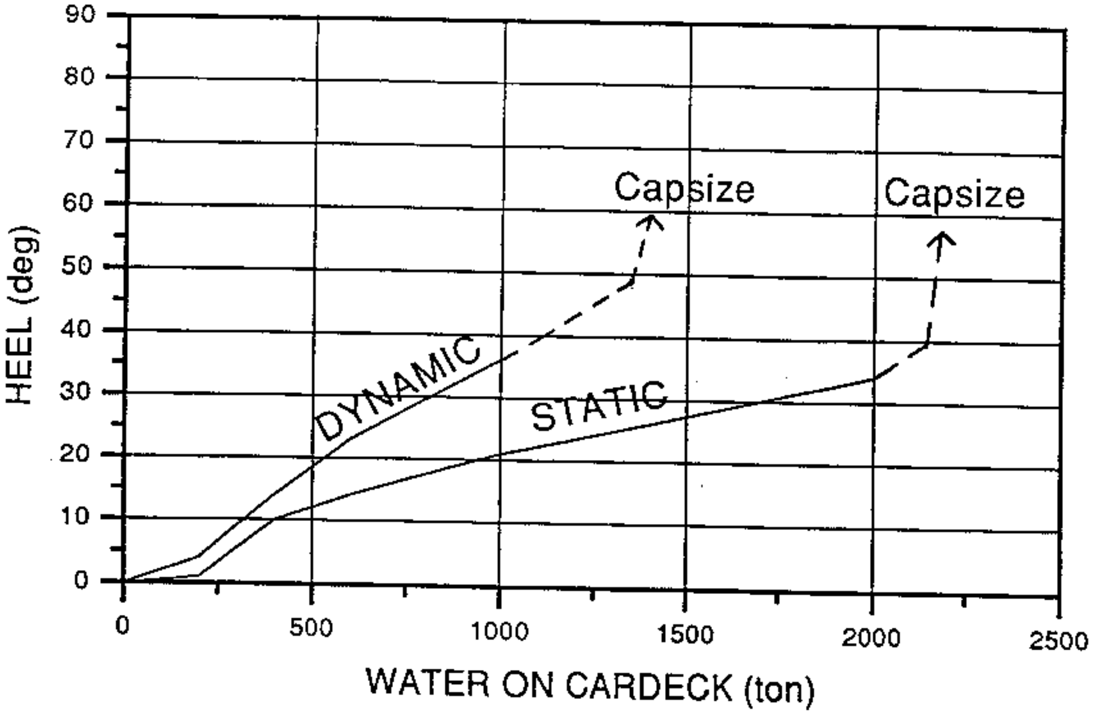

Figure 4.10 Static and dynamic heel angles. Side above 4th deck not included, preliminary load condition.

