Bundesstelle für Seeunfalluntersuchung
Federal Bureau of Maritime Casualty Investigation
Federal Higher Authority subordinated to the Ministry
of Transport, Building and Urban Affairs

Investigation Report 45/07

Less Serious Marine Casualty

Loss overboard of 10 containers from JRS CANIS at estuary of Elbe River on 12 January 2007 at 02:40

1 October 2008

www.bsu-bund.de

The investigation was conducted in conformity with the law to improve safety of shipping by investigating marine casualties and other incidents (Maritime Safety Investigation Law/Seesicherheits-Untersuchungs-Gesetz, SUG) of 16 June 2002.

According to this, the sole objective of the investigation is to prevent future accidents and malfunctions. The investigation does not serve to ascertain fault, liability or claims.

This report should not be used in court proceedings or proceedings of the Maritime Board. Reference is made to § 19 paragraph 4 of the SUG.

The German text shall prevail in the interpretation of the Investigation Report.

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1 Summary of the Marine Casualty

The container ship JRS CANIS was at Bremerhaven on 11 January 2007 between 19:30 and 22:30 [1]. After unloading and loading, the crew checked that the containers were secured. The ship departed at 23:06 under pilot advice heading for St. Petersburg.

According to the weather forecast for the German Bight, there was a storm developing that night originating from west to west-northwest 8 to 9 gusting to 11 Bft, with sea rising to 8 metres.

The pilot disembarked on 12 January 2007 at 00:45.

The ship's speed was adapted to the sea conditions. After passing buoy 4a, German Bight Traffic was informed that the JRS CANIS was on her way to the Kiel Canal. At this point, the ship was pitching and rolling severely.

A true course of 330° was applied and the ship was sailing at about 7 kn. After passing an oncoming vessel, the course was altered to 060° and the speed was changed to about 15.5 kn.

The wind was approaching from 285° at force 9 Bft. Sea force was about 7 to 8, up to 5 m high, coming from WSW to WNW.

At 02:40 the ship keeled briefly to each side, several times, by up to 20°. The bridge crew were able to see that the container stack on the port side leaned inwards while the container stack on the starboard side shifted outwards. At the same time 10 containers were lost overboard.

The German Bight Vessel Traffic Service was immediately informed of the incident.

Then an inspection was made on deck to determine the damage. The decision was made to continue the voyage to the Kiel Canal at a reduced speed.

At 07:12, the JRS CANIS moored at Brunsbüttel where the first investigations began onboard.

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[1] All times given in this report are local times (CET=UTC+1h)

2 Scene of the accident

Type of event: Less serious marine casualty
Containers lost overboard
Date/time: 12. January 2007 – 02:40
Location: Estuary of the Elbe River
Latitude/longitude: φ 53°57.5'N λ 008°05.5'E

Section from the chart INT 1413, BSH (Federal Maritime and Hydrographic Agency)

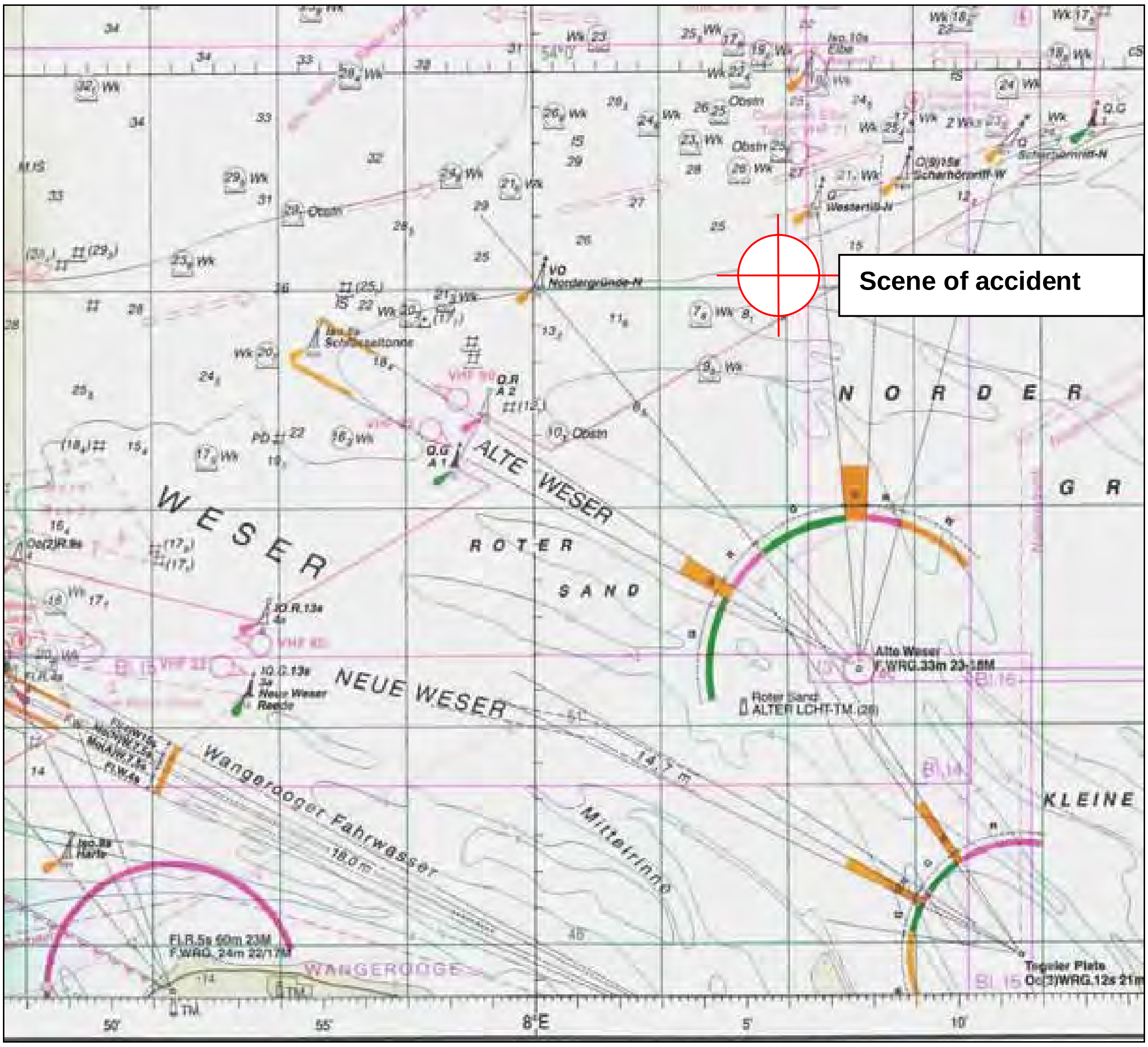

Figure 1: Chart

3 Vessel Particulars

3.1 Photo

Figure 2: Photograph of the vessel

3.2 Particulars

Name of the vessel:	JRS CANIS
Type of vessel:	Container ship
Nationality/flag:	Cyprus
Port of registry:	Limassol
IMO number:	9339014
Call sign:	C4LN2
Vessel operator:	S&D Shipmanagement GmbH & Co. KG
Year built:	2006
Shipyard/yard number:	MAWEI SHIPYARD
Classification society:	GL
Length overall:	129.20 m
Breadth overall:	20.60 m
Gross tonnage:	7.545
Deadweight:	8,262 t
Draught at time of accident:	V: 7.09 m A: 7,49
Engine rating:	7,200 kW
Main engine:	Caterpillar MAK 9M43C
(Service) Speed:	17.5 kn
Hull material:	Steel
Number of crew:	13

4 Course of the accident and investigation

The container ship JRS CANIS moored in Bremerhaven on 11 January 2007 at 19:30. Unloading and loading were completed at 22:30. On instruction by the master, the chief mate and crew checked that the containers were secure before departing, and everything was found to be correct. The ship departed at 23:06 under pilot advice heading for St. Petersburg.

The weather forecast for German Bight at this time was apparently for a wind from west to west-northwest 8 to 9 gusting to 11 Bft, with the sea rising to 8 metres.

On 12 January 2007 at 00:45, the pilot disembarked at Neufeld Reede and the voyage was continued under VHF advice of the Vessel Traffic Service up to Buoy 4a.

The ship's speed was apparently adjusted to the sea conditions. After passing Buoy 4a, German Bight Traffic were informed that the JRS CANIS was in the region and on her way to the Kiel Canal. At this point, the ship was pitching and rolling severely.

A true course of 330° was applied and the ship was steered at about 7 kn. After passing an oncoming vessel, the course was altered to 060° and the speed was changed to about 15.5 kn.

The wind was approaching from 285° at force 9 Bft. Sea force was about 7 to 8, up to 5 m high, coming from WSW to WNW. Visibility was apparently good.

At 02:40, shortly after passing Nordergründe, the ship heeled over briefly to each side, several times, by up to 20°. The bridge crew were able to see that the container stack on the port side leaned inwards while the container stack on the starboard side shifted outwards. At the same time 10 containers were lost overboard. The position was recorded at 053°57.5‘N 008°03.5‘E.

The German Bight Vessel Traffic Service was informed immediately.

Then an inspection was made on deck to determine the damage. The decision was made to continue the voyage to the Kiel Canal at a reduced speed.

At 07:12, the JRS CANIS was said to have been fast at Brunsbüttel where the first investigations began onboard.

5 Investigation

With the increase in container transport by sea, the number of container ships is also growing. An associated phenomenon is that containers fall overboard or collide into each other. In addition to known causes such as wind, waves and the resultant natural motion of the ship, parametric rolling also influences the stability of the ship.

This investigation therefore focused on the following questions:

1. Was the loss of cargo due to resonance effects caused by sea conditions?
2. Did the crew have the opportunity to recognise this beforehand? In this respect, we should also address the question of whether the use of so-called wave and surface current monitoring software could have prevented the loss of cargo.
3. What role did the lashing material play? (Twistlocks)

5.1 Environmental conditions

A fundamental factor in processing the aforementioned questions further is to detail as precisely as possible the environmental conditions. Consequently the DWD[2] was commissioned to prepare a weather report. In order to describe the characteristics at sea more precisely, the BSH[3] was also asked to prepare a statement regarding the conditions at sea at the time of the accident.

5.1.1 Weather conditions

The DWD has access to hourly weather reports from shore and coastal stations for the relevant area and for the desired period of time due to an international system of information exchange.

The weather conditions in the North Sea were marked by several low-pressured areas with cores over the North Atlantic, the North Sea and the Baltic Sea. A distinct pressure gradient initially developed into a severe southwesterly storm over the German Bight in the morning of 11 January 2007. The storm calmed down in the afternoon and veered to the west. In the first half of the night into 12 January 2007 winds reached storm force again; in the second half of the night the wind veered to the northwest.

It was cloudy to severely overcast, and there were repeated showers. Horizontal visibility was between 2 and 5 sm. There was a half-moon.

The wind blew from west to northwest with an average force of 9 Bft. Gusts of 11 to 12 Bft were recorded. These values refer to the 10 minute average of wind speeds, measured at a height of 10 m.

There are no ship's observations or buoy measurements of the sea state at the time of the accident. Nevertheless, we can estimate the typical (significant) wave height of the wind sea from the ratios between wind force, effective wind duration and effective wind direction.

When deep water conditions are undisturbed, as was recorded for the accident position, a directionally stable average wind of force 8 to 9 Bft, sustained over 6 hours, can create a wind sea with a significant wave height of 5 to 6 m and periods of 7 to 8 s.

---

[2] DWD = Deutscher Wetterdienst/Germany's National Meteorological Service

[3] BSH = Bundesamt für Seeschifffahrt und Hydrographie/Federal Maritime and Hydrographic Agency

These values refer to the characteristic (also called significant) wave height. It corresponds to the arithmetic mean calculated from the upper third of the wave heights during a period of observation. This means that a number of individual waves are higher than the significant wave height. In rare cases, individual waves can exceed the significant wave height by 70 to 100 %.

5.1.2 Sea conditions

The data available at the BSH regarding sea state conditions on 12 January 2007 have been summarised in the following figures and tables:

1. Graphic time series of measurements from stations at FINO[4] (Fig. 5), Heligoland (Fig. 4) and Elbe (Fig. 3),
2. Table of sea parameters from the sea model at the three places of measurement and for the scene of accident at Nordergründe (Fig. 6),
3. Charts showing the significant wave heights on 12 January 2007 at 01:00 and 04:00 (Fig. 7 and 8).

Unfortunately, the data connection to the receiver system on the Elbe measuring buoy was disturbed in January, which meant that only a few measured values were transmitted via satellite. There is therefore no data available for the time of the accident.

A comparison of the two other measuring buoys at Heligoland (Fig. 4) and at the FINO platform (Fig. 5) with the numerical sea model from the DWD show that the calculated wave heights were too high, especially on the day before. On the morning of 12 January 2007 the model results once again match the FINO measurement; however, at Heligoland they were still about 3/4 m too high.

Since measurements were missing for the Elbe station (Fig. 3), we can only assume that the calculated wave heights were too high by roughly the same amount. The time progression at Heligoland and the Elbe station is very similar.

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[4] FINO = Research platforms in the North and Baltic Seas