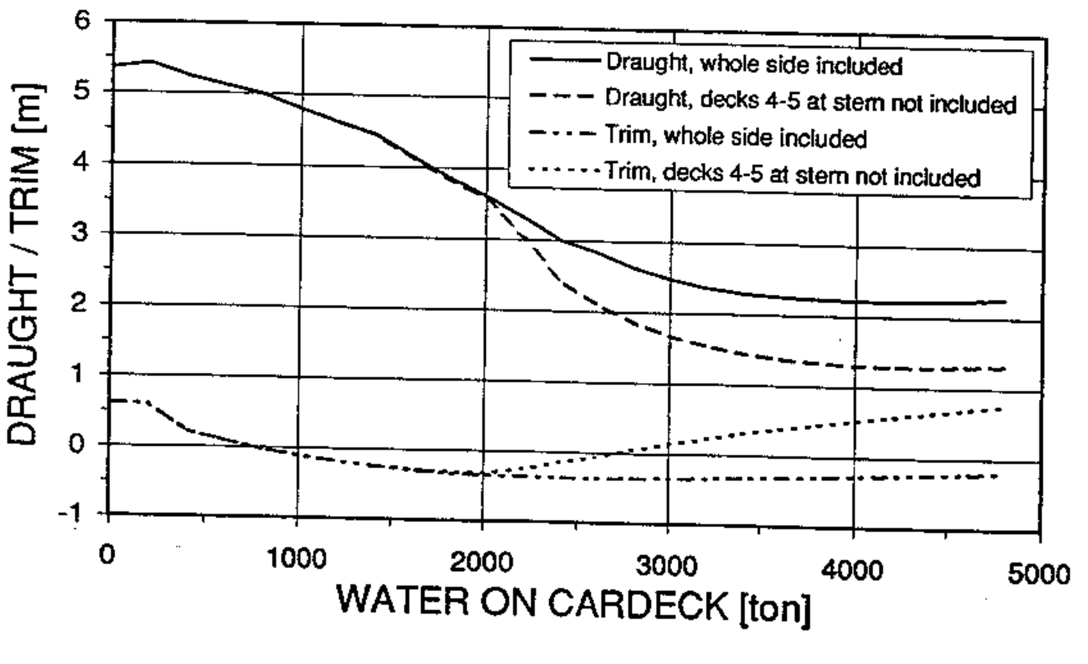

Figure 4.11 Draught and trim, whole side included and decks 4-5 at stern not included, actual load condition without the visor.

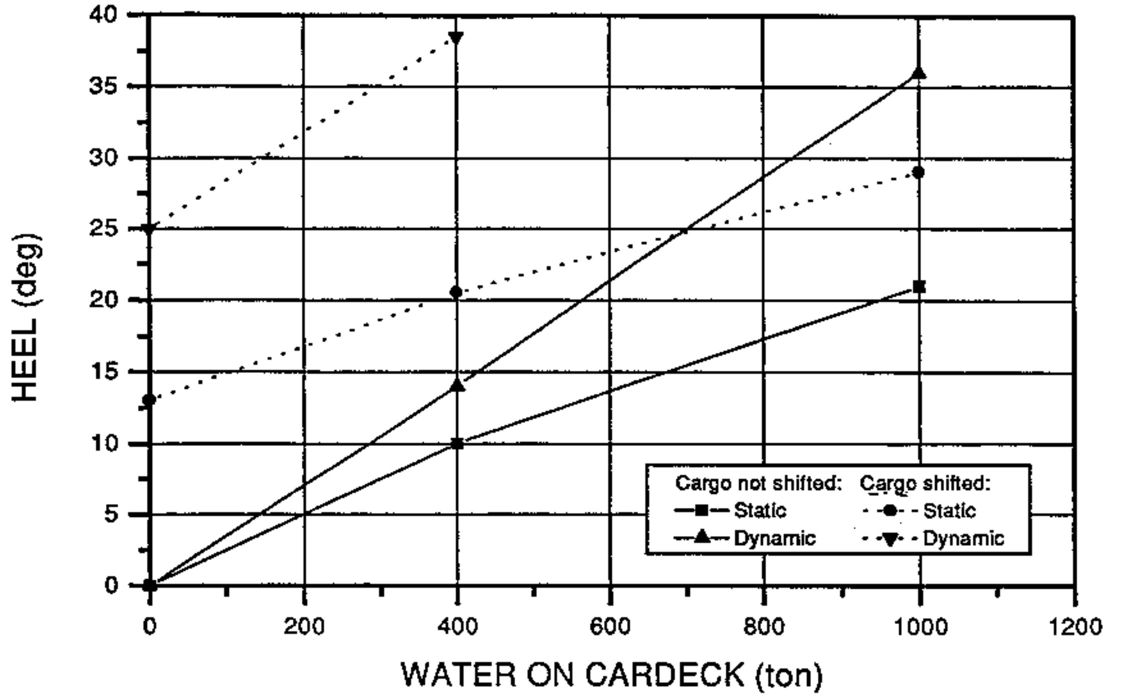

Figure 4.12 Static and dynamic heel angles, effect of cargo shift, side above 4th deck not included.

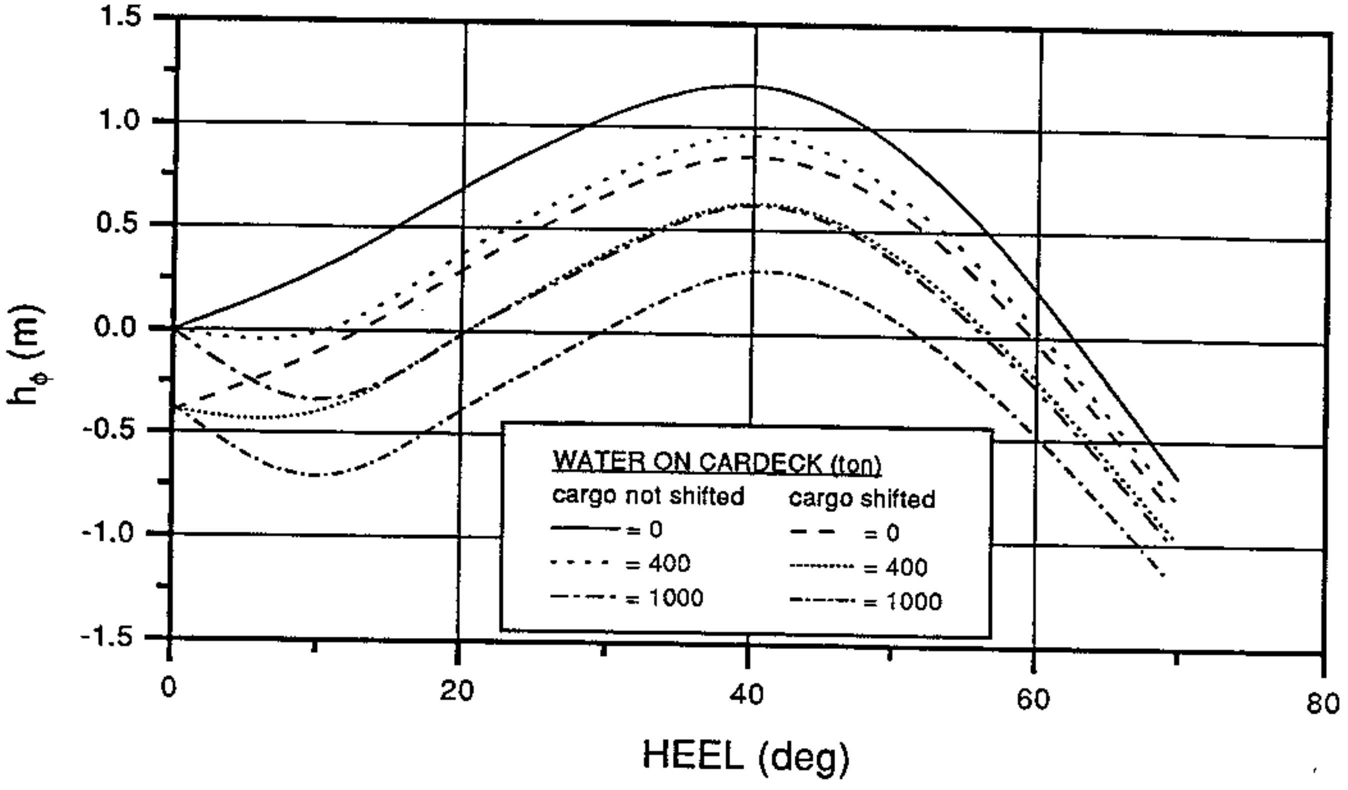

Figure 4.13 Static stability curves, effect of cargo shift. Side above 4th deck not included, preliminary load condition.