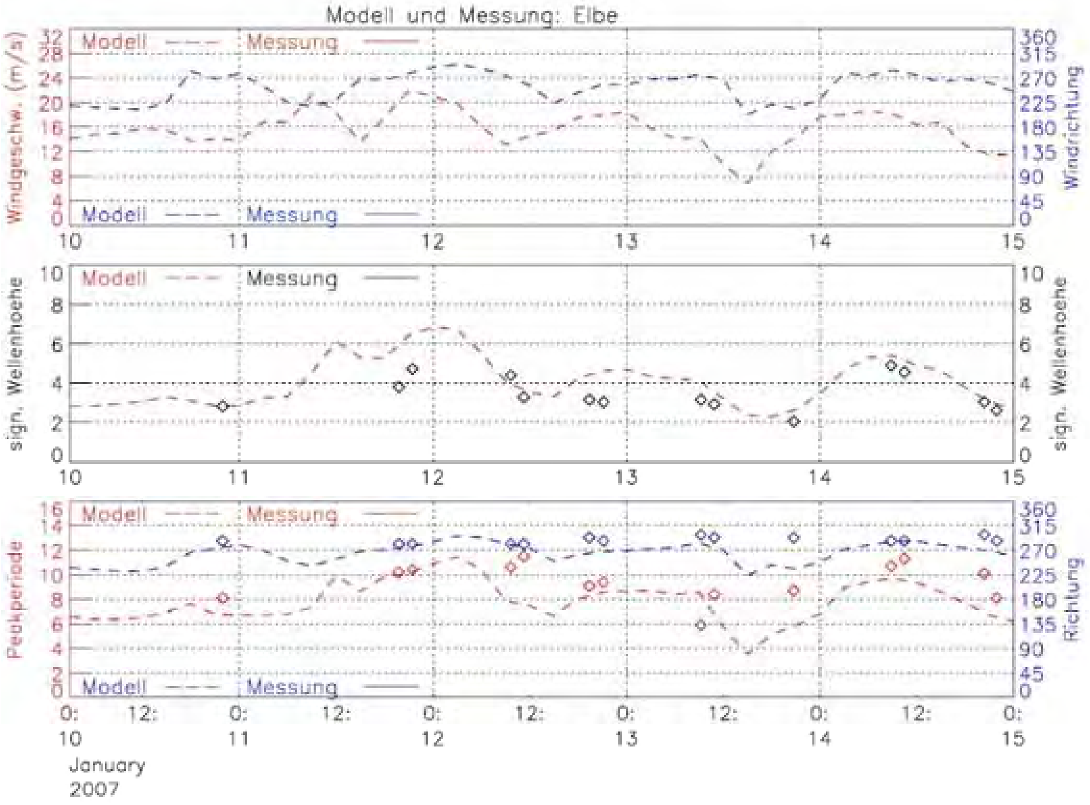

Figure 3: Weather data from the Elbe station

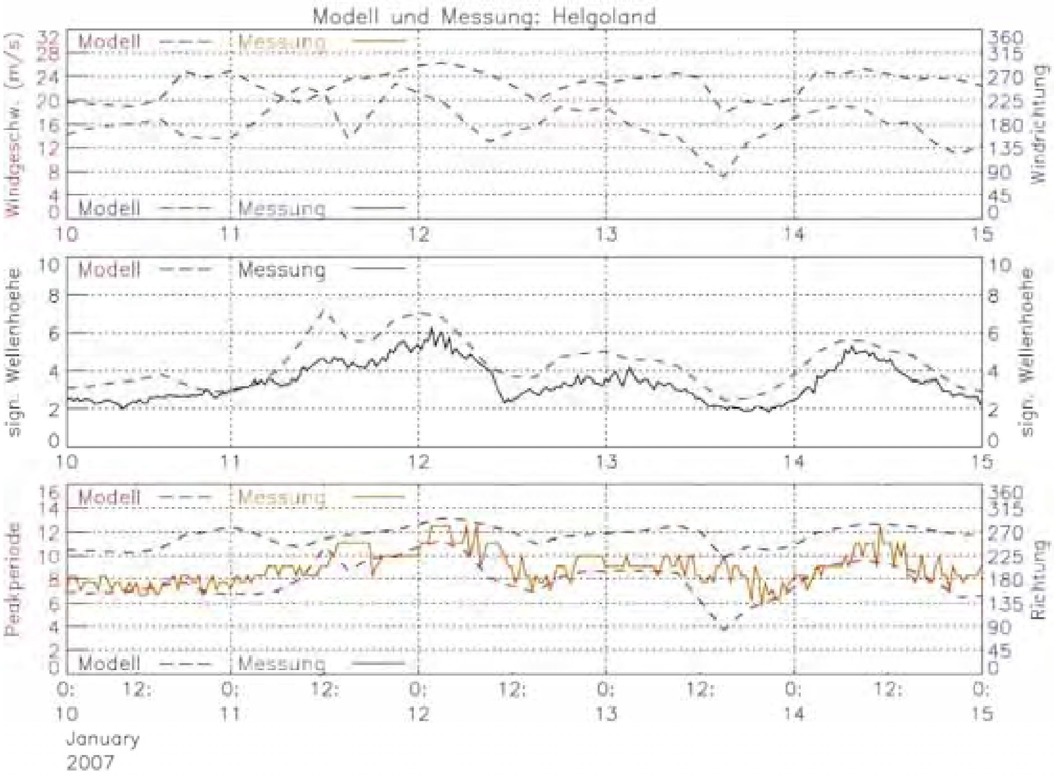

Figure 4: Weather data from the Heligoland station

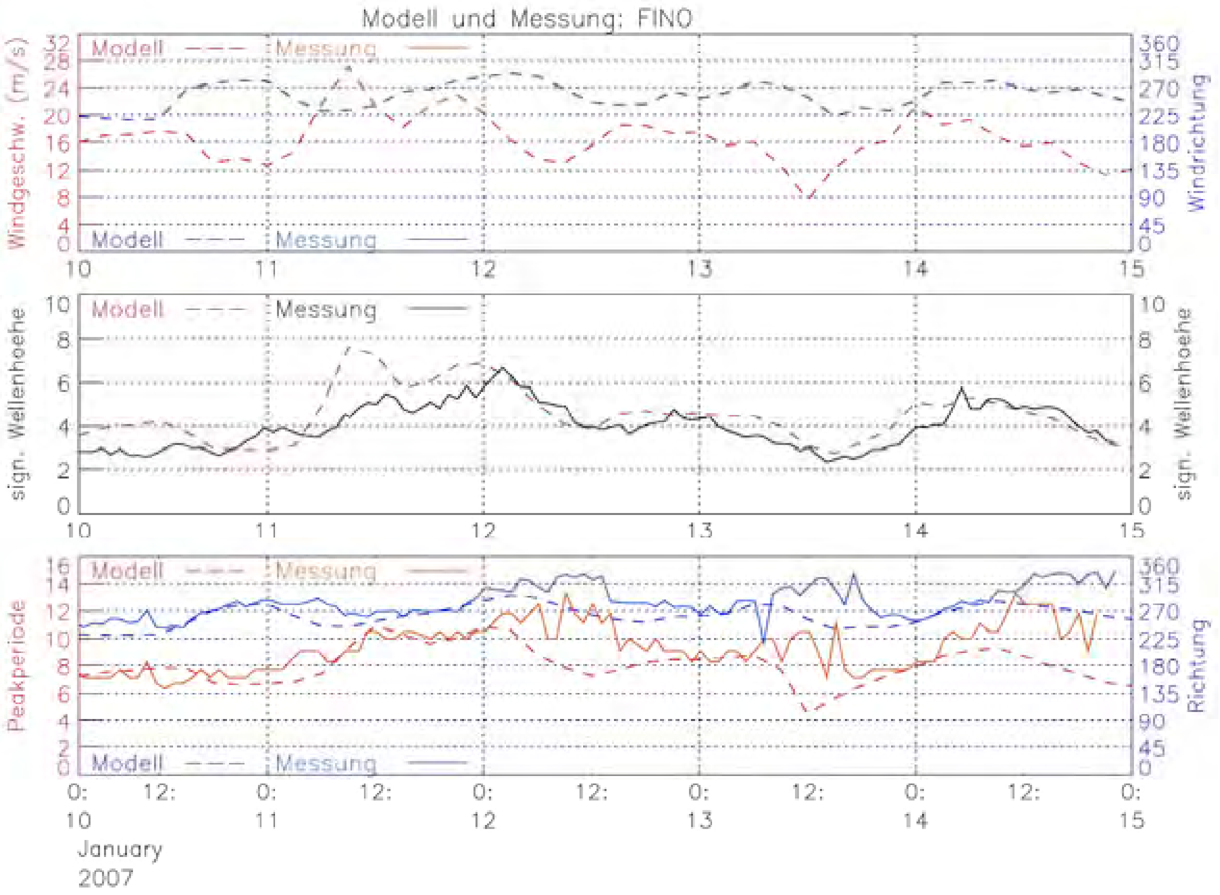

Figure 5: Weather data from the FINO station

Station Date Time	HMO	U	WD	HMO	SD	TP	HMO	SD	TP
2 NOGR	m	m/s	deg	m	deg	s	m	deg	s
2007011200	6.65	20.78	288	6.62	287	11.05	0.6	304	13.83
2007011203	6.69	19.86	295	6.58	298	11.64	1.21	327	15.46

Figure 6: DWD local sea model simulations

The calculated wave heights at the Nordergründe position (Fig. 6) are just a bit lower than at the Elbe station. However, the spatial resolution of the sea model must be taken into account; this consists of 6 nautical miles. The resolution is apparent from the grid pattern on both charts. Local differences within the grid cells (e.g. different depths of water) cannot be reproduced by the model.

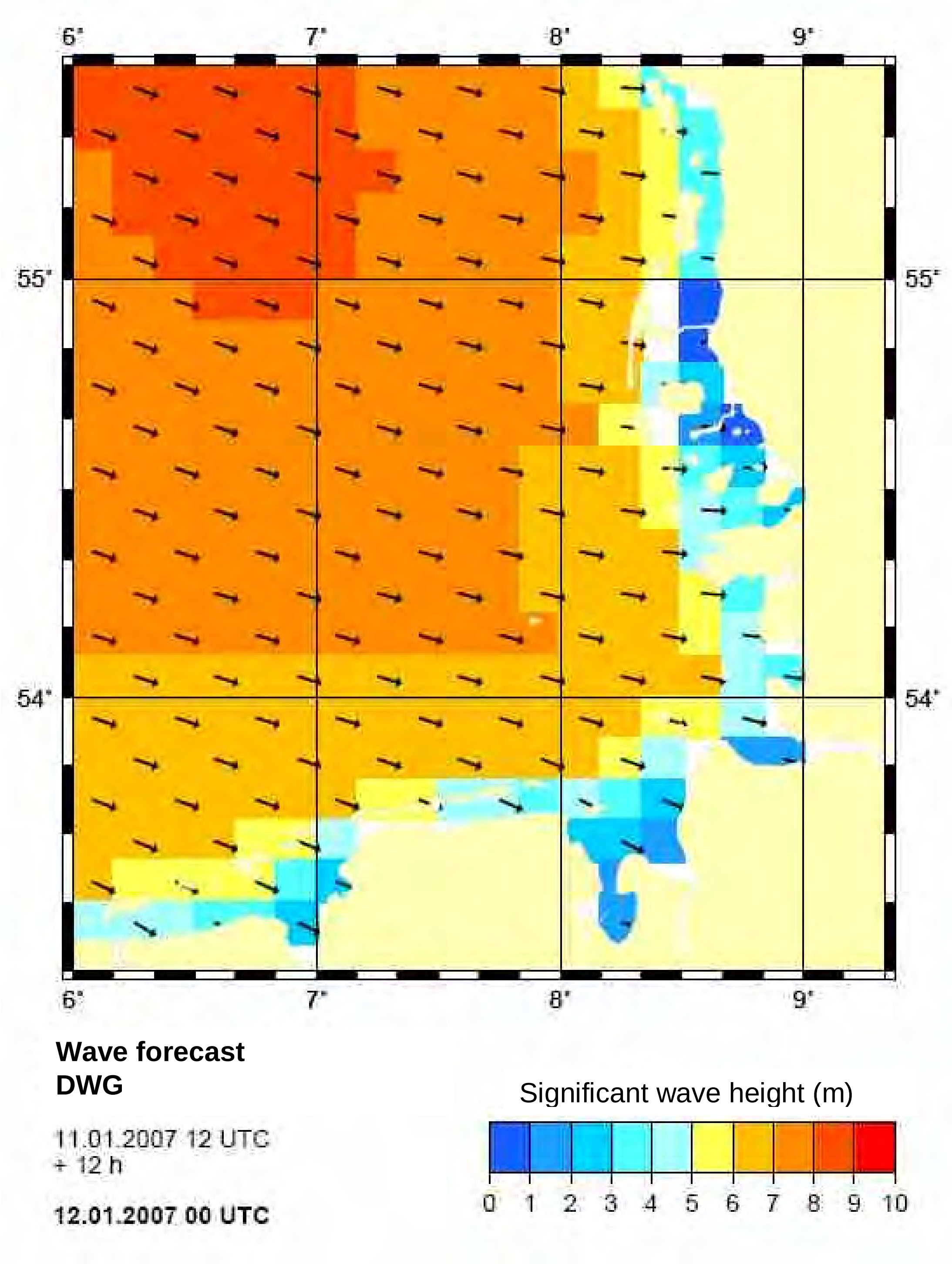

Figure 7: Wave forecast 01:00

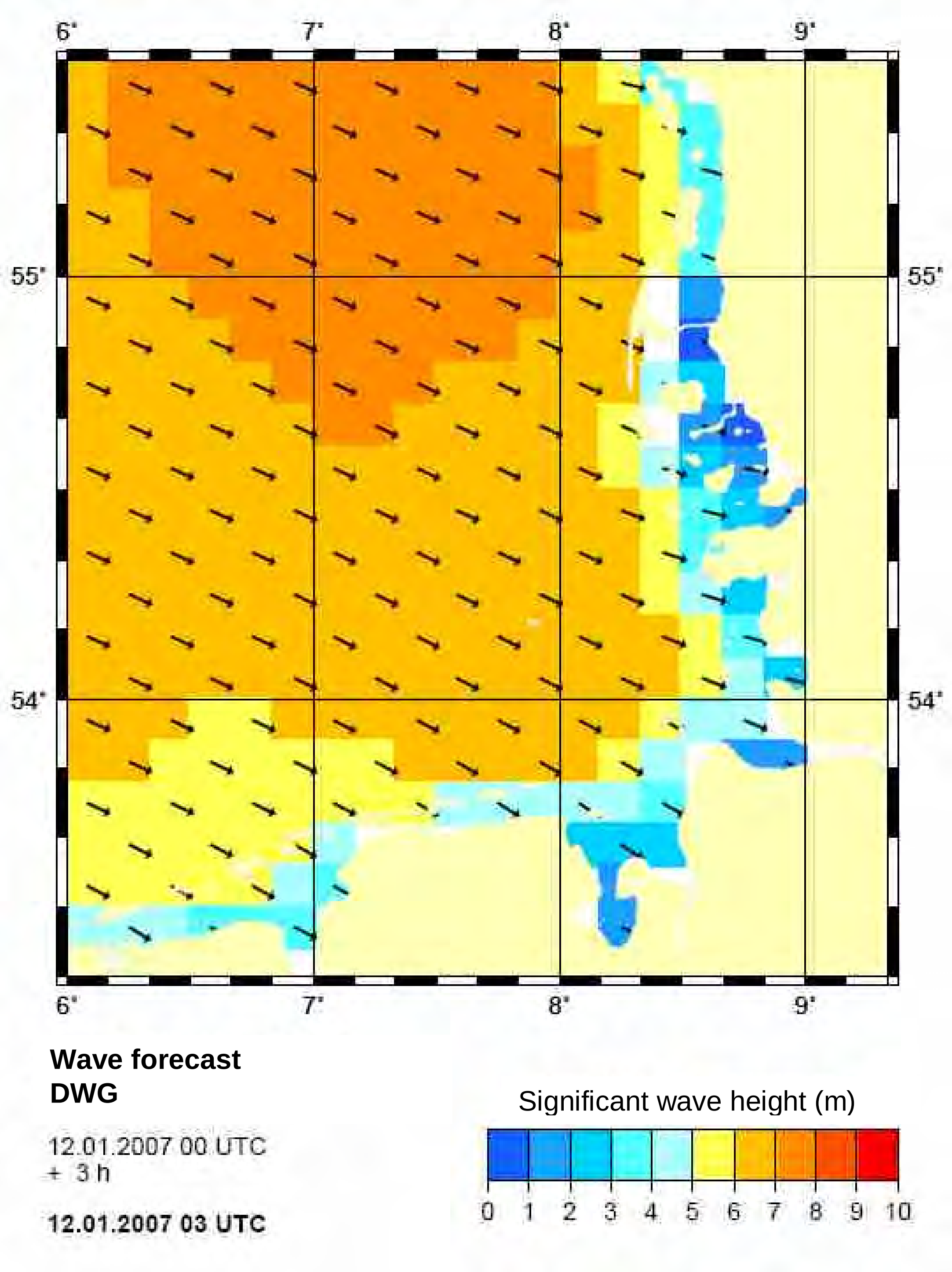

Figure 8: Wave forecast 04:00

While taking into account the inherent uncertainties, we can assume a value of about 6 m for the wave height around Nordergründe. All wave heights, measured values and model calculations are significant wave heights. The direction which the waves came from was WNW to NW. There were further discrepancies here between the measurement and the forecast at FINO. The wave periods were about 11 to 12 s at all stations with corresponding wave lengths of 150 m over a water depth of 20 m.

The following figure illustrates the environmental conditions.

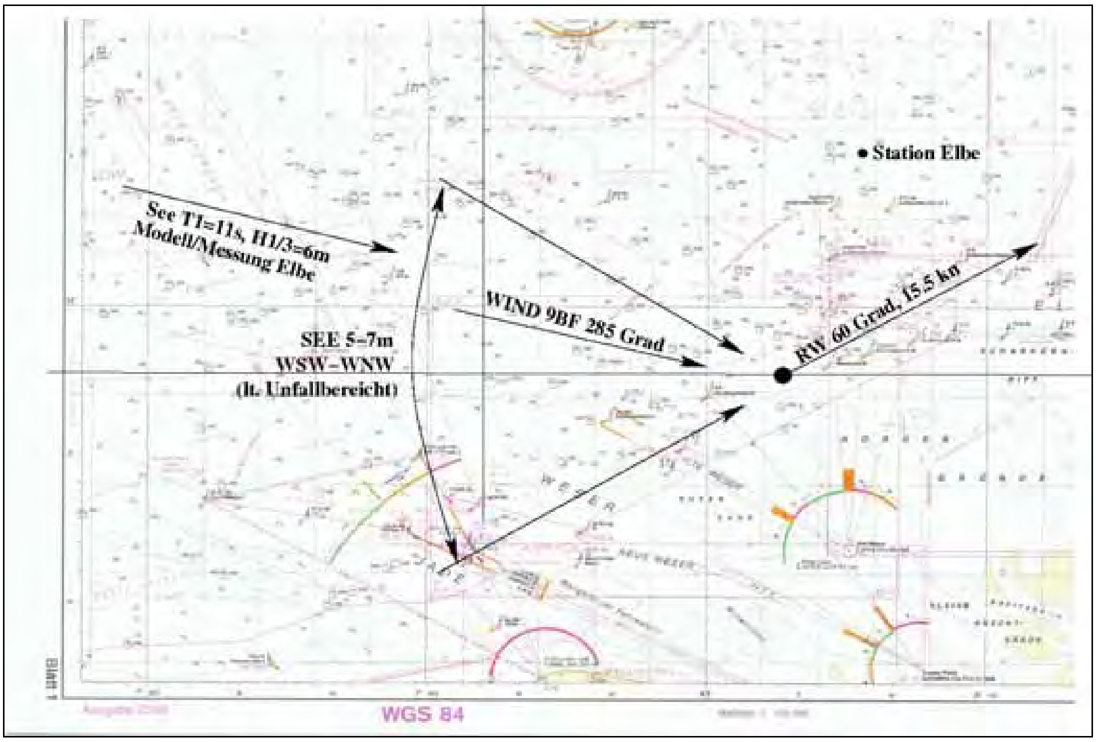

Figure 9: Summary of the situation around the JRS CANIS at the time of the accident.

5.2 Loading situation

During the investigation, it became apparent that the affected Bay 28 was not uniformly loaded. Rows 4213/4214 to 8213/8214 remained empty (see Fig. 10).
Furthermore, all containers in Bay 28 were loaded relatively heavily, to at least 9 t. Layers 3, 4 and 5 in particular were loaded with heavy containers. Figure 55 listed in the appendix shows the permissible stack weights[5].

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[5] stack weights = max. weight of the container layer

Figure 10: Loading situation at the time of the accident

5.3 Hydrodynamic investigations

The questions listed at the beginning

1. Was the loss of cargo due to resonance effects caused by sea conditions?
2. Did the crew have the opportunity to recognise this beforehand? In this respect, we should also address the question of whether the use of so-called wave and surface current monitoring software could have prevented the loss of cargo.
3. What role did the lashing material play? (Twistlocks)

were passed by the Federal Bureau of Maritime Casualty Investigation to two institutes in order to gain a more comprehensive picture of the subject matter. The Bureau commissioned both the Institute for Ship Design and Ship Theory[6] and the Warnemünde Department for Marine Studies at Wismar University of Technology, Business and Design, with preparing survey reports. Both experts had the same basic data as listed in this report.

The findings from these survey reports, as extracts or to a degree word for word, but in any case retaining the original meaning are given in the following.

5.3.1 Survey report of the TU Hamburg Harburg

The BSU presented amongst others documents including a lines plan and general arrangement plan of the ship. These were then entered into the **E4** calculation software at our institute. This program generated a computational model for all theoretical ship-related questions. The following figure shows the computational model of the JRS CANIS generated from the documents submitted to us.

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[6] at the TUHH – Technical University of Hamburg Harburg