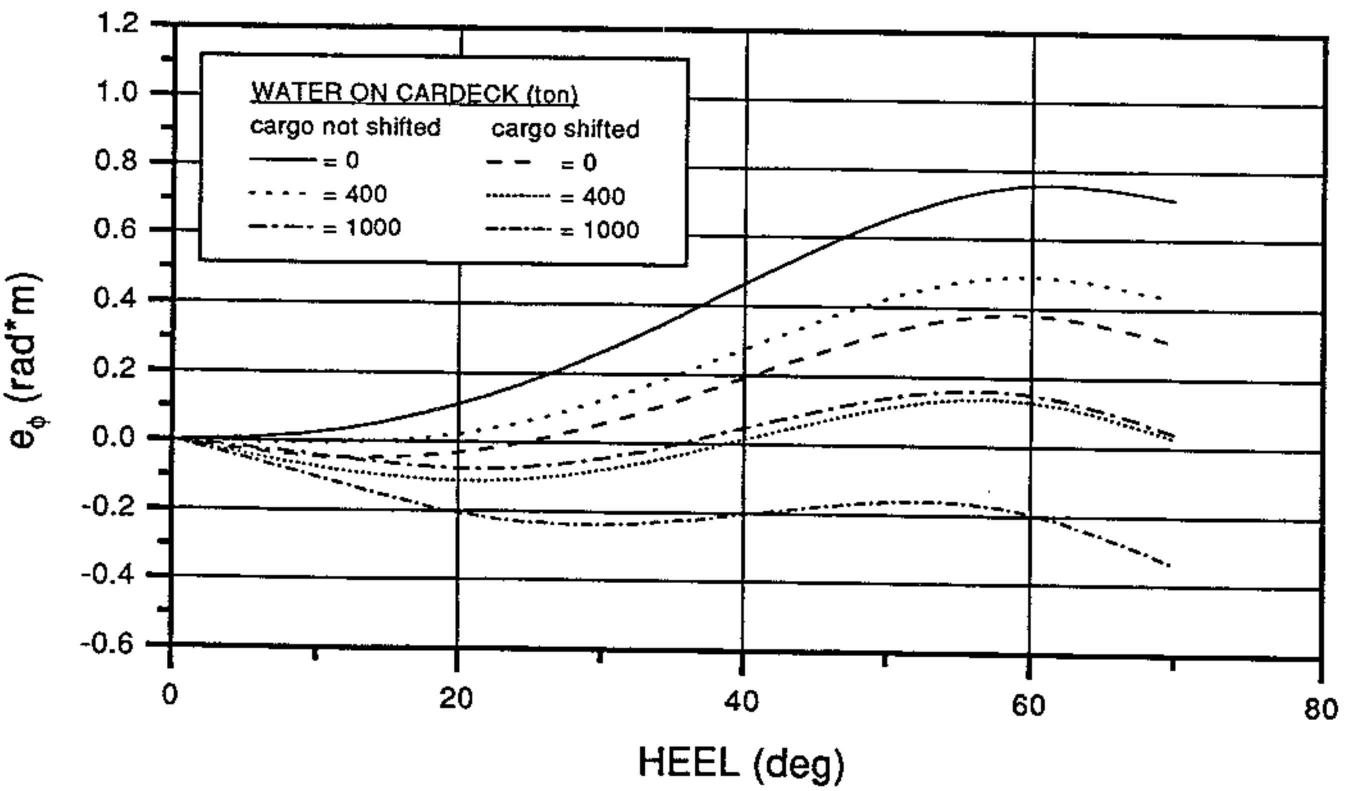

Figure 4.14 Dynamic stability curves, effect of cargo shift. Side above 4th deck not included, preliminary load condition.