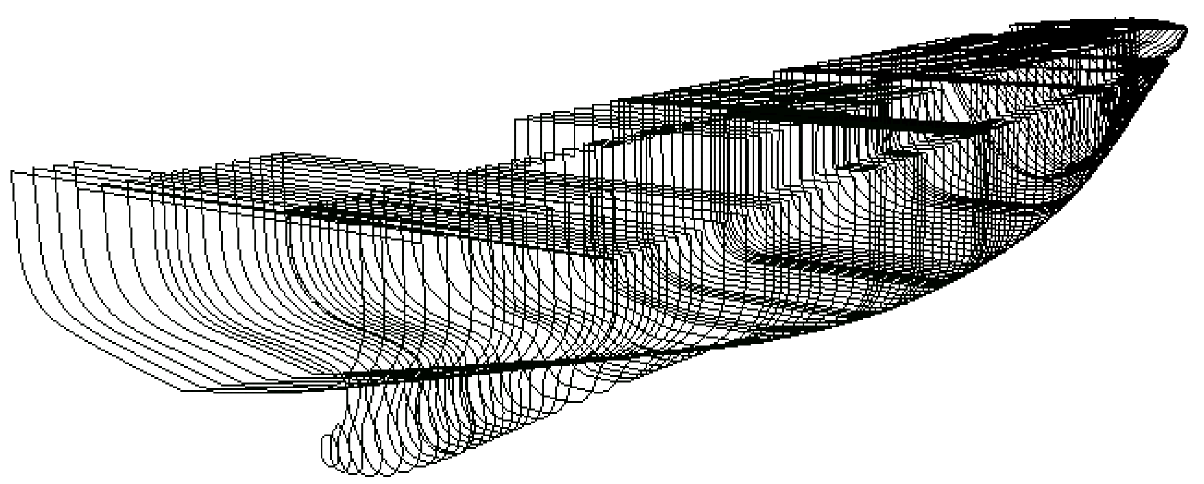

Figure 11: Computational model of the JRS CANIS

The loading situation of the ship was presented by the BSU in the form of an onboard computer printout of the MACS 3 (SEACOS). The corresponding values for ship weight and loads were also entered into our calculation software. Consequently, the condition and situation of the ship at the time of the accident (according to our calculations) was as follows:

```
-----------------------------------------------------------------------

                    Load case: ACCIDENT VOYAGE
-----------------------------------------------------------------------
Light Ship's Weight:                           4276.800 t
long. centre of gravity of light ship:           50.720 m fr. AP
transv. centre of gravity of light ship:         -0.170 m fr. CL
vertic. centre of gravity of light ship:          8.710 m fr. BL
-----------------------------------------------------------------------
Deadweight:                                    7653.700 t
long. centre of gravity of load case:             62.379 m fr. AP
transv. centre of gravity of load case:            0.056 m fr. CL
vertic. centre of gravity of load case:            8.285 m fr. BL
-----------------------------------------------------------------------
Total Weight:                                 11930.500 t
result. long. centre of gravity:                 58.200 m fr. AP
result. transv. centre of gravity:               -0.025 m fr. CL
result. vertic. centre of gravity:                8.437 m fr. BL
-----------------------------------------------------------------------

Components of Deadweight:

Payload Piecewise Items:

 Item Designation   | Mass  |  XCG  |  YCG  |  ZCG  |
                    |   t   |m f. AP|m f. CL|m a. BL|
--------------------+-------+-------+-------+-------+
Total Container     | 5642.0| 57.520|  0.010|  9.890|
--------------------+-------+-------+-------+-------+
 Total Payload Pcs | 5642.0| 57.520|  0.010|  9.890|
--------------------+-------+-------+-------+-------+
```

```
Bunker and Store Items:

 Item Designation   | Mass  |  XCG  |  YCG  |  ZCG  |
                    |   t   |m f. AP|m f. CL|m a. BL|
--------------------+-------+-------+-------+-------+
Total Diesel Oil    |   32.3| 30.420| -2.840|  7.290|
Total Fresh Water   |   93.2| 31.200|  0.480|  6.020|
Total HFO           |  316.5| 41.000|  0.920|  2.500|
Total Lube Oil      |   37.2| 23.280| -4.910|  4.990|
Total Miscellaneous |   40.8| 10.620| -1.300|  2.220|
Constanta           |  100.0| 35.000|  0.000| 10.000|
--------------------+-------+-------+-------+-------+
 Total Stores       |  620.0| 34.946|  0.014|  4.619|
--------------------+-------+-------+-------+-------+


Ballast Items:

 Tank Designation   | Fill | Rho |  Mass |  XCG  |  YCG  |  ZCG  |FrS MOM|
                    |  %   | t/m3|    t  |m f. AP|m f. CL|m a. BL|  mt   |
--------------------+------+-----+-------+-------+-------+-------+-------+
Total Ballast       |  0.00|0.563| 1391.7| 94.300|  0.260|  3.410|   595.|
--------------------+------+-----+-------+-------+-------+-------+-------+
 Total Ballast                   | 1391.7| 94.300|  0.260|  3.410|   595.|
--------------------+------+-----+-------+-------+-------+-------+-------+


Equilibrium Floating Condition of Case:
ACCIDENT VOYAGE

Shell Plating Factor:   1.006   |Density of Sea Water:   1.000 t/m3
-----------------------------------------------------------------------

For the determination of the floating condition, the VCG is
corrected for all partly filled tanks according to the initial
free surface moment as stated in the load case item tables below.

-----------------------------------------------------------------------

Equilibrium Floating Condition :

Ship's Weight                          :  11930.501 t
Longit. Centre of Gravity             :     58.200 m.b.AP
Transv. Centre of Gravity             :     -0.025 m.f.CL
Vertic. Centre of Gravity (Solid)     :      8.437 m.a.BL
Free Surface Correction of V.C.G.    :     0.075 m
Vertic. Centre of Gravity (Corrected)  :      8.512 m.a.BL
Draft at A.P    (moulded)             :      7.499 m
Draft at LBP/2  (moulded)             :      7.289 m
Draft at F.P    (moulded)             :      7.080 m
Trim (pos. fwd)                       :     -0.419 m
Heel (pos. stbd)                      :      1.081 Deg.
Volume (incl. Shell Plating)          :  11930.501 m3
Longit. Centre of Buoyancy            :     58.184 m.b.AP
Transv. Centre of Buoyancy            :     -0.108 m.f.CL
Vertic. Centre of Buoyancy            :      4.113 m.a.BL
Area of Waterline                     :   2184.080 m2
Longit. Centre of Waterline           :     53.931 m.b.AP
Transv. Centre of Waterline           :     -0.188 m.f.CL
Metacentric Height                    :      1.336 m
```

Our calculations, when compared with the values of the onboard computer, give the following draughts:

	TUHH	MACS 3
D aft	7.499 m	7.49 m
D mid-section	7.289 m	7.29 m
D fore	7.080 m	7.08 m
GM	1.336 m	1.32 m

The discrepancies are virtually negligible so we must assume that the shape of the ship and the loading situation have been recorded with a sufficient degree of accuracy by our model. Any additional free surfaces that may have arisen from consumption of fuel or such like between departure up to the time of the accident (compared with the onboard printout) are in any case so minimal that they have no measurable influence on the result. For this reason, they have been eliminated from consideration in the following.

Another thing to establish is that the mean draught is lower than the draught at summer freeboard, i.e. the ship was definitely not overloaded. Similarly, the GM with a value of 1.32 m is clearly above the minimum GM value of 0.80 m, i.e. the ship's stability was in any case sufficient according to applicable regulations.

The righting levers of the ship are reproduced in the following figure, for still water (left) and also for an assumed wave 170 m long (about 11 s) and 7 m high (right).

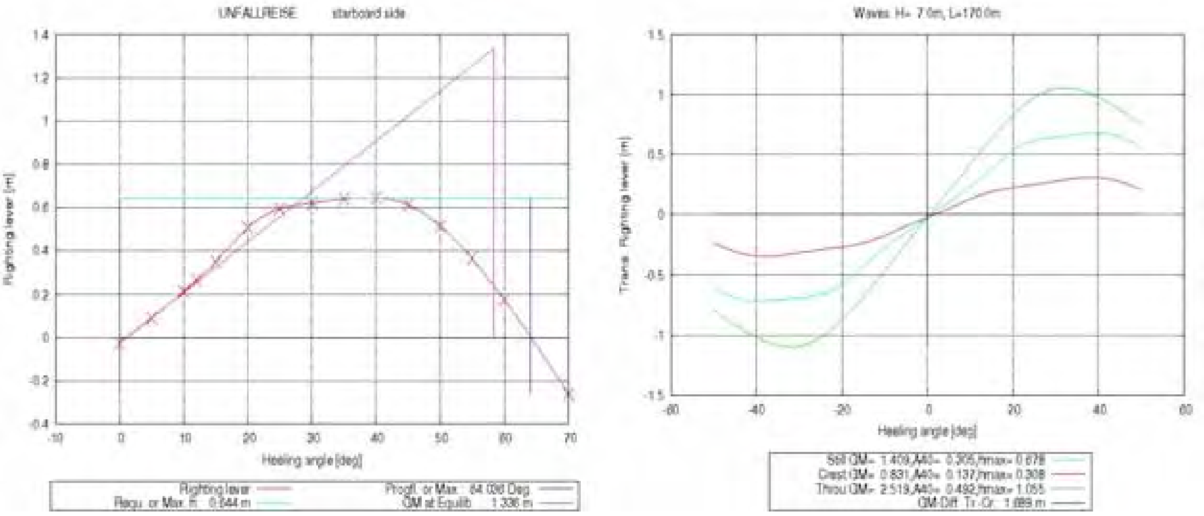

Figure 12: Righting lever curves for still water as well as crests and troughs for the JRS CANIS.

The still water levers indicate very good stability; the maximum lever is about 0.64 m and the range of stability is more than 60°. For the assumed wave measuring 170 m long and 7 m high, there are clearly positive lever arms with a very large range. Prior investigations by our institute have shown that a ship can be viewed as sufficiently secure against loss of stability at sea when the area under a still water lever arm curve of up to 40° makes up approx. 70 % of the differential area between wave crest and trough. These conditions are met for this case.

Consequently we believe not only that the existing stability met applicable regulations, but that the stability is also sufficient to prevent loss of stability in heavy weather. Since the ship's stability is very good, there is no immediate danger to the ship in stern seas in respect of the stability of the ship, as long as no directly critical resonances are encountered. In any case, the stability must have appeared sufficient to the crew even in stern sea.

5.3.1.1 Some principles regarding excessive roll angles in heavy weather

Vessels in heavy seas are essentially at risk when the sea is a head sea or stern sea. This is due to the periodically changing lever arms in the waves. Since the vessel is not directly forced into a rolling motion (such as e.g. in a beam sea), but is indirectly influenced by the periodically changing lever arms, we call this type of rolling motion parametric excitation **or parametric rolling**. Fundamentally the vessel is at risk in these circumstances from two phenomena which mostly occur in combination: In principle, the stability for practical vessel shapes is always lower on the wave crest than in still water, and is always higher in the trough than in still water. The change in stability here depends solely on the vessel's shape not on the stability itself. The behaviour of the vessel at sea is essentially determined by the relationship of the actual stability to the fluctuations in stability at sea.

If the overall vessel stability is low or there are large fluctuations in stability and the crest stability is too low or even negative, then this can lead specifically to extreme roll angles if the ship rides for a long enough period on the crest. This phenomenon is called **loss of stability on the crest** (or pure loss of stability). Since this loss of stability relies on the vessel riding for a sufficiently long period on the wave crest, there is nearly always a pure loss of stability with a stern sea, because that is the only time when the relative speeds between vessel and wave crest are sufficiently small. However, this so-called loss of stability hardly ever appears in its pure form, but is most often superimposed by other effects. If substantial heeling occurs due to e.g. loss of stability in a stern sea, then in extreme cases the ship can **broach**; a phenomenon that used to be seen often in capsizing accidents with smaller-sized coasters. The so-called resonance effects are particularly hazardous in head and stern seas. In this case the wave encounter periods fall at the same time as either the single (1:1) or double roll period (2:1) of the ship. The so-called **2:1 resonance** is especially hazardous, which is characterised by one roll period per two pitch periods. This resonance is particularly hazardous because the wave crest is (about) at the midship section when the vessel is floating (roughly) upright which makes the vessel heel to one side due to the loss of stability. Once the ship has reached the maximum heeling angle, the wave crest has roughly reached the prominent ends of the ship, and the ship is up-righted violently. As a consequence of this interplay, extremely severe rolling motions can quickly be generated in areas of **irregular waves**, whereby the wave related lever arm fluctuations between wave crest and wave trough work as an essential influencing variable. These lever arm fluctuations must generally take on critical values, which certainly happens with common vessel shapes when the wave length is about 0.7 - 1.3 times the length of the ship, whereas it must be said that the shorter waves, e.g. 0.7L are often the most dangerous. In order for the wave encounter period to coincide approximately with the double roll period, there have to be particular relationships between the initial metacentric height of the ship (presupposing that the righting lever for small inclinations can be expressed with sufficient accuracy by the straight line of the initial metacentre, which is the case in this incident with up to approx. 15°, cf Fig. 12 on left), the encounter angle and the vessel's speed with a given sea state (significant wave length 0.7 - 1.3 L). We need to differentiate here fundamentally between two cases:

If the vessel is sailing **in stern seas**, then a 2:1 resonance is generally only possible with relatively low to average vessel speed, and also only then when the initial metacentric height is very low. This is then practically expressed in very large roll angles which can lead to capsizing but which due to the low stability do not generate very high accelerations. An additional point essential for understanding the processes in stern seas is the fact that the natural roll period of the vessel can itself be subjected to severe fluctuations as it is not the initial metacentric height of the still water condition that is relevant at sea but the corresponding crest and trough conditions. This means that the natural roll period of the vessel adjusts to the corresponding excitation, in fact to an increasing range as the wave stability between crest and trough changes. In practice, this implies that there is no sharp resonance with an irregular stern sea (as there is with a regular sea state), but there is always a wide band width of courses and velocities which can generate excessively large roll angles. If the ship has very large stability fluctuations between crest and trough simultaneously, which are only dependent on the hull shape but not on the absolute stability itself, while at the same time retaining very low stability, then excessively large roll angles can be generated in stern seas in very many situations because the approximate coincidence of the double natural rolling period with the loss of stability on the wave crest are superimposed over each other. **For the vessel's command, this means that the vessel must not move too slowly when sailing in stern seas with low stability,** as otherwise there is a risk of entering the 2:1 resonance and putting the vessel in considerable danger (presupposing that the vessel does not broach-to).

If the vessel is sailing **in a head sea**, then the 2:1 case will only occur with a relatively high initial stability, likewise at relatively low speeds. Due to the high initial stability, excessively large roll angles are usually not generated (large here meaning roll angles that could lead to capsizing), although extremely large accelerations are often created. In fact most cases of loss of cargo were observed in conditions where the vessels were moving slowly in a head sea with a very large GM, which has internationally led to the conclusion that so-called parametric roll only occurs in head seas. In contrast to stern seas, the riding period of the vessel on the crest while sailing in a head sea is relatively brief, and if absolute stability is sufficient, the vessel does not adapt so well to the excitation as in a stern sea. This practically means that the 2:1 resonance in head seas must be encountered exactly to generate really large roll angles.
In this context, an important situation in a head sea is one where also large roll angles can be generated although they should not be designated primarily as parametric roll: If the vessel is running with force against a head sea and is hit by a large wave against an extremely prominent forward frame, then it will loose speed drastically and in extreme cases it will stop. As a result of this, the next wave(s) that hits the ship can create a considerable roll angle because there is hardly any roll damping due to the reduced speed. However, this is separate phenomenon.

The so-called **1:1 resonance**, where one roll period coincides with one pitch period, usually occurs with vessels solely in stern seas, and usually at relatively high speeds likewise with low stability. Since the roll damping effect is often very high due to relatively high speeds, the 1:1 resonance generally does not generate such hazardous roll angles as the 2:1 resonance. These general effects are illustrated in the following polar co-ordinate diagrams:

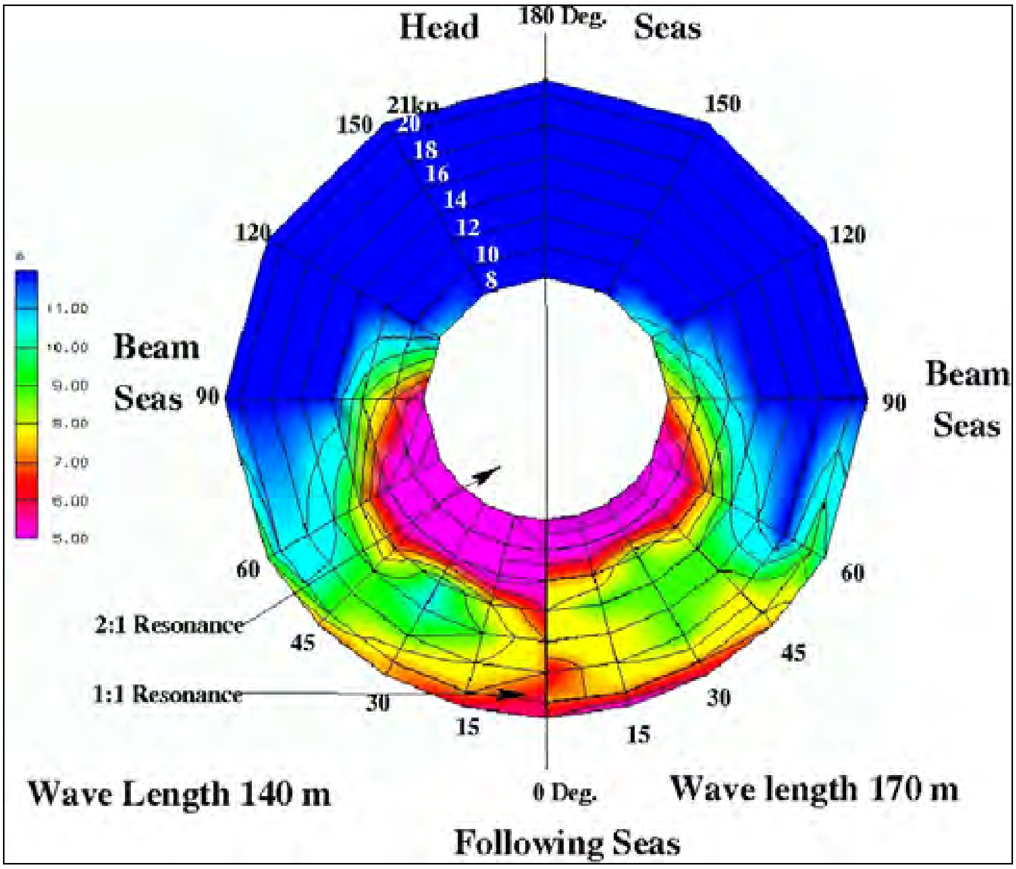

Figure 13: Illustration of the basic wave effects

for severe rolling in a natural sea state for a 5000 TEU container ship with two different significant wave lengths. The colours denote at which (significant) wave heights a certain roll angle is exceeded.

Fig. 13 shows a polar co-ordinate diagram for a typical 5000 TEU container ship that runs with an approx. 1.0 m GM. The ship's bow is always pointing up, and the encounter angle between ship and sea is dissipated in circumferential direction. The ship's speed is plotted on the radial axis. Each diagram is coloured according to the significant wave height which leads to a certain roll angle being exceeded. On the far left, the behaviour of the ship in a sea state with 140 m significant wave length is shown; the right-hand section for a significant wave length of 170 m. (Because the diagrams come from a simulation, the waves could also be higher than the actual maximum given for this particular length.) Initially you see a pink stripe of very low wave heights. These wave heights lead to the roll angle being exceeded in particular for encounter angles between about 0-45° (0 degrees means an exact stern sea, 180 degrees means an exact head sea.) This area can be directly allocated to the 2:1 resonance which would lie between about 4 and 6 kn depending on the encounter angle. This very nicely shows how the ship adjusts to the excitation as a wide range of courses and speeds leads to large roll angles. Somewhat less defined, we see the

1:1 resonance in stern seas which is at about 20-21 kn for a GM of 1.0 m. Since the roll damping effect is considerable, you need much higher waves to produce a roll angle corresponding to the 2:1 situation. On the right-hand side of the image, you see the same ship but in longer waves with a 170 m significant length. You can clearly see that the critical resonances overall have shifted to lower speeds. Otherwise the image is very similar to the previous one. Even longer waves would shift the critical resonances overall to even lower speeds.

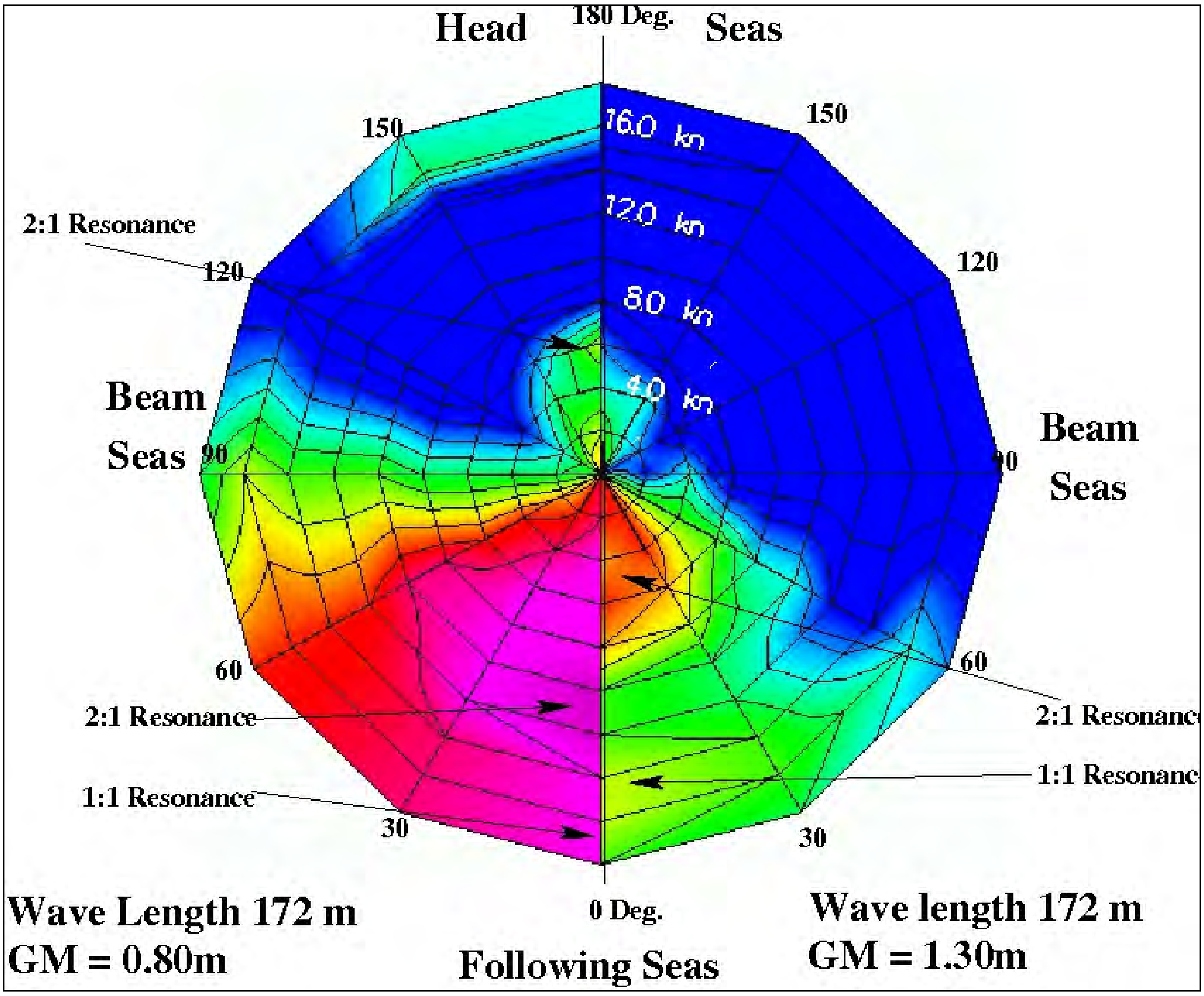

Figure 14: Wave effects for severe rolling

Illustration of the basic wave effects for severe rolling in a natural sea state for a RoRo ship with two different stability conditions. The colours denote at which (significant) wave heights a certain roll angle is exceeded.

Fig. 14 is a polar co-ordinate diagram for a RoRo ship which overall has too low stability with simultaneously extreme lever arm fluctuations. Consequently, with a GM value of 0.80 m, the problem of loss of stability on the wave crest dominates. Large roll angles are thus generated for nearly all courses in stern seas. On the other hand, the 2:1 resonance is clearly recognisable, and the 1:1 resonance in stern seas is also apparent. Due to the very large initial GM with simultaneously large fluctuations, we can now also identify the 2:1 resonance in a head see, at about a 6 kn heading. Since the ship rides for longer on the crest at lower speeds and roll damping simultaneously declines, large roll angles can still be generated at speeds lower than

6 kn in head seas. The image becomes completely different when the stability is increased (far right). Now the critical resonances shift again to lower speeds, but at the same time the effect of the loss of stability on the wave crest loses significant as the ship now has thoroughly positive levers on the crest due to the generally high range of stability. The 2:1 resonances are still identifiable (specifically at lower speeds) but their effect in respect of large roll angles is considerably reduced. A qualitatively comparable effect would have also occurred if the GM increase had not been created by a reduction in the level of the centre of gravity, but e.g. by a very stern-heavy trim. In any case, the examples show that in addition to the actual resonances (1:1 and 2:1) there are many other situations in which a ship can be at risk of large roll angles, and at the same time not every resonance automatically leads to the ship being at risk. In the context of the questions to be addressed in this survey report, the following factors are therefore crucial:

In general, vessels with low GM values in stern seas are at risk and this is where primarily large roll angles occur. If the stability is low, then critical situations do not in general occur in head seas unless the stability is extremely low. If the ship in a stern sea has high stability, it is generally not at risk, but in head seas it can experience large rolling accelerations, although the roll angles generated are not too major due to the high range of stability.

<u>These considerations apply in principle for all vessels.</u>

In extreme cases, it could however present a danger for the vessel in situations which lie outside the critical resonances. No general recommendations can be given for this at all as the movement of the vessel depends very individually on the specific response of the vessel in the relevant sea state. For a given sea state, course and speed, this also depends decisively on the individual hull shape, its lever fluctuations, and on the inertia of the ship and its roll damping.

For completeness' sake, it is worth mentioning that large roll angles or roll accelerations can occasionally also be generated if the ship is broaching-to. This is generally the case if the speed is low or even at zero (so-called **dead ship condition**). Large roll angles are generated when waves collide with the ship diagonally to the ship's own natural rolling frequency. The roll damping effect can be very low due to the low speed. On the other hand, a considerable proportion of the energy exposed to the ship by the sea is dissipated by the drifting motion of the ship; consequently this situation generally poses no real risk for the ship in respect of capsizing.
There is generally only a risk in a beam sea for small ships with very high GM values, primarily when they have high mass moments of inertia.

5.3.1.2 Brief description of the used seaway simulation program E4ROLLS

The simulation code ROLLS which forms the basis of our seaway methodology was developed by Söding and Kröger at the former institute for ship building at Hamburg University in the context of investigating the capsizing accident of the E.L.M.A. TRES in 1987.
ROLLS has been especially developed for calculating large roll angles in (approx.) head and stern seas where it is particularly important to detect the non-linear aspects

of the rolling motion. (If you were to detect the rolling motion linearly, as e.g. in linear strip methods, then you would replace the lever arm curve of the ship with the straight line of the equation $h=GM*\varphi$, i.e. the risk of the ship capsizing would be excluded right from the start.) The concept of the program is to describe the movement of the ship in all 6 degrees of freedom, while however only applying the rolling motion and longitudinal movement non-linearly. The other motions, namely pitch, heave, yaw and sway are calculated by linear transfer functions. However the interplay with non-linear motions is taken into consideration. The linear transfer functions are calculated with a program that calculates the hydrodynamic masses using the Rankine source methods according to Yeung. In contrast to the old Lewis frame method, it has the advantage of being better able to take into account the general hull shape, which delivers better results primarily for large B/T ratios which are common for RoRo ships or ferries. The righting lever of the ship at sea is calculated using the approved concept of Grim's equivalent wave. This makes the program extremely quick, meaning that numerous situations have only become calculable as a direct result of the program. Since the sway and yaw of the ship can only be detected linearly, ROLLS cannot describe the broaching-to of a ship. For the same reason, the risk of a broached ship at low speeds is overestimated by ROLLS because the energy exposed to the ship by the sea is not sufficiently converted into a drift motion.

In the context of the BMBF[7] sponsored joint project ROLLS, SinSee[8] and LaSSe[9], the method was consistently redeveloped by the FSG[10]/TUHH consortium to give us the current version of this method, the E4ROLLS, which has also been validated by extensive model tests at the HSVA[11]. In the BMBF project LaSSe, numerical tests of major capsizing incidents were carried out where the additional effects of shifting of cargo or water ingress were also modelled. At the HSVA, the code has been validated and applied successfully for some time for capsizing problems of RoRo passenger ships where large volumes of water can penetrate the car deck. If you require more information on the seaway simulation code E4ROLLS, please go to our website at www.ssi.tu-harburg.de.

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[7] Federal Ministry of Education and Research

[8] Simulation and test methods which can be used to investigate capsizing behaviour under extreme sea conditions

[9] Loads on ships at sea

[10] Flensburger Schiffbau-Gesellschaft mbH & Co KG

[11] Hamburg Ship Building Test Institute

5.3.1.3 Some results of the linear strip theory

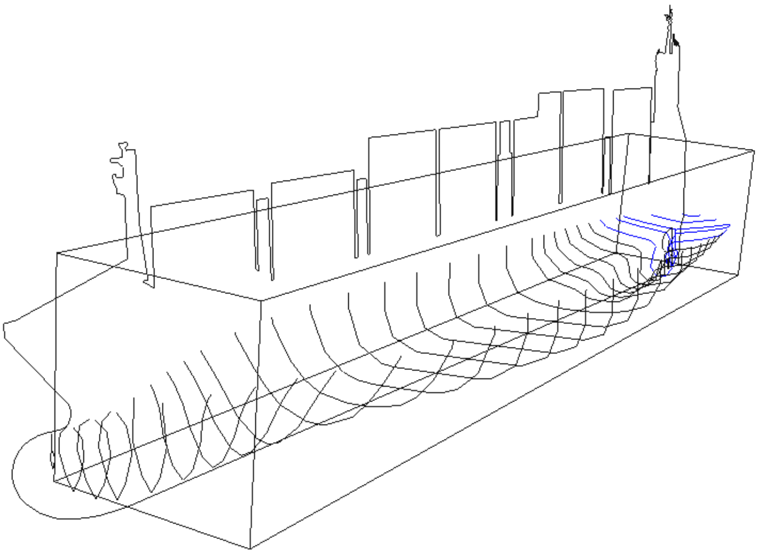


Figure 15: Computational model for determining linear transfer functions. The cuboid represents an equivalent that has similar moments of inertia.

The linear transfer functions were calculated based on the hull shape and the submitted cargo distribution of the ship. To calculate the mass moments of inertia for the light ship, a normal mass displacement for this type of ship was used from our database. The influence of these kinds of discrepancies on the overall result is negligible in our experience. Consequently, a roll inertia radius was determined for the JRS CANIS of 0.37 B dry (i.e. without the proportion of hydrodynamic masses) and 0.39 B including the hydrodynamic mass. This gives a roll period in still water of about 13.7 s, which, due to the lever arm characteristics of the ship, is valid up to about 15°. Above 15°, the roll period declines somewhat because the lever arm curve is above the straight line h=GM*φ. However, these observations are only valid for still water and could be different at sea (see above). In general, no unusual effects, such as an increased tendency to pitching or heaving, were established when calculating the transfer functions. For this reason, there is no initial expectation that the non-linear simulations in the time domain will deliver any unusual results in this respect.

5.3.1.4 Regarding the question of applying environmental conditions

The question regarding the actual environmental conditions to be applied is always the point of greatest uncertainty for investigations such as this. This is because even with good visibility it is extremely difficult to assess the sea state from onboard. This applies both to the significant height and to a greater degree to the significant period. In this case, the incident occurred in relatively flat water with a depth of 20-25 m, where the tendency to ground swells can be taken for granted. Our simulation code creates an irregular sea state with the aid of a JONSWAP spectrum where the energy distribution is applied using a $\cos^2$ distribution. This is certainly why the steepness of the waves is underestimated where there are ground swells.
However, the BSU presented us with measurements from nearby sea state measuring stations. Data from the ELBE station (see Fig. 3) appeared the most suitable for our investigations.

According to the ELBE measurements, or rather according to the measurements submitted by the BSU, the approximate sea direction at the time of the accident was 280-290° (i.e. an encounter angle of about 45° from the aft) with a significant period of 10-11 s and a significant wave height of 8 m. The wind speed was about 18 m/s. These values tally very well with the information from the crew; no information was given for the wave period.
However, since the measurements (or model calculations) are associated with specific uncertainties, all calculations are carried out for several significant periods.
There is an additional uncertainly arising from the influence of the current which can lead to a falsification of the actual period.
For this reason as well, all calculations are made based on a wide range of coincidental sea states.

5.3.1.5 Results for non-linear sea state calculations: roll angle

The crew stated that the ship had rolled several times at an angle of 15-20° before the loss of the cargo. Angles (especially roll angles) are often assessed very realistically by the crew in contrast to assessments of the sea state. For this reason, it makes sense to initially check in what kind of situations the aforementioned roll angles are reached. This is not just important in order to make an assessment of whether the ship was endangered by critical resonances (although a resonance, as explained above, does not always give an accurate statement regarding the specific risk status of the ship). Primarily, this allows us to clarify whether all known factors fit within the context of the simulation. Consequently, computations were made for different significant periods, namely 9.5 s, 10.5 s and 11.5 s (correspondingly significant wave length in deep water of 141, 172 and 206 m). The 9.5 s period was also considered since the associated significant wave length (in deep water) corresponds roughly to the ship length.

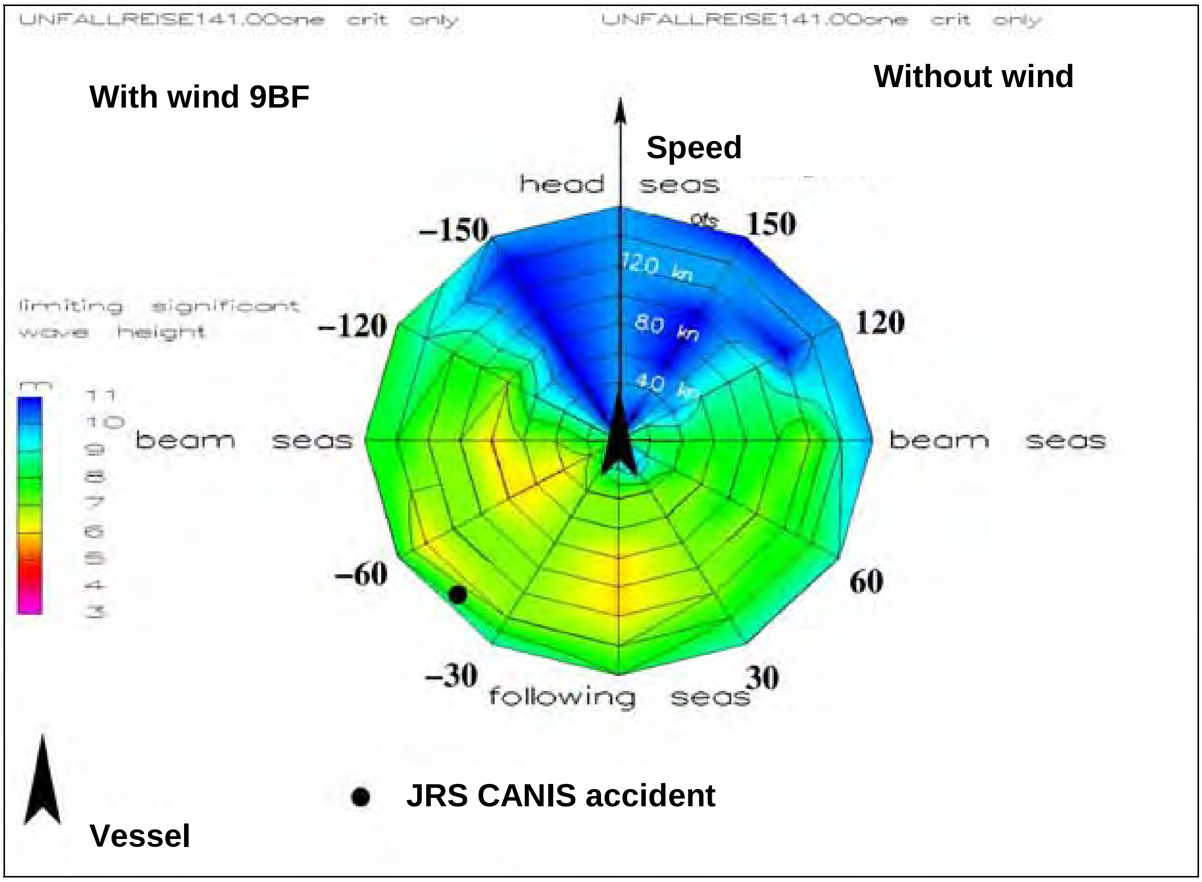


Figure 16: Calculated significant wave heights for generating a roll angle of 20°, **significant period 9.5 s**

Calculated significant wave heights for generating a roll angle of 20°, 99 % quantile (i.e. 99 % of the calculated roll angle is below 20°), significant period 9.5 s. Left side of the polar co-ordinate diagram: Including the influence of a 9 Bft wind, right side: without the influence of wind.

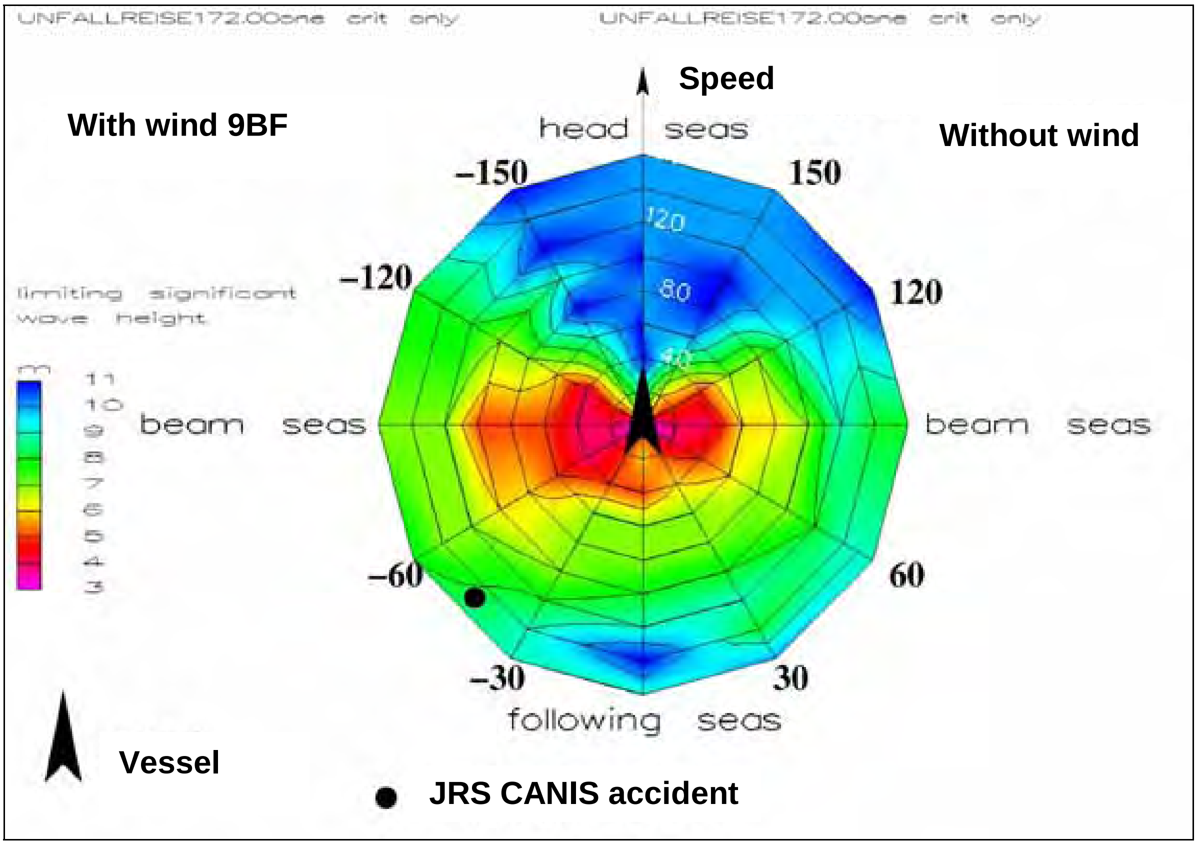


Figure 17: Calculated significant wave heights for generating a roll angle of 20°, **significant period 10.5 s**

Calculated significant wave heights for generating a roll angle of 20°, 99 % quantile, significant period 10.5 s. On the left: Including the influence of a 9 Bft wind, on the right: without the influence of wind.