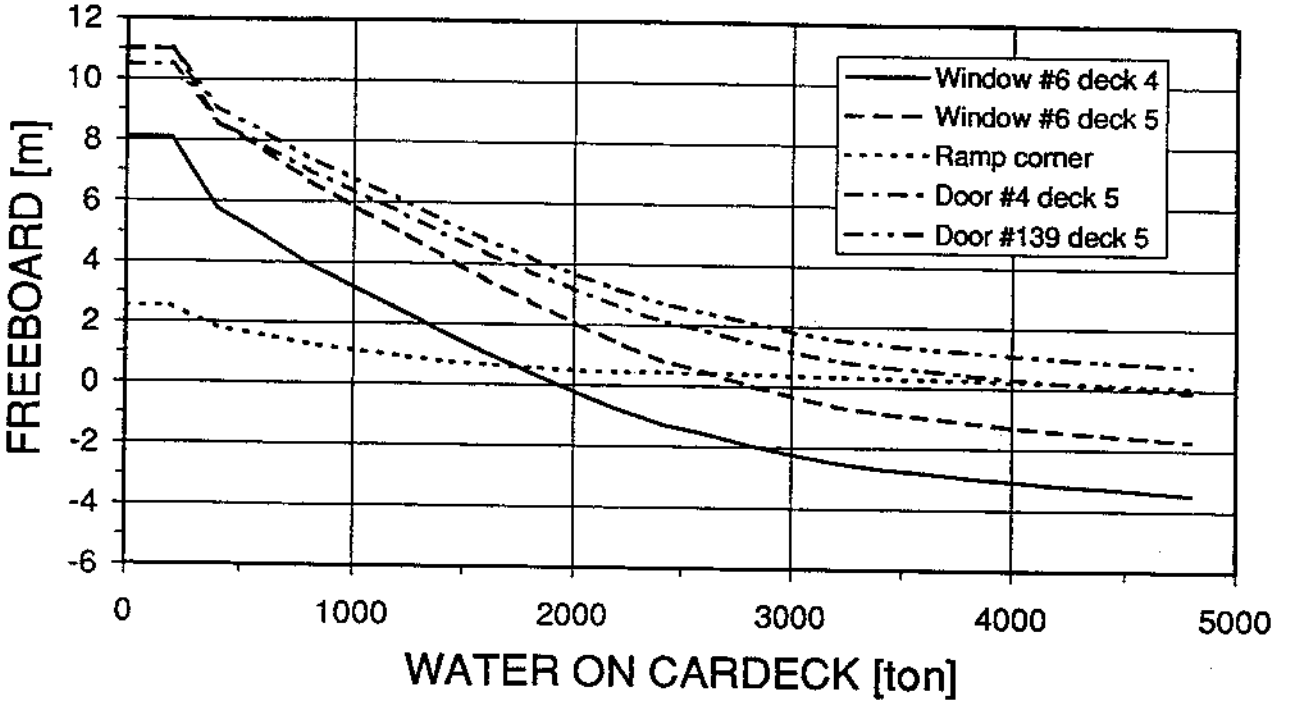

Figure 4.15 Freeboard to some critical openings.