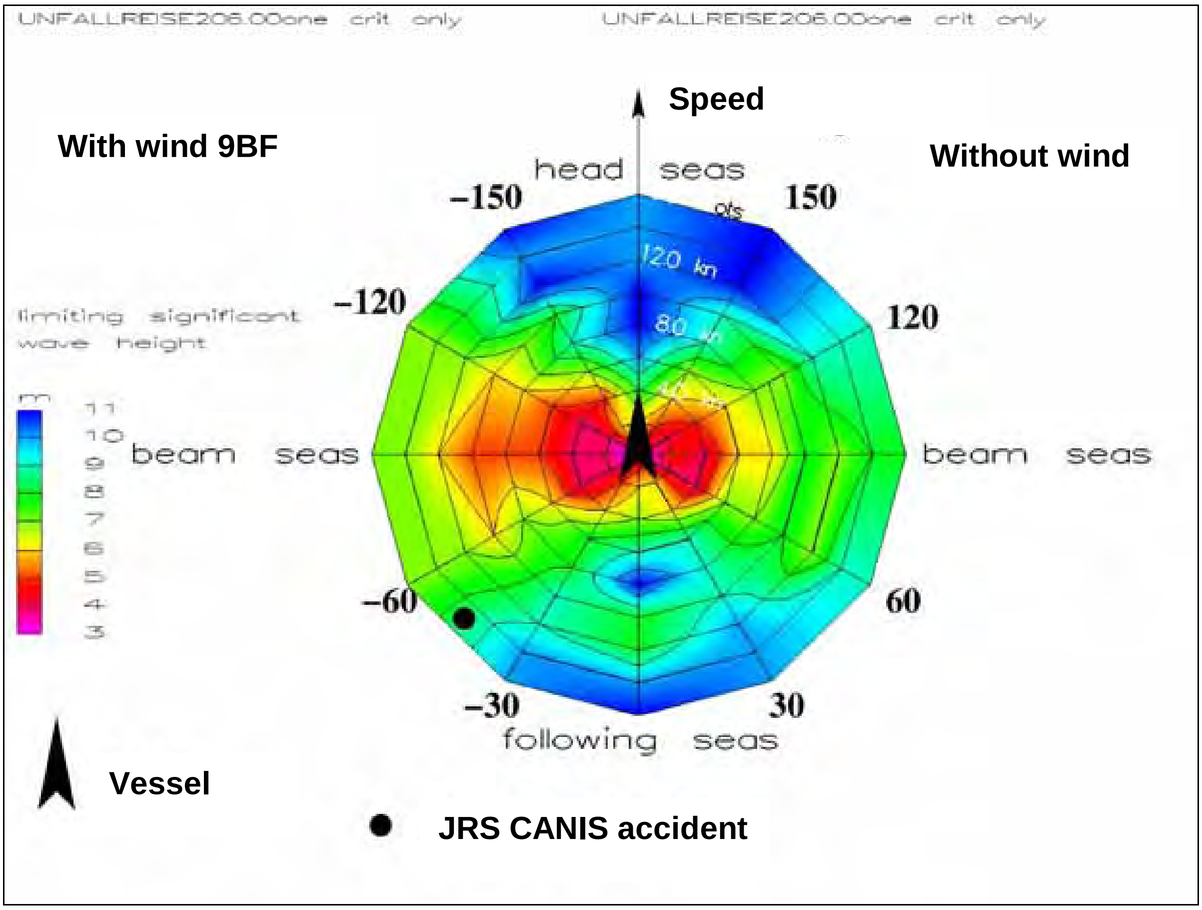


Figure 18: Calculated significant wave heights for generating a roll angle of 20°, **significant period 11.5 s**

Calculated significant wave heights for generating a roll angle of 20°, 99 % quantile, significant period 11.5 s. On the left: Including the influence of a 9 Bft wind, on the right: without the influence of wind.

Initially, the results of the calculations generally show that a roll angle of about 15-20° (as observed by the crew) is achieved with a fair degree of probability taking all three situations into account. Accordingly the statements of the crew are realistic. Since the significant period was supposedly between 10.5 and 11.5 s (which would dictate a tendency for the waves to have been on the steeper side than is given in our model due to the formation of ground swell) the occurrence of the specified, repeated roll angle of 15-20° can be viewed as very probable. Due to the very large range of vessel stability, the 2:1 resonance has practically no effect, likewise the 1:1 resonance. This corresponds to the aforementioned expectations, that we cannot fundamentally assume a risk state in a stern sea due to the stability being more than sufficient. Furthermore, calculations show a certain influence by the wind, i.e. that the heeling angle generated is somewhat more pronounced due to the wind. However, the influence is not so major that it can be viewed as the cause of the loss of cargo. An interesting fact is that a risk state when broaching-to at low speeds is indicated for larger wave lengths. As a result the transfer functions of the rolling motion were examined once again and they showed that the linear transfer functions reach their peak roughly in the range of a period of 11-15 s at speeds of between 0 and 8 kn (Nb: The natural roll period of the vessel at the time of the accident was about 13.7 s). However, due to linearisation of the sway, the rolling motion of the vessel is overestimated by our simulations. In any case, the fact (confirmed unanimously by all calculations) is **that the situation that led to the accident most certainly was not triggered by a resonance effect.** Using the most probable significant periods as a starting point, the vessel rolls at approx. 20° on nearly all courses and at nearly all speeds. If there was indeed a risk from resonance, then this only applied to a broaching situation at low speeds.

According to a statement by the crew, the vessel was steering a course of 330° at approx. 7 kn before the actual accident. According to calculations, this situation would have also generated larger roll angles where the ship would have pitched more severely than in a stern sea. This tallies with the statement by the crew:

"At this point the ship pitched and rolled severely."

There was no statement made concerning the degree of the roll angle. Consequently, the following section will determine the accelerations in both situations that would affect the container stacks in question.

In summary, the following can be established from an analysis of the situations and conditions that lead to an approx. 20° roll angle: The roll angle observed by the crew of about 15 to 20° approximately matches the roll angles of the simulation which you would expect in a natural sea state with a significant period of around 11 s, especially if the sea would also tend to ground swells.

Based on calculations, we can exclude with an almost certain degree of probability that the observed roll angle were a consequence of the vessel being under the influence of a critical resonance. The calculations clearly show that comparable roll angles would have also occurred in a wide number of other situations. Based on the calculated roll angles, it would also be theoretically possible for the containers to have been damaged while sailing in a head sea at reduced speed.

5.3.1.6 The accelerations influencing the container stack

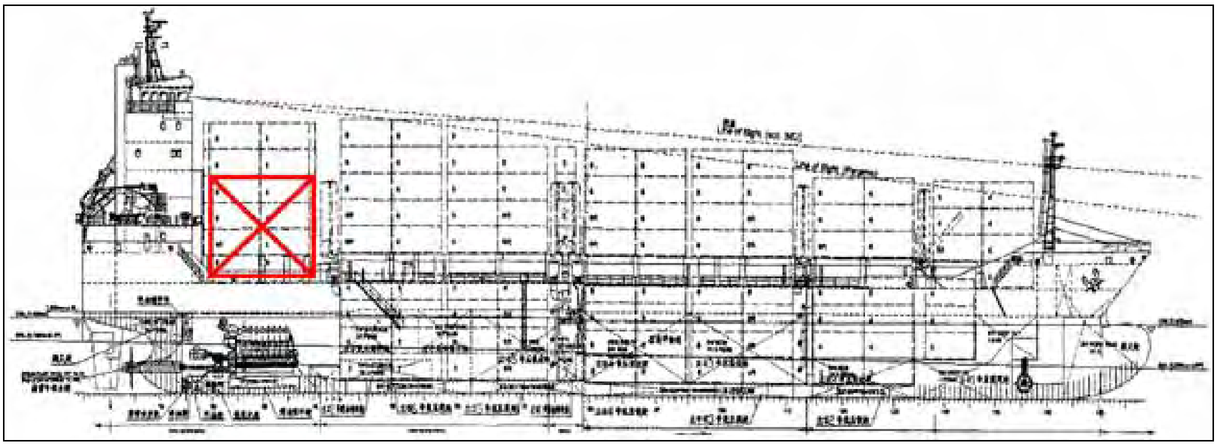


Figure 19: General arrangement plan of the JRS CANIS. The bay in question for the acceleration calculations is marked red.

The following will determine the extant accelerations for those circumstances where a roll angle of 20° was established in the previous section.
At the same time, the accelerations on the port outside container stack will be determined because according to statements this is the stack that broke and hit the starboard stack with a high drop speed.
The accelerations occurring here are determined for the geometric central point of each container in the bay, and appear as follows based on the general arrangement plan:

	XCG v. H.L. [m]	YCG a. MS [m]	ZCG ü. BL [m]
1. layer:	17,400	9,100	12,200
2. layer:	17,400	9,100	14,800
3. layer:	17,400	9,100	17,400
4. layer:	17,400	9,100	20,000

In order to determine the accelerations, simulations were carried out of 10000 s each, and the static distribution of the vertical and transverse accelerations for the first and fourth layers were determined for each situation. Intermediate values can be interpolated linearly from this. The results are summarized in the following figures:

5.3.1.6.1 Accelerations for the circumstances of the accident

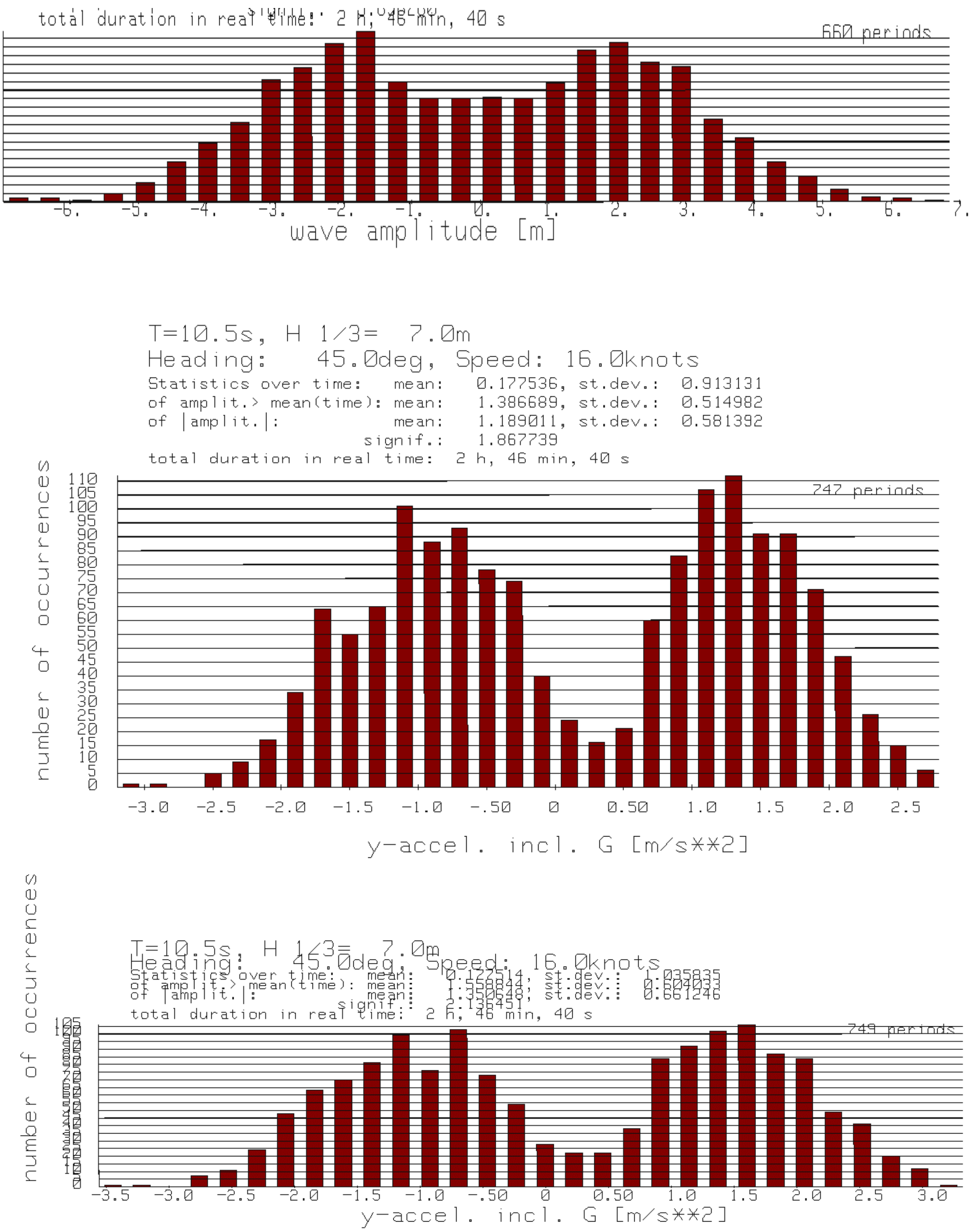
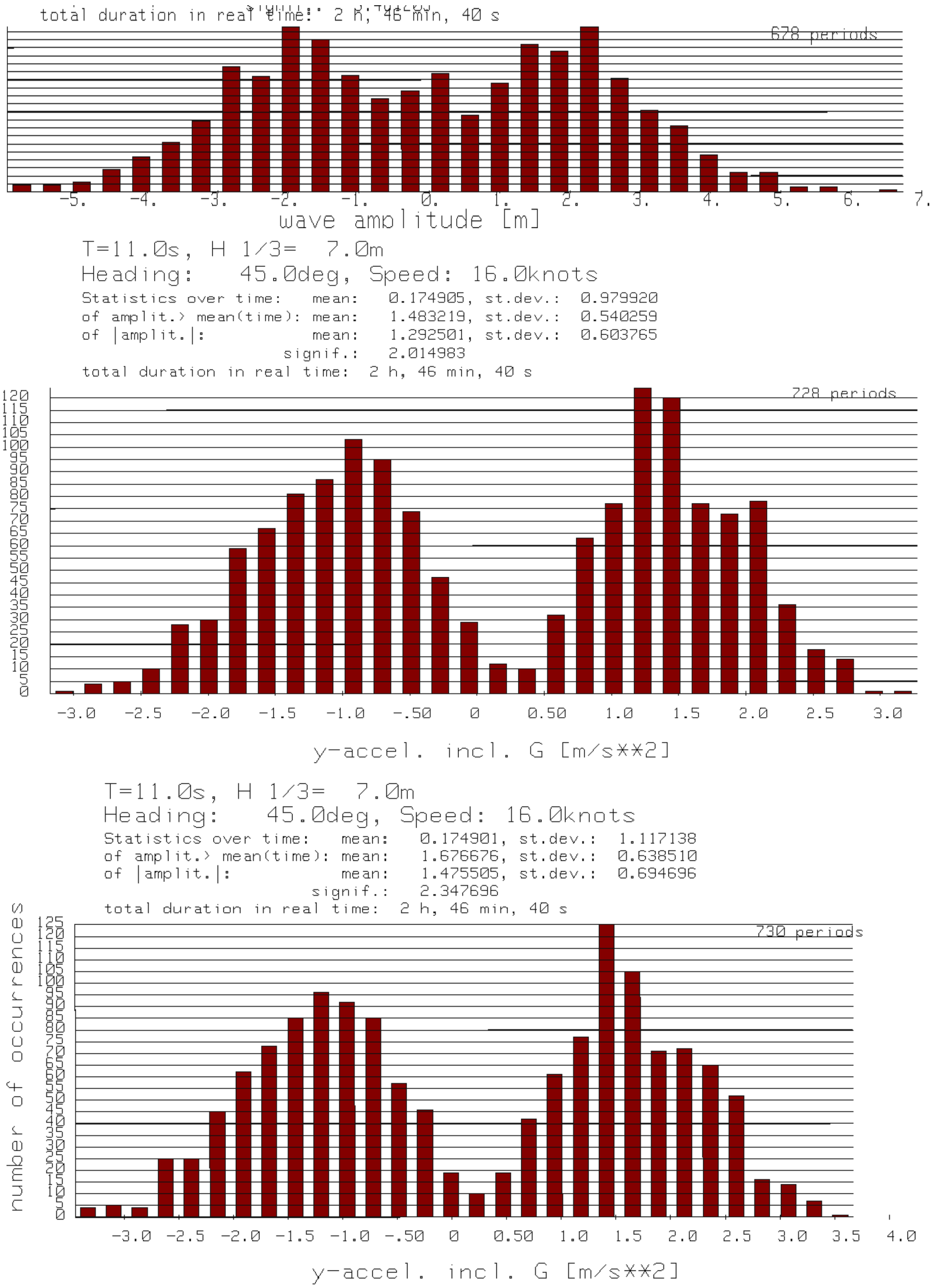


Figure 20: Static distribution of wave amplitudes

(top) as well as transverse accelerations of the bay in question. Centre: 1. layer (z=12.200 m ü- BL), bottom: 4. layer (z=20.000 m ü. BL.) T1 = 10.5 s, encounter angle 45°.



```
total duration in real time: 2 h, 46 min, 40 s
```

```
T=11.0s, H 1/3=  7.0m
Heading:   45.0deg, Speed: 16.0knots
Statistics over time:    mean:   0.174905, st.dev.:  0.979920
of amplit.> mean(time): mean:   1.483219, st.dev.:  0.540259
of |amplit.|:            mean:   1.292501, st.dev.:  0.603765
                       signif.:  2.014983
total duration in real time:  2 h, 46 min, 40 s
```

```
T=11.0s, H 1/3=  7.0m
Heading:   45.0deg, Speed: 16.0knots
Statistics over time:    mean:   0.174901, st.dev.:  1.117138
of amplit.> mean(time): mean:   1.676676, st.dev.:  0.638510
of |amplit.|:            mean:   1.475505, st.dev.:  0.694696
                       signif.:  2.347696
total duration in real time:  2 h, 46 min, 40 s
```

Figure 21: Static distribution of wave amplitudes at **T1 = 11 s**

(top) as well as transverse accelerations of the bay in question. Centre: 1. layer (z=12.200 m ü- BL), bottom: 4. layer (z=20.000 m ü. BL.) ***T1 = 11 s*** *(most probable case), encounter angle 45°.*

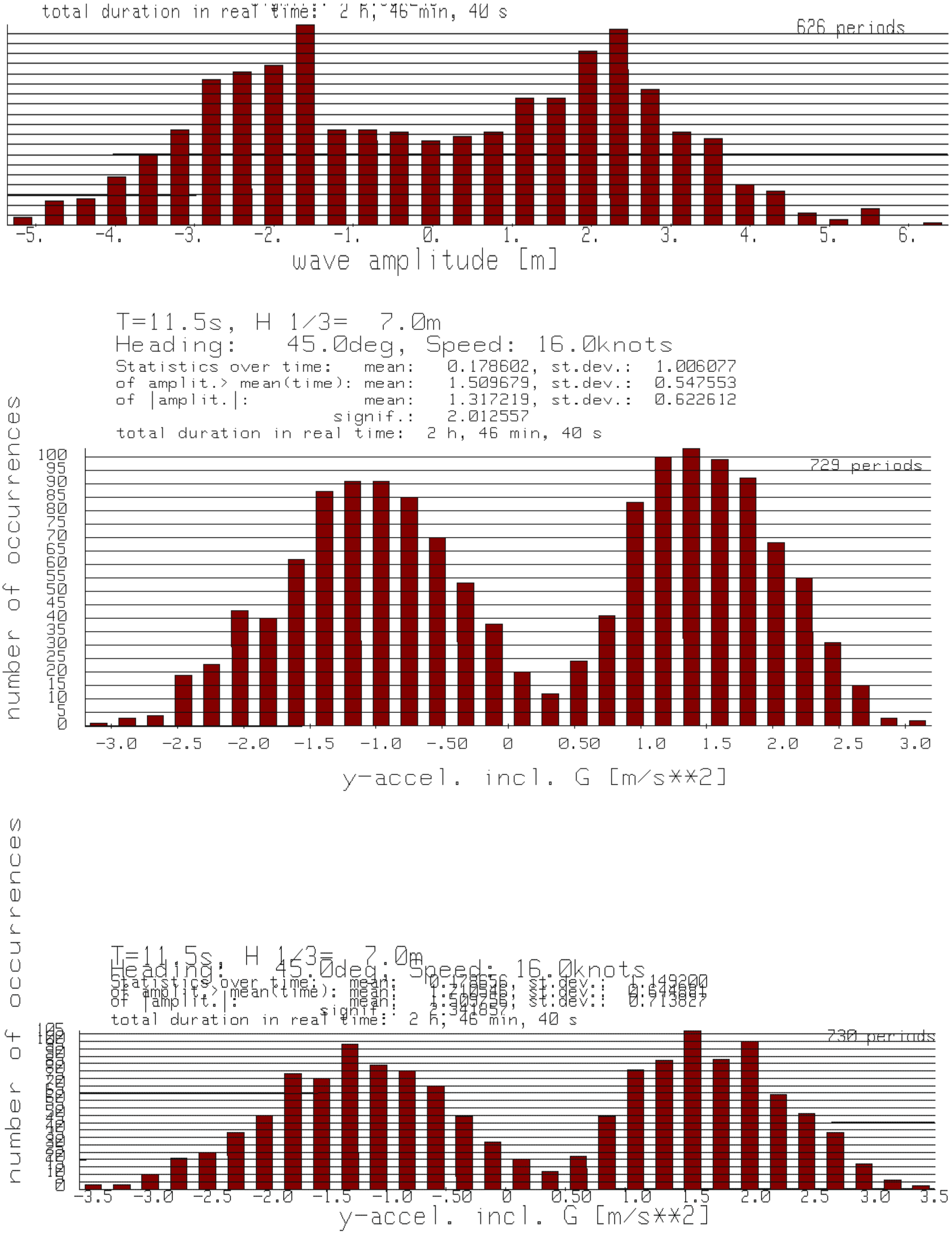


Figure 22: Static distribution of wave amplitudes at **T1 = 11.5 s**

(top) as well as transverse accelerations of the bay in question. Centre: 1. layer (z=12.200 m ü- BL), bottom: 4. layer (z=20.000 m ü. BL.) T1 = 11.5 s, encounter angle 45°.