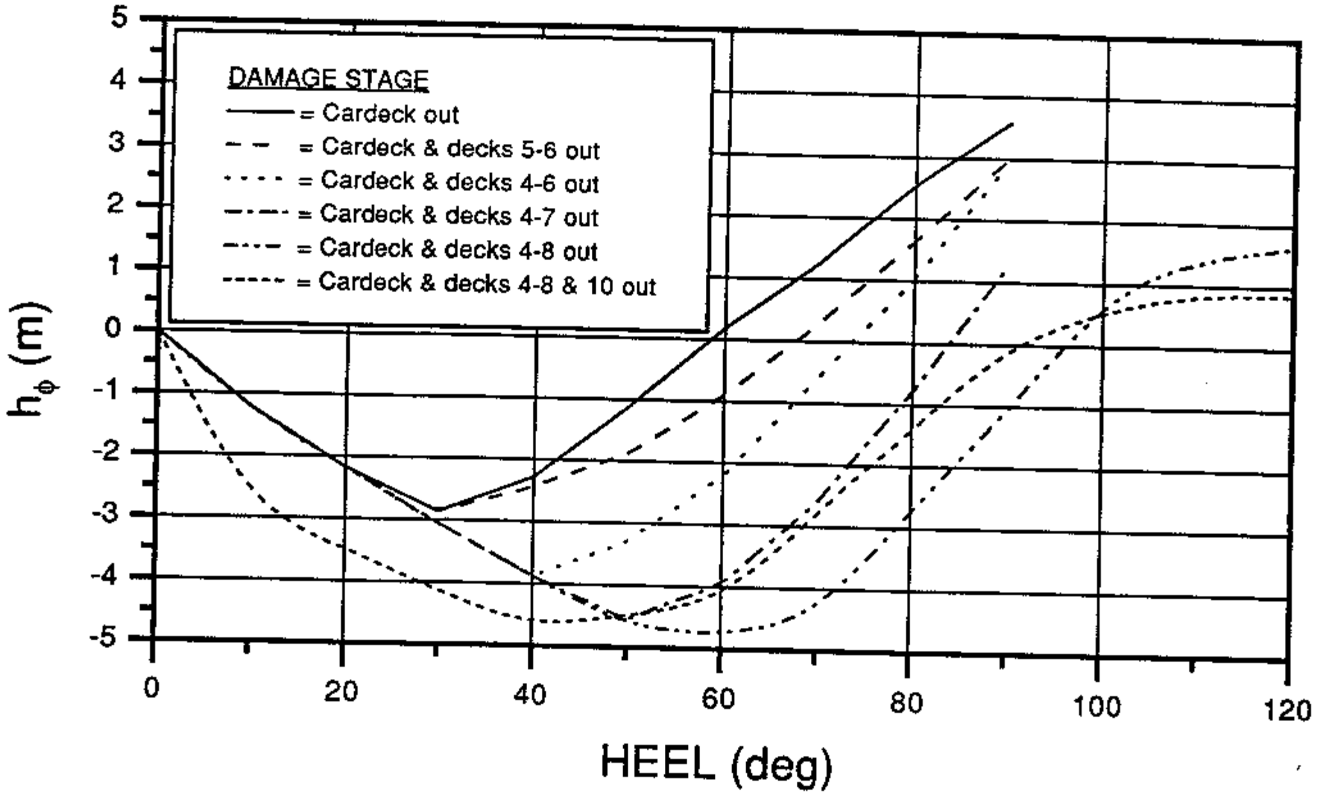

Figure 4.16 Static stability curves, effect of damage stage, 3200 ton water on cardeck.

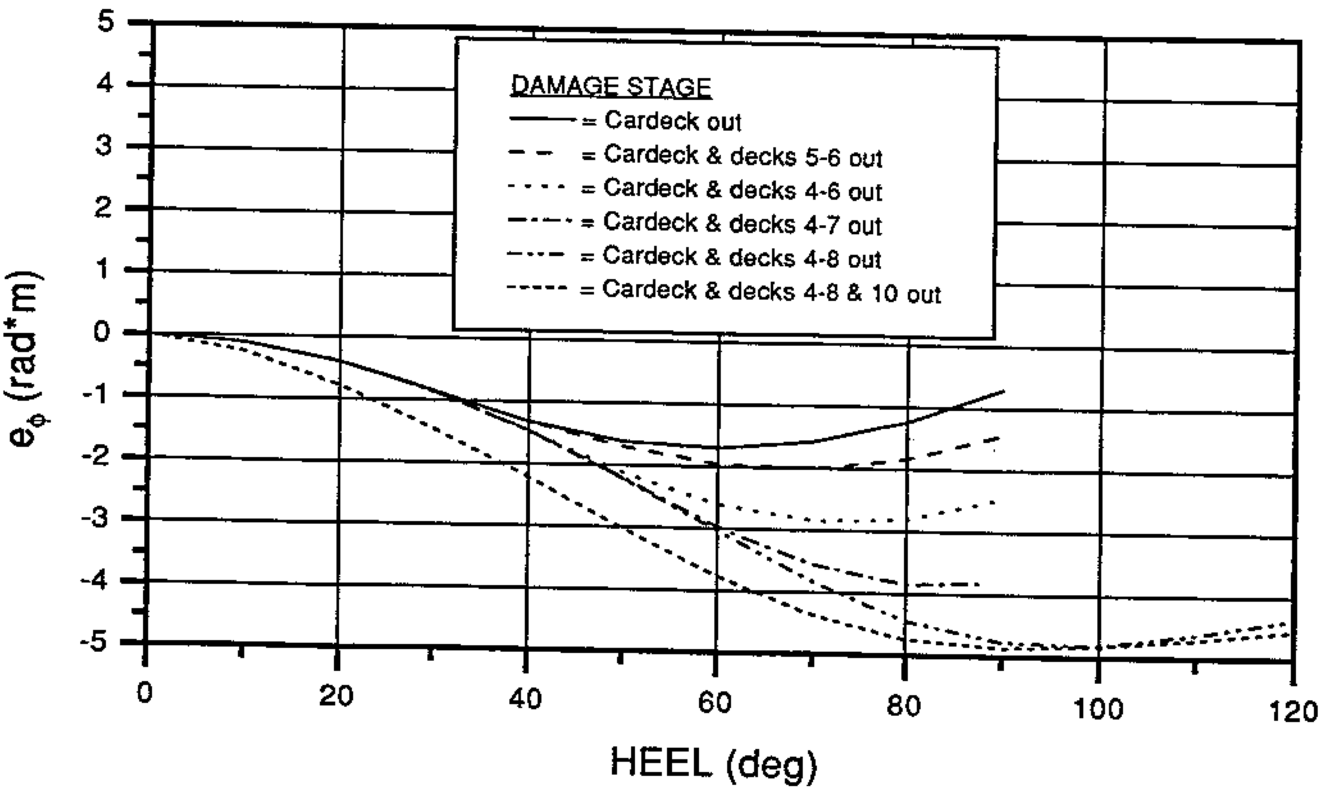

Figure 4.17 Dynamic stability curves, effect of damage stage, 3200 ton water on cardeck.