For the environmental conditions that formed the background for this accident, calculating the transverse accelerations resulted in maximum values of about 3.5 to 4 m/s^2 for the fourth layer and about 3 to 3.5 m/s^2 for the first layer. The maximum acceleration values do not differ greatly for the significant periods in question of 10.5 s to 11.5 s; the dispersion is on about the same scale as wave variations based on different random numbers.

Concerning that the design criterion for loading/lashing was about 0.5 g (4.9 m/s^2), then this limit value would not have been reached yet at the probable time of the accident. If however (as in this case) the container weights are unfavourably distributed within a stack and if relatively heavy containers are placed on top, or the lashing is insufficient, then it is possible that the lashing would break already at lower transverse accelerations than the theoretical 0.5 g.

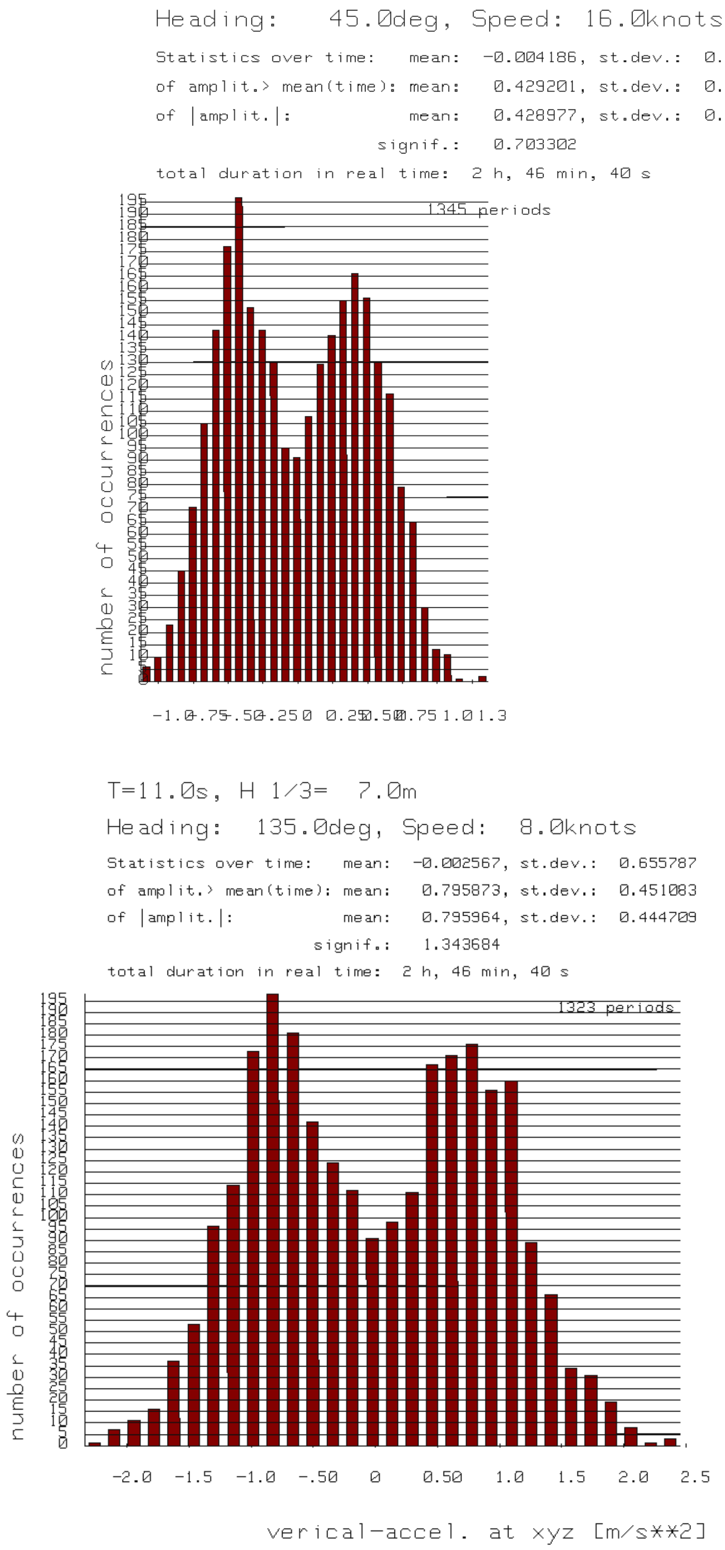
The vertical accelerations occurred at the time of the accident (cf. Fig. 23 above) are roughly maximum 1 to 1.3 m/s^2, i.e. considerably below 1.0 g.

Assuming that an automatic twistlock would not be triggered accidentally below a vertical acceleration of 1.0 g (this would be equivalent to if the load pressure of the container was just at zero), this would seem less probable in view of the relatively low vertical accelerations expected in principle for a stern sea.

For this reason, it is most probable that the loss of cargo occurred as a result of a forced break of the lashing due to the transverse accelerations experienced at that time. This is based on the fact that the vertical accelerations are clearly below the limit value for an accidental release of the twistlock, but that the transverse accelerations come close to the theoretical design limit value. However, the calculated values for the transverse acceleration are still below the theoretical design limit value of 0.5 g for the lashing.

The next section will examine to what range conditions could have arisen that led to large accelerations resulting from the previous course status of the ship, namely 7 kn on a 330° course, i.e. at about 45° against the waves.

5.3.1.6.2 Accelerations that occurred during slow movement against a head sea

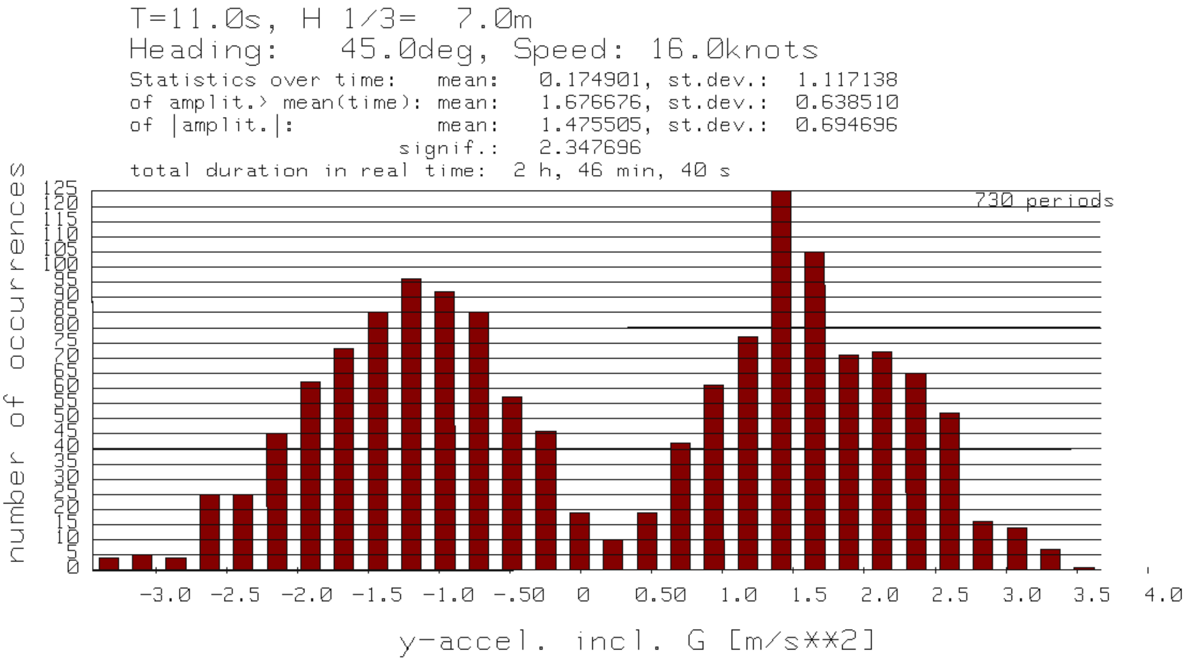


```
Heading:   45.0deg, Speed: 16.0knots
Statistics over time:   mean:  -0.004186, st.dev.:  0.365740
of amplit.> mean(time): mean:   0.429201, st.dev.:  0.246321
of |amplit.|:           mean:   0.428977, st.dev.:  0.236911
                      signif.:   0.703302
total duration in real time:  2 h, 46 min, 40 s
```

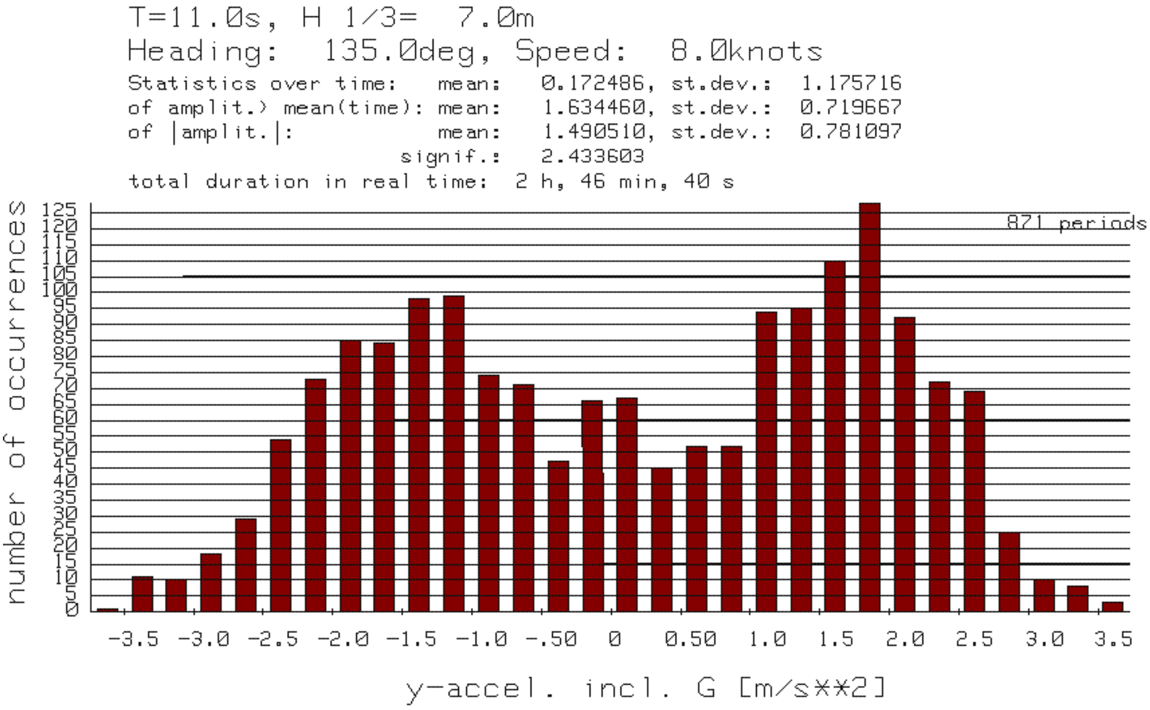
```
T=11.0s, H 1/3=  7.0m
Heading:  135.0deg, Speed:  8.0knots
Statistics over time:   mean:  -0.002567, st.dev.:  0.655787
of amplit.> mean(time): mean:   0.795873, st.dev.:  0.451083
of |amplit.|:           mean:   0.795964, st.dev.:  0.444709
                      signif.:   1.343684
total duration in real time:  2 h, 46 min, 40 s
```

Figure 23: Static distribution of vertical accelerations

for the bay in question, 4th layer: Top: Situation for the accident, v=16 kn, encounter angle 45°, Bottom: Before the accident against a head sea, v=8 kn., encounter angle 135°.



```
T=11.0s, H 1/3=  7.0m
Heading:   45.0deg, Speed: 16.0knots
Statistics over time:     mean:   0.174901, st.dev.:  1.117138
of amplit.> mean(time): mean:    1.676676, st.dev.:  0.638510
of |amplit.|:             mean:    1.475505, st.dev.:  0.694696
                        signif.:  2.347696
total duration in real time:  2 h, 46 min, 40 s
```



```
T=11.0s, H 1/3=  7.0m
Heading:  135.0deg, Speed:  8.0knots
Statistics over time:    mean:   0.172486, st.dev.:  1.175716
of amplit.> mean(time): mean:    1.634460, st.dev.:  0.719667
of |amplit.|:            mean:    1.490510, st.dev.:  0.781097
                       signif.:  2.433603
total duration in real time:  2 h, 46 min, 40 s
```

Figure 24: Static distribution of transverse accelerations

for the bay in question, 4th layer: Top: Situation for the accident, v=16 kn, encounter angle 45°, Bottom: Before the accident against a head sea, v=8 kn., encounter angle 135°.

According to the statement provided, the ship steered briefly a course of 330° before the actual accident due to an evasion manoeuvre; the speed was about 7 kn. An evaluation of these roll angles has shown that we must expect similar roll angles for this course if you base it roughly on the same sea state. However, experience has shown that when sailing against a head sea the pitch motion is greater, which leads to higher vertical accelerations. This is why, for reasons of comparison, a case with 8 kn and an encounter angle of 135° was also considered (8 kn instead of 7 kn because all essential preliminary calculations had already been carried out for this case when calculating the roll angle). The comparison of accelerations calculated for this situation with those occurring at the time of the accident is shown in Fig. 23 and 24. For a sea state with T1=11 s against a head sea, approx. maximum vertical accelerations of about 2.5 m/s^2 are reached in the fourth layer, i.e. more than double the amount than for the actual accident situation. At the same time, the transverse accelerations are of the same scale as for the accident situation. Nevertheless, in neither case are limit values for a clear failure/break achieved, either vertically (clearly) or transversely (narrowly). If we assume that the same sea state prevailed at this point as later on for the actual accident situation, then a loss of containers due to overall higher vertical accelerations would actually be more probable than for the specific accident situation based on calculations.

In the expert's opinion, this allows us to draw the following potential conclusions to explain the loss of cargo.

5.3.1.7 Causes for the loss of cargo

It is possible that the lashing experienced a certain range of prior damage which could have then led to a forced break of the lashing later on due to transversal acceleration based on the calculated acceleration values for a course at low speed moving transversely against the sea which theoretically could have led to the loss of cargo.

Furthermore, it is known from other cases that slamming pressures can occur at the stern of the ship travelling in a stern sea where the ship has a flat transom. This generates sudden vertical accelerations which can reach a magnitude of 1 g. Consequently, it would be conceivable that the loss of cargo was due to a combination of sufficiently large transverse acceleration and this kind of sudden load pressure. However, no statements have been made in this regard.

As expert, it is our opinion that it is probable for the actual loss of cargo to be due to a combination of at least two of the three aforementioned phenomena.

The fact that the central two rows of the bay in question were empty, combined with the very high container weights, may have contributed to the failure of the lashing while sailing in a stern sea.

These factors also show that, in our opinion as expert, the loss of cargo cannot be clearly allocated to one particular cause, and that it might have been difficult for the crew to identify that there was an immediate threat with regard to a loss of cargo.

In the expert's opinion, the amount of damage that occurred is greater as a result of sailing with both inside rows empty than if they had also been filled with lashed containers. However, it is impossible to predict whether the damage would have even occurred with filled inside rows.

5.3.1.8 The possibility of predicting critical sea state situations during onboard operation

Another question to be answered is whether the crew could have recognised that there was a risk of loosing loads during the prevailing situation at the time of the accident. As the aforementioned factors show, the crew could not assess the situation. The BSU subsequently expanded this question to include an assessment by the expert regarding the currently available technical facilities that should warn the crew onboard against sea-state related problems. This gives the question a more general character to the effect whether it can currently be viewed as the state of the art of technology to give sailing recommendations onboard to avoid sea-state related problems directly associated with the occurrence of large roll angles.

The basis for this consideration is that, whatever kind of tool is used, it should give sufficient warnings and recommendations to a **crew that has not been especially trained in its use**.

The following crucial, influencing parameters follow from the aforementioned general basis which affect the behaviour of the vessel in bad weather with regard to large roll angles:

- Stability of the ship and general characteristic of the lever arm curves (degressive or progressive) for corresponding peak and trough conditions, as well as
- A general change to these variables by altering the float position or stability.
- Sea state of the currently natural sea, primarily the typical period and significant height (if a 1 peak spectrum), otherwise the entire spectrum.
- Course and speed of the ship, in particular critical resonance ranges.
- Actual roll damping as well as the current mass moment of inertia around the rolling axis.

In this respect, advice given onboard can fall into two subcategories:

- First, a particular situation must be identified as dangerous. This requires a sufficiently precise knowledge of the vessel's current status, the environmental conditions and the exact response of the ship in this situation.
- Second, recommendations can be given which suggest another, less hazardous situation. In addition to the above, the same information must be known with certainty for the suggested situation.