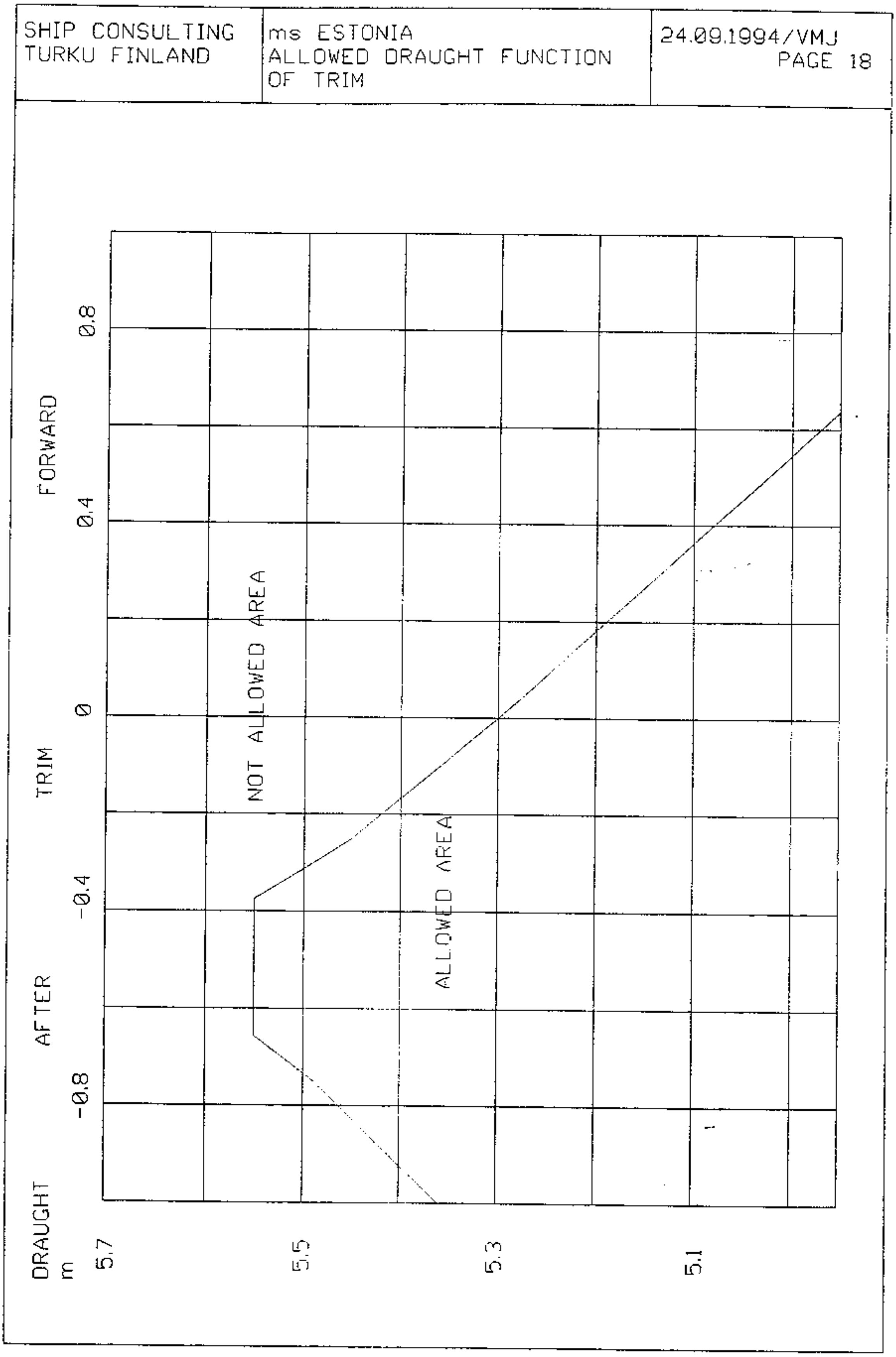

Figure 4.18 The allowed and not allowed trim/draught combinations for MV Estonia.

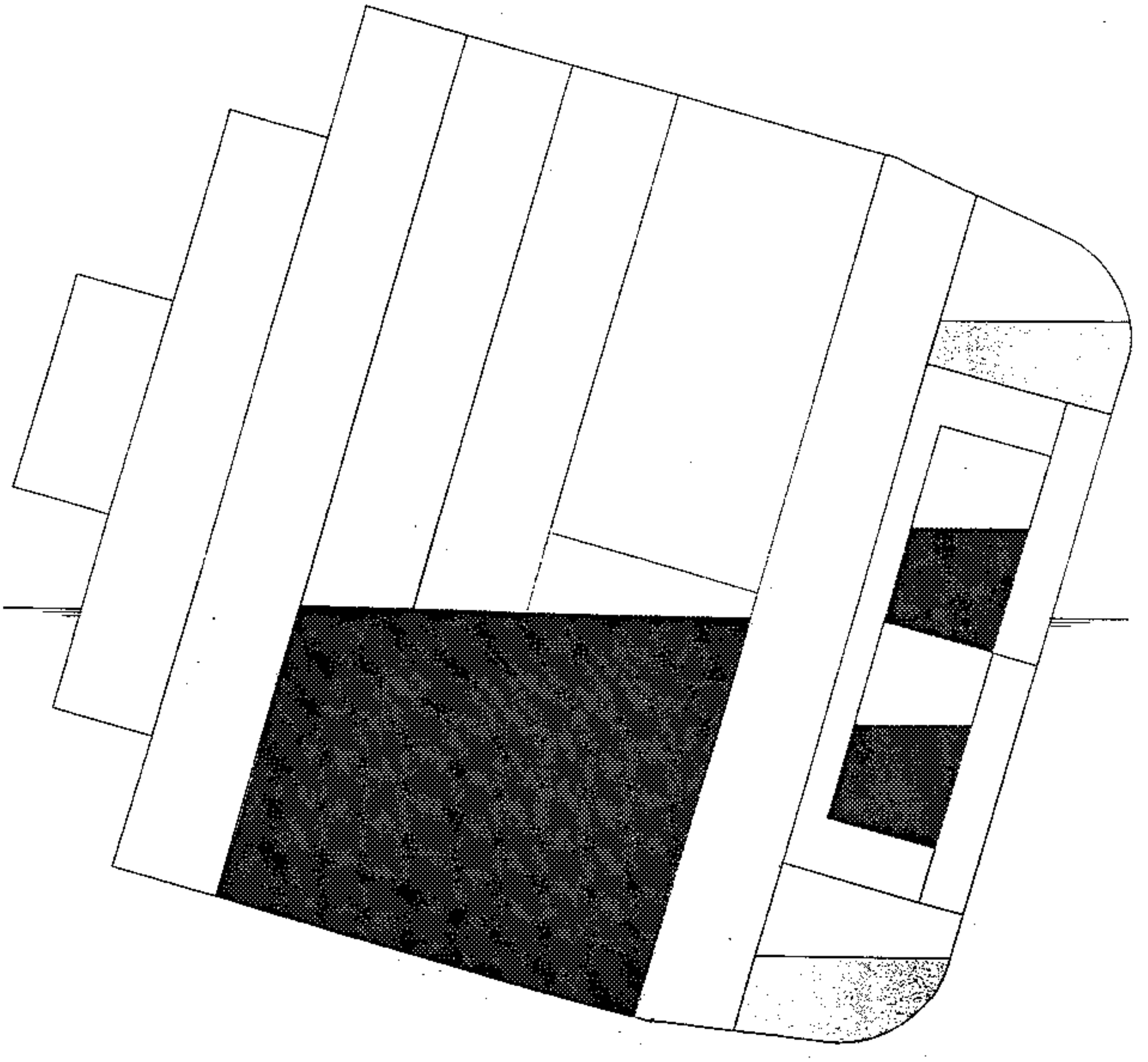

Figure 4.19 The equilibrium floating position of the ship for the case when the cardeck and decks between 4-6 are out. The cross-section is at the longitudinal coordinate x=79.4 m from the after perpendicular.