The first requirement (i.e. to recognise hazardous situations) gives us the following simple catalogue of requirements:

Firstly, the vessel's command must be sufficiently and clearly informed about the current status of the ship. This is based on the initial situation at the start of the voyage and the changes that made during the voyage (e.g. consumed supplies, additional ballast water, etc.). A research project carried out in the context of the EU clearly shows that the greatest uncertainties in the entire process are still due to the fact that the stability of the ship is often not known with sufficient accuracy due to the often only roughly estimated centre of gravity. Since the stability of the ship can be interpreted as a small difference between two very large distances, one of which we can now reliably determine, namely the KM (with small pitches) or the cross curve (with larger inclinations), all uncertainties regarding the centre of gravity transfer their full effect onto the stability. Any change to the stability (whether intentional or due to uncertainties in their calculation) fully affect the behaviour of the vessel at sea; this applies both to the general response behaviour of the vessel itself and the current situation regarding possible resonances. Consequently, in terms of reliable onboard advice, it is essential that either the stability of the vessel is known with sufficient accuracy (this would be a mandatory precondition in order to be able to suggest any kind of alternative situations), or if this is not sufficiently precise for practical reasons, then at least a lever arm strip must be taken as the basis with which to evaluate a certain range of situations. Similarly, we need to be clear that the data, which has up to now been recorded by onboard computers, is never precise enough or even sufficient enough to produce sufficiently accurate input data for the sea state calculations (or their evaluation).

For this reason, the outcome indicates that the essential input data necessary for accurate onboard advice regarding the occurrence of large roll angles is not of sufficient quality to enable reliable advice to be given in all circumstances. This consideration applies in general and irrespective of the actual design of the advice tool (irrespective of whether calculations onboard are made online or whether previously calculated data records are interpreted).

Secondly, the vessel's command must have sufficiently accurate knowledge of the environmental situation, in particular the sea state. Practical trials on this subject have shown that it is also practically impossible for even a very experienced crew to determine the essential sea state parameters with sufficient accuracy by observation. Even judging the significant wave height does not give the level of accuracy required for serious advice, and assessments of the significant period create an even greater spread of values. The obvious consequence is that it is an absolute prerequisite to detect the current sea state using measuring technology, e.g. with a marine radar. Nowadays, this technology is in principle available, i.e. by using a reliable marine radar we can detect the sea state at some distance from the ship with sufficient accuracy. The expert is of the opinion, that this information alone already poses a considerably step forward, as e.g. at night or in poor visibility conditions they have to assess the situation purely based on the current vessel movements without this kind of aid. Nevertheless, (in the expert's opinion) there is still no entirely satisfactory solution for the problem which could be used to extrapolate the sea state at the position of the vessel using sea data measured from a long distance. From the perspective of a navigator, this appears to be an academic problem, but it has the following important, practical consequences for designing an advice tool:
Since the prevailing sea state at the vessel's position is not known with sufficient accuracy, it is also not a sufficiently reliable option to use measurements carried out online (e.g. the movement behaviour of the vessel) to calibrate an online computational model based on the measured movements. This is because the movement of the vessel may indeed be known (perhaps measured) specifically in

terms of the current state but the associated environmental conditions at the position of the vessel are not known.
Another essential problem is how to record and process the so-called two-peak spectra like those that can appear e.g. by an overlapping of wind sea and swell from different directions. These frequently lead to extremely steep waves from several directions. In this situation, it is extremely difficult to give advice on changing the current situation of the vessel because resonances can occur in several situations Due to the very wide range of possible spectra, it is almost impracticable to calculate enough of these kinds of situations beforehand and to interpret anything from them. The behaviour of the vessel just in a one-peak spectrum is already very complicated, and, in the opinion of the expert, the behaviour of a vessel in a two-peak spectrum is not seriously predictably without having carried out corresponding calculations.

This means that it must be an obligatory component of a sea state advice system to detect the sea state with sufficient accuracy using a marine radar. In the expert's opinion, this is currently possible with sufficient accuracy at some distance from the vessel. However, there is not yet any sufficiently reliably way to integrate the actual, measured sea state into the theoretical model, especially not in a case of extremely complicated spectra with more than one peak

Thirdly, the vessel's command must have precise knowledge of how the vessel will respond to any given sea state. On the one hand, this presupposes that there is sufficiently correct theory and method onboard to predict the expected vessel movements with a practically sufficient range of accuracy; on the other hand, it presupposes that this theory and method can be operated reliably enough by an untrained user. In the opinion of the expert, it is currently not possible to fulfil both prerequisites **at the same time**. This is basically because the sea state problems, in particular those affecting large roll angles, are so complex in their entirety that it has not been possible so far (and supposedly will not be possible in the foreseeable future) to have a single sea state method that can predict all crucial sea state effects with enough accuracy. Consequently, in practice we are limited to developing and applying particular, specialised procedures which can only usefully predict particular specific sea state effects, but cannot in principle be applied to other effects. (E.g. the E4ROLLS method used in the context of this survey can predict large roll angles very well in head seas or stern seas; however, large roll angles when broaching-to can only be predicted with average to poor accuracy and broaching itself cannot be predicted at all). When used for this specific purpose, namely as a support in designing vessels or for assessment of vessels by a third party, it is entirely sufficient. These kinds of methods are based on specific simplifications of specific sea state effects (that are irrelevant to this problem) based on the modelling applied in the method. For this reason, the use of such methods presupposes extensive **specialist training** and a lot of experience in modelling because the corresponding computational engineer must decide accurately in the individual case whether the respective model assumptions are valid or not for the relevant case. As a result, a high level of specialist knowledge is required to create such data and to interpret it. If this is available in a sufficient form and such methods are also available, then in most cases you can correctly predict the at-sea behaviour of vessels and design vessels specifically with certain sea-going characteristics.

In contrast to all other vessel movements (excluding broaching-to), large roll angles are particularly difficult because the roll behaviour of the vessel at sea is extremely non-linear and can only be correctly portrayed in natural seas with short-crested waves.

Therefore, the expert's opinion is that the current status of technology is capable or will soon be capable of calculating and analysing the at-sea behaviour of vessels (including large roll angles) for <u>the design of vessels by correspondingly trained personnel</u>.

The following minimum requirements are given in order for one method on its own to be suitable for providing useful prognoses in respect of large roll angles under the specified preconditions:

- The rolling motion must be modelled entirely non-linearly (for a linear process, just replace the lever arm curve with a straight line GM φ). This method must calculate in the time domain.
- Interplay with other degrees of freedom must be calculated with sufficient accuracy.
- The method must be able to correctly record the righting lever at sea and its changes (either pressure integration on the hull or an equivalent-wave concept according to Grim. Linearised branching theory only with an initial GM is no use).
- The method must of course calculate natural, irregular sea states (information gathered from regular waves are useless for practical sea state questions) and be able to deal with spectra of several peaks.
- The methods must correctly compute the influence of the course speed.
- Roll damping must not be modelled linearly; this applies in particular to free surfaces, such as Flume or Interring tanks.
- In order to use such a method onboard, it is absolutely necessary that the sea state is measured and entered into the method, e.g. by a marine radar.

From this it is apparent that such methods require a considerable amount of specialist knowledge on the part of the user in order to produce reliable results.

The reliability of the results not only depends on the quality of the corresponding sea state method (if it meets the aforementioned minimum standard); it primarily depends on the qualifications of the corresponding user of the method.

When using such methods or the results produced by such methods onboard, it must taken account into the fact that there is usually a lack of corresponding qualifications onboard. This means that certain simplifications need to be made for the practical use of such methods onboard both in the use of the method and in the interpretation or generation of results, so that the crew can at least use these processes to evaluate hazardous situations.

However, simplifications always mean that certain physical factors that complicate a problem are left out once it is established that they only have an insignificant influence on the result. This means that the simplified method will produce incorrect results in those cases where simplification is not permitted. On the other hand, this cannot be assessed by the crew onboard and they will only notice the discrepancy when the method's forecast does not match the actual behaviour of the vessel, and they will consequently lose trust in such a method. For all sea-related questions, especially questions of large roll angles, the situation is such that any simplification leading to methods that can be used onboard in practice also lead to a lack of discrimination regarding sea state problems, because too many important phenomena are left out. Subsequently the overall results are often incorrect. Either the prevailing systems are so conservative (due to the many simplifications) that they are practically incapable of permitting a sensible assessment of the sailing status (in which case it is useless for the crew), or too many potentially hazardous situations are overlooked (in which case it is seriously dangerous). If, as a superficial minimum standard for such a system, we set a requirement which states that overall more useful instructions than harmful instructions should be given regarding the occurrence or avoidance of large roll angles, then, in the view of the expert, we must clearly state that none of the systems available at this point in time meet this requirement. (In fact, none of the systems is currently **permitted** for onboard use which firstly, from a scientific perspective, is due to the fact that none of the systems actually meet the aforementioned requirements, and secondly from a practical perspective this is because, due to the complexity of the problem (see above), there are not yet any guidelines which would allow certification of such systems by appropriate institutions). On the contrary, the crew would be more likely to make incorrect rather than correct decisions due to the many simplifications.

To summarize, the expert is of the opinion, that the loss of cargo in this case would not have been prevented even if a type of currently available wave and surface current monitoring software had been on board. This is because, in spite of the general ability to compute sea state problems using appropriate simulation programs, no one has yet concretely managed to simplify the complicated methods for reliable computation of large roll angles to such a degree that the methods arising from these simplifications are appropriate for onboard use and bring more benefits than harm in practical onboard use. In the opinion of the expert, this situation is unlikely to change in the near future.

5.3.2 Survey report of the Warnemünde Department for Maritime Studies

The measurements of the Elbe measuring buoy located near the scene of the accident were chosen for the commissioned investigation as representative sea state data. This gives the following data for the subsequent investigations:

Wave height:	6 m; average wave direction: 280°
Wave period:	The following wave periods are covered by the investigation:

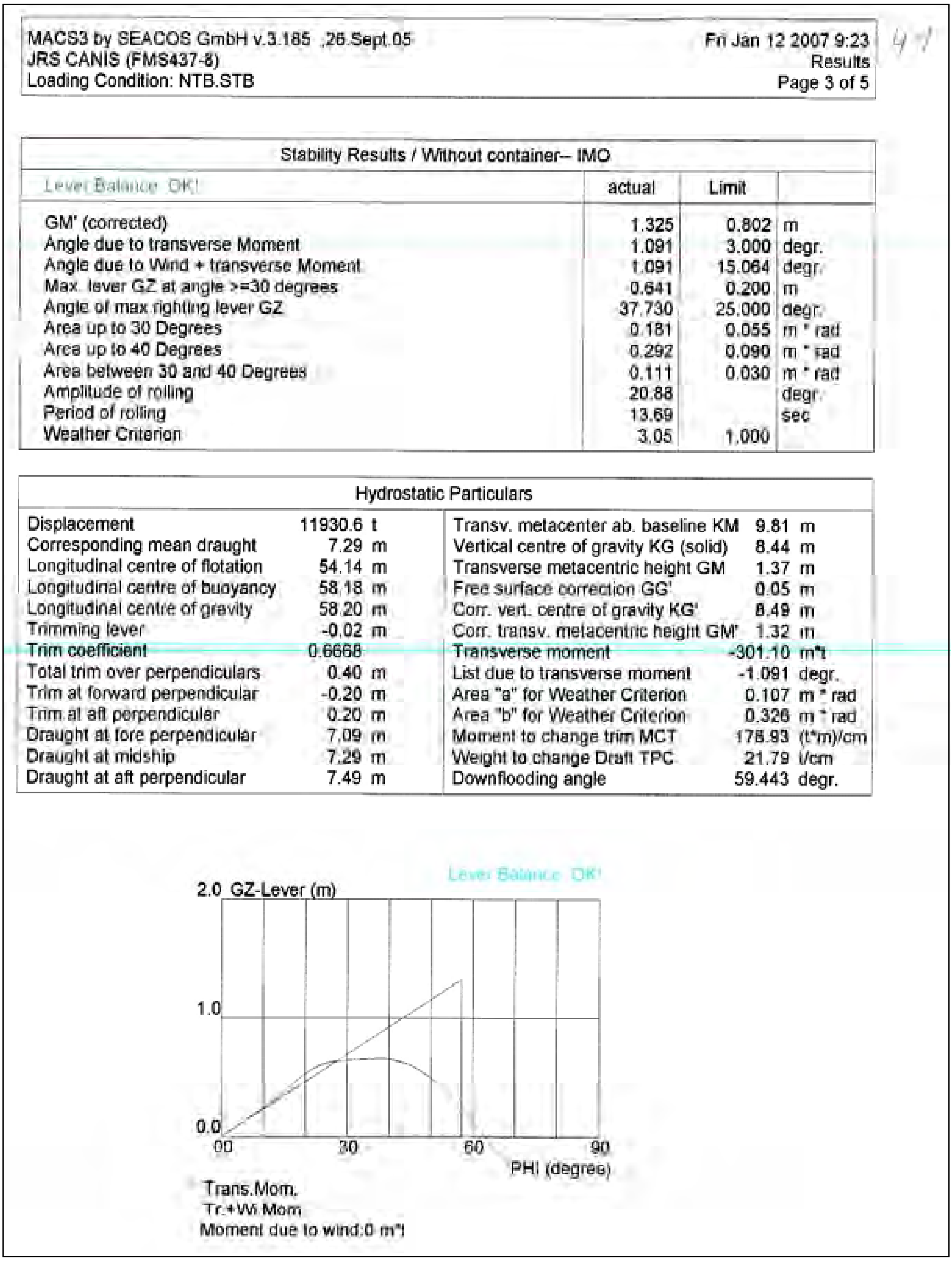
Tw = 10, 11 and 12 s.

Information was given in the form of a load computer extract for the stability status, according to which the vessel maintains stability conditions (see Fig. 25).

At the time of the accident on 12 January 2007 at 02:45, the vessel JRS CANIS was in the traffic separation scheme "Terschelling/German Bight" heading for the estuary mouth of the Elbe River at the "Grünen Tonnenstrich" (green barrel buoy line).
As a consequence of three quickly consecutive, approx. 7 m high waves, the vessel heeled starboard at about 15–20°. Rows 4414-8414 and 4614-8814 tipped to starboard. Due to the fact that the storage areas of the innermost two rows were empty (storage areas of the first row port side and starboard (4214 - 8214 and 4114 - 8114) in bay 28 (last bay) remained empty), the affected, falling rows were able to hit row 4314-8314 with a correspondingly high drop speed at an unfavourable angle. This domino effect broke the holding devices of the three starboard rows of bay 28 and the containers fell into the sea.

The ECDIS data also states that up to about 02:35 (i.e. just before the incident), the ship was sailing COG=056° and SOG=16 kn (+/-0.1). This information can be viewed as confirmed since it comes from the GPS. LOG=16 kn (+/-0.2) is also indicated.
Then the values begin to decrease until reaching COG=035° and SOG=10 kn. From about 02:40, the vessel turns back and gather speed again. It is not known whether these changes were intentionally brought about by the vessel's command, or by the quick sequence of hard waves from the port side (according to the master's statement) and by the containers falling overboard.

At the time of the accident, the vessel was on a course of COG=060° and the speed was 15.5 kn.
This information will be used to create diagrams/images for evaluation and in the discussion of the aforementioned alternative courses and speeds.



MACS3 by SEACOS GmbH v.3.185 ,26.Sept.05
JRS CANIS (FMS437-8)
Loading Condition: NTB.STB

Fri Jan 12 2007 9:23
Results
Page 3 of 5

4/1

Stability Results / Without container– IMO

Lever Balance OK!	actual	Limit	
GM' (corrected)	1.325	0.802	m
Angle due to transverse Moment	1.091	3.000	degr.
Angle due to Wind + transverse Moment	1.091	15.064	degr.
Max. lever GZ at angle >=30 degrees	0.641	0.200	m
Angle of max righting lever GZ	37.730	25.000	degr.
Area up to 30 Degrees	0.181	0.055	m * rad
Area up to 40 Degrees	0.292	0.090	m * rad
Area between 30 and 40 Degrees	0.111	0.030	m * rad
Amplitude of rolling	20.88		degr.
Period of rolling	13.69		sec
Weather Criterion	3.05	1.000	

Hydrostatic Particulars

Displacement	11930.6	t	Transv. metacenter ab. baseline KM	9.81	m
Corresponding mean draught	7.29	m	Vertical centre of gravity KG (solid)	8.44	m
Longitudinal centre of flotation	54.14	m	Transverse metacentric height GM	1.37	m
Longitudinal centre of buoyancy	58.18	m	Free surface correction GG'	0.05	m
Longitudinal centre of gravity	58.20	m	Corr. vert. centre of gravity KG'	8.49	m
Trimming lever	-0.02	m	Corr. transv. metacentric height GM'	1.32	m
Trim coefficient	0.6668		Transverse moment	-301.10	m*t
Total trim over perpendiculars	0.40	m	List due to transverse moment	-1.091	degr.
Trim at forward perpendicular	-0.20	m	Area "a" for Weather Criterion	0.107	m * rad
Trim at aft perpendicular	0.20	m	Area "b" for Weather Criterion	0.326	m * rad
Draught at fore perpendicular	7.09	m	Moment to change trim MCT	178.93	(t*m)/cm
Draught at midship	7.29	m	Weight to change Draft TPC	21.79	t/cm
Draught at aft perpendicular	7.49	m	Downflooding angle	59.443	degr.

Trans.Mom.
Tr.+Wi.Mom
Moment due to wind:0 m*t

Figure 25: JRS CANIS - stability information as load computer extract

5.3.2.1 Calculations of endangerment from the sea state in relation to resonance and other effects

5.3.2.1.1 General explanation of the endangerment's and methods

Recently there have been several incidents of major damage due to severe rolling of ships at sea, which dictates a need for such endangerment's to be properly assessed.
Figure 26 offers an overview of the potential endangerment's:

Phenomena	Occurrence		Effect
	Direction	**Periods/Encounter**	
1. Synchronous rolling motion resonance	All directions possible	Wave encounter period coincides with the natural rolling period of a ship	Heavy oscillations with high amplitude
2. Parametric rolling motion resonance	Specifically for head and stern wave conditions	Wave encounter period is approximately equal to half of the natural roll period of the ship	Heavy oscillations with high amplitude
3. Reduction of stability riding on the wave crests of high wave groups	Following and quartering seas	Wave length larger than 0.8xLpp and significant wave height is larger than 0.04 x Lpp	Large roll angle and capsizing
4. Surf-riding and broaching-to	Following and quartering seas	The critical wave speed is considered to be about 1.8√Lpp ~ 3.0√Lpp with respect to ships' length	Course deviation and capsizing

Figure 26: Summary of wave effects and conditions for their occurrence

There are a range of procedures for assessing the endangerment, whereby priority must be given to procedures that can be used by the vessel's command.

a) On the one hand, there are the guidelines of the See-BG (Marine Insurance and Safety Association) from 2003 (German version) and 2004 (English version [8][12]), which are based on the corresponding guidelines of the IMO[2], [4] and even go beyond the information stated there. In 2007, an updated but unfortunately very much abbreviated version was published [9].

b) On the other hand, a procedure has been developed by the expert which is fundamentally based on the same premises as in the guidelines of the See-BG and the IMO, but which gives calculable and clear results for assessing the endangerment situation in a simple way; [10] and [11] give a detailed description, and an updated summary has been published in [12].

The following will initially examine whether there was a resonance danger in the accident situation according to methods a) from [8] and [9]. Subsequently, a

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[12] [..] References - survey report by Prof. Dr. habil. Knud Benedict, for explanations see p. 89/90

comprehensive evaluation of the entire endangerment situation will be carried out according to b).

5.3.2.1.2 Separate example calculation for roll and wave encounter periods, resonance

To calculate the roll period, the information contained in Fig. 25 regarding GM and lever arms is applied according to the procedures used in [8] with the following results:

Roll period Tr(10°) with small roll angles up to approx. 5°-10°:

$$Tr(10°) = \frac{Cr \cdot B}{\sqrt{GM}}$$

Key to equation:

GM – initial stability, metacentric height [m]; here GM[m]= 1.325
B – ship's beam
Cr - inertia coefficient for rolling: This can be calculated from Cr = 2*c using the given ship dimensions draught d and Lpp. Where:
c = 0.373 + 0.023(B/d) - 0.043(Lpp/100)

Which gives:

$$Tr(10°) = \frac{Cr \cdot B}{\sqrt{GM}} = \underline{\underline{13,7\,\mathrm{s}}}$$

A roll period Tr(40°) for large roll angles up to approx. 40° ([7], s.a.[8]):

$$Tr(40°) = \frac{Cr \cdot B}{9,4}\left(\frac{2,2}{\sqrt{v}} + \frac{2}{\sqrt{w}} + \frac{4}{\sqrt{x}} + \frac{4}{\sqrt{y}} + \frac{1}{\sqrt{z}}\right) \quad [s]$$

Where:

v = 0.6 * GZ_40
w = GZ_20 + 4*GZ_30 + 1.6*GZ_40
x = w + 1.5*GZ_10 – 3*GZ_20 – GZ_30
y = w + 2.5*GZ_10 + GZ_20
z = y + 1.5*GZ_10

With lever arm values GZ_ for the corresponding roll angles

GZ_10_[m]=0.23; GZ_20_[m]=0.5; GZ_30_[m]=0.64; GZ_40_[m]=0.64

You get the following result:

$$Tr(40°) = \frac{Cr \cdot B}{9,4}\left(\frac{2,2}{\sqrt{v}} + \frac{2}{\sqrt{w}} + \frac{4}{\sqrt{x}} + \frac{4}{\sqrt{y}} + \frac{1}{\sqrt{z}}\right) = \underline{\underline{15.7\,s}}$$

This produces a situation where the roll period is only Tr(10°)=13.7 s with small roll angles, but the rolling period increases to Tr(40°) = 15.7 s with large roll amplitudes as a consequence of decreasing righting levers (lever arm values are below the tangent on the lever arm curve, see graphic diagram in Fig. 30).

5.3.2.2 Wave encounter periods and resonance danger

5.3.2.2.1 Calculating the wave encounter periods

The TE encounter period between the waves and the ship can be calculated according to the current guideline of the See-BG [9] as follows:

$$TE = \frac{k \cdot Tw^2}{k \cdot Tw + 0{,}514 \cdot V \cdot \cos\gamma}$$

Key to the equation:

TE: encounter period in s.
k: wave factor = 1.56 (in particular for swell)
Tw: wave period in s.
V: ship's speed in knots.
γ: angle between keel direction and wave direction (γ = 0° means an exact head sea)

For a vessel moving at approx. 15.5 kn on a course of 060°, waves from 280°, with a wave period of Tw=10, this gives an encounter period of **TE=16.4 s**
(Tw=11 s gives TE=17.1 s and Tw=12 s gives TE=17.8 s).

5.3.2.2.2 Separate evaluation of the resonance danger

This TE encounter period is compared with the natural roll period Tr to separately evaluate the resonance danger.
Direct resonance with especially large roll amplitudes is to be expected if the encounter period TE is the same as the natural roll period, i.e. the ratio is Tr / TE = 1.0. If the ratio is near 1, i.e. in the range of 0.8 ≤ Tr / TE ≤ 1.1, then we can still expect up to 50% of the maximum resonance amplitudes. We speak of synchronous resonance with these ratios.
Parametric rolling or resonance occurs especially in head or stern seas when the encounter period is roughly double the size of the natural roll period. There is direct parametric rolling resonance with a ratio of Tr / TE = 2.0. If the ratio is near 2.0, i.e. within a range of 1.8 ≤ Tr / TE ≤ 2.1 then we can still reckon with up to 50% of the amplitudes.
The following situation prevailed at the time of the accident for both natural roll periods:

Situation for Tr(10°): Tr / TE = Tr(10°)/TE=13.7 s/16.4 s = **0.84**
Situation for Tr(40°): Tr / TE = Tr(40°)/TE=15.7 s/16.4 s = **0.96**

This means that the ship is inside the resonance range for synchronous rolling for small roll angles as well as within the critical course and speed range for resonance for large roll angle amplitudes. This is probably the reason for the tendency to develop large roll amplitudes as these can build up from small roll angles and enter a resonance phase even with a short-lived large wave. **On the other hand, there is no recognisable danger of parametric rolling.**

However it is impossible to gain a complete overview from these separate methods of calculation in order to identify which decisions could have been made to avoid the resonance. For this reason, the following chapters will apply a more comprehensive and expanded, appropriate method for calculating and representing the resonance situation; this will also take into account the other endangerment potentials such as encountering wave groups and surf-riding

5.3.2.3 Illustration of a potential endangerment situation in a polar co-ordinate diagram

The following will also use a simple method for calculating the necessary information for illustrating potentially hazardous conditions for synchronous and parametric resonance in a clearly arranged polar co-ordinate diagram using the basic data of the vessel and the sea state. This is a method that can also be carried out manually onboard. Information relating to observing the dangers arising from the effect of high wave groups or surf-riding and broaching can be included in line with the suggested calculations of the IMO.

A decisive factor is knowing that boundary lines for dangerous areas lying directly on courses along the wave direction can be very easily determined for calculating resonance areas by applying the formula using speed V:

$$V = \frac{k \cdot Tw}{0{,}514 \cdot \cos\gamma} \cdot \left(\frac{Tr}{TE} - 1 \right)$$

Since cos is γ =+/-1 for courses in a head sea γ=0° and in a stern sea γ =180°, by applying the corresponding encounter period TE for the limits of the resonance area you get formulas for the corresponding encounter velocities in compliance with the aforementioned conditions, e.g. TE= Tr / 0.8 or TE= Tr / 1.1 (Figure 28).

The results are then entered in a polar co-ordinate diagram as in Figure 27, similar to a radar plotting sheet, but with speed values on the axes instead of distances. The wave direction is entered as a straight line and the speeds are placed along this line - positive with a head sea and negative with a following sea. This image shows the points marked by small circles and figures which are numbered corresponding to the respective formula in Figure 28. In addition, it also lists the formulas for calculating areas with a danger of surf-riding and of encountering high wave groups. A general example for a freight ship with the given data is used in Figure 27.

The following areas where endangerment situations may arise can be highlighted by entering the results for this example into the resonance diagram:

Synchronous excitation is shown as a (red) stripe over the entire angle range of the polar co-ordinate diagram, orthogonal to the wave direction. This area represents the ranges 0.8 ≤ Tr / TE ≤ 1.1; a line is shown in the middle for the direct resonance TE=Tr.

Parametric excitation is shown only for one sector for an angle of approx. 30° around the wave direction for head seas or stern seas. This area represents the ranges 1.8 ≤

Tr / TE ≤ 2.1; a line is shown in the middle for the direct parametric resonance TE=2•Tr.
Dangerous surf-riding conditions occur in zones from +45 to -45° around the sea direction line in a stern sea where the limit values for speeds can be calculated as follows: Vsurf 1.8 represents the beginning of the critical speed which is reached up to Vsurf 3.0. This includes the marginal zone where there is still a danger of surf-riding. It begins at Vsurf 1.4.
Dangerous encounters with wave groups occur in stern seas in zones +45 to -45° around the wave direction line where limit values for the speed range 0.8<V/T<2 can be drawn from the lower V_DWGr_0.8 and upper limits V_DWGr_2.0.

If there is proximity to resonance on a given course, then it is easy enough to make a visual assessment of measures from the polar co-ordinate diagram: measures including a change in course, of speed or measures for altering stability, i.e. determining alternative GM values to prevent resonance if course and speed are to be maintained with the excitation period. Consequently the resonance strip must be shifted far enough that these conditions lie on the margins so the vessel can be sailed with virtually no resonance.

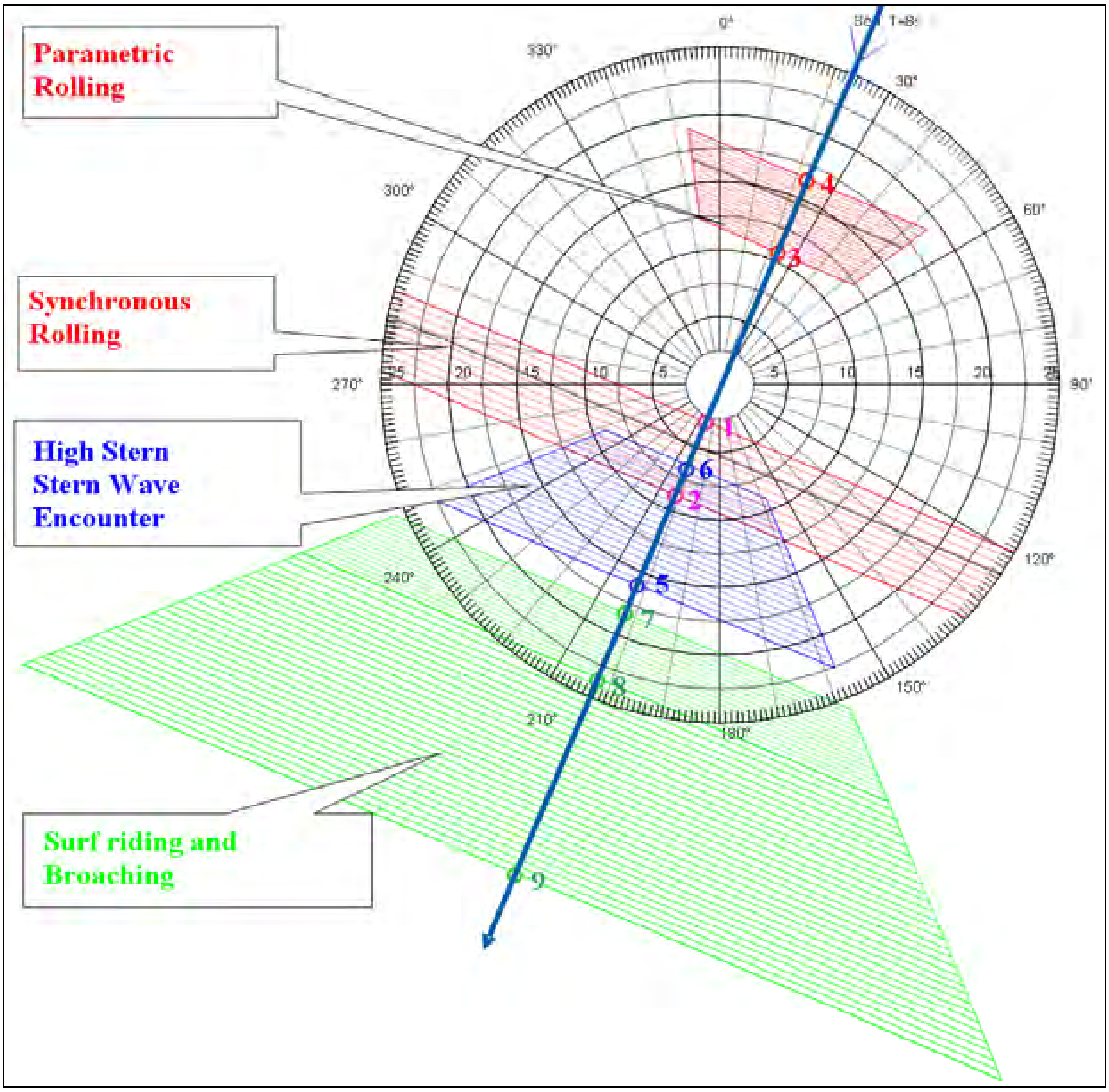


Figure 27: Results shown in a polar co-ordinate diagram with hazardous areas, calculated by the corresponding formulas from Fig. 28, designated by coloured circles.

(Example vessel: Lpp=170 m, B = 17.6 m; inertia coefficient for rolling Cr = 0.74; i.e. Tr=Tr(10°)= 10 s; waves from 23° with Tw= 8 s in swell (k=1.56)

Phenomena	Direction/ Sector/Area	Equations to calculate speed values as a basis for the diagram elements (numbers acc. to circles in Figure 27)	
1. Synchronous rolling motion resonance	Stripe segments over diagram; all directions possible	**1. for TE=Tr/0.8:** $V_{0.8} = \frac{k \cdot Tw}{0.514} \cdot \left(\frac{Tw}{Tr/0.8} - 1 \right)$	**2. for TE=Tr/1.1:** $V_{1.1} = \frac{k \cdot Tw}{0.514} \cdot \left(\frac{Tw}{Tr/1.1} - 1 \right)$
2. Parametric rolling motion resonance	Segment for direct head and stern wave conditions +/- 30°	**3. for TE=Tr/1.8:** $V_{1.8} = \frac{k \cdot Tw}{0.514} \cdot \left(\frac{Tw}{Tr/1.8} - 1 \right)$	**4. for TE=Tr/2.1:** $V_{2.1} = \frac{k \cdot Tw}{0.514} \cdot \left(\frac{Tw}{Tr/2.1} - 1 \right)$
3. Reduction of stability riding on the crest in wave groups	Segment for direct following and quartering seas +/-45°	**5.** $\mathrm{V}\_DWaveGr_{0.8} = -0.8 * \mathrm{T_w}$ **6.** $\mathrm{V}\_DWaveGr_{2.0} = -2.0 * \mathrm{T_w}$	
4. Surf-riding and broaching-to	Segment for direct following and quartering seas +/-45°	**7.** $Vsurf_{1.4} = -1.4 * \sqrt{Lpp}$ (marginale Zone) **8.** $Vsurf_{1.8} = -1.8 * \sqrt{Lpp}$ **9.** $Vsurf_{3.0} = -3.0 * \sqrt{Lpp}$	

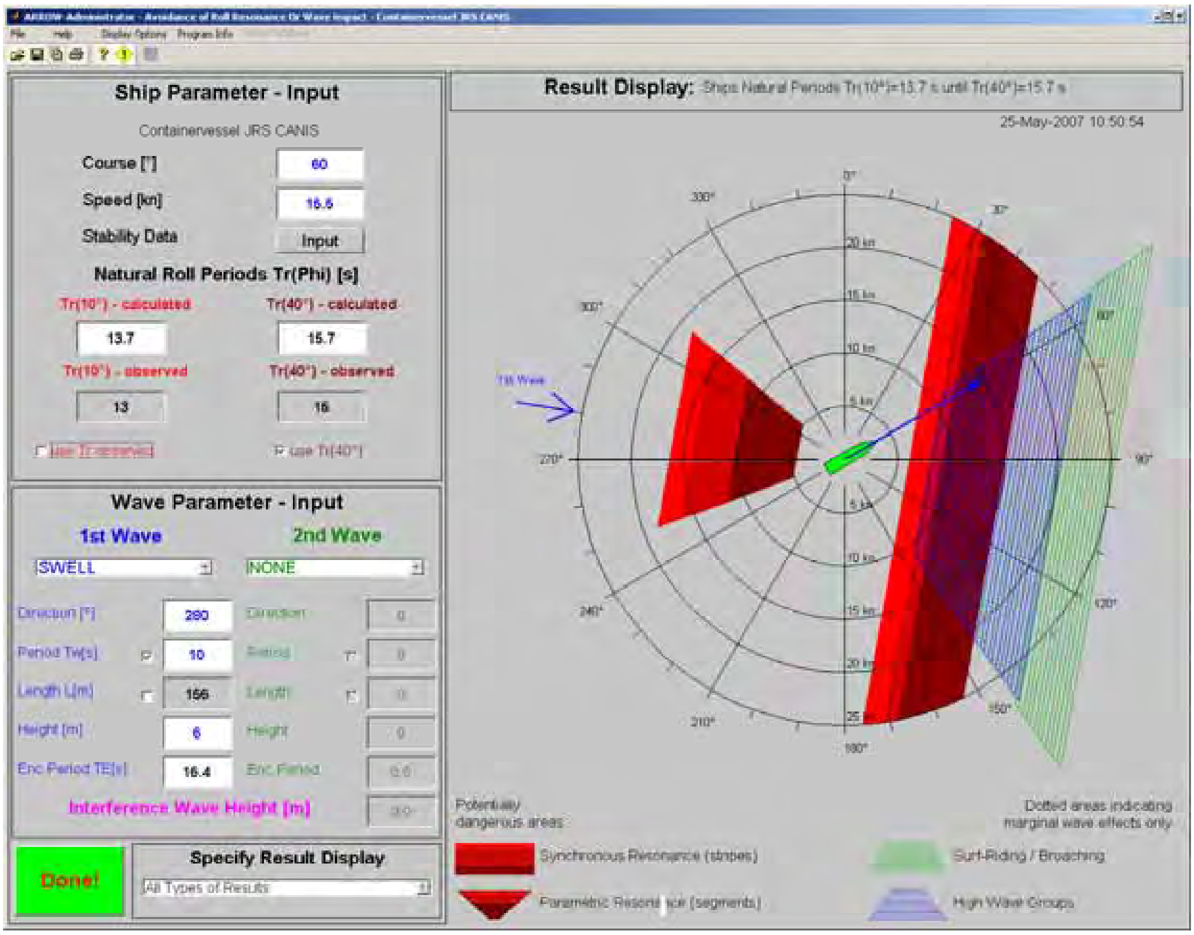
Figure 28: Summary of wave effects and formulas for calculating the values for representation in a polar co-ordinate diagram Fig. 27

Therefore in principle, a situation can even be assessed using manually calculated and drawn diagrams. For more complex situations, e.g. where there are several wave systems, it is however much better to simplify any evaluation of the situation by using computer-aided support, e.g. by using the following software.

5.3.2.4 Extended assessment of endangerment's using the ARROW program

5.3.2.4.1 Brief description of the program

The software program ARROW (Avoid Rolling Resonances Or Wave impact) was developed in order to calculate potentially hazardous situations more easily and to be able to gain a clearer overview of situations (Fig. 29). It enables quick variation of the relevant parameters for decision-making while taking into account the specified dangers in the prevailing situation and in voyage planning. More detailed descriptions can be found in [11], [11], [13]. Only a small amount of data for vessel and sea conditions have to be entered in the Ship Parameter Input Data (top left) and Wave Parameter Input (bottom left) interfaces to produce results on the result display (right).



ARROW Administrator - Avoidance of Roll Resonance Or Wave Impact - Containervessel JRS CANIS

Ship Parameter - Input

Containervessel JRS CANIS

Course [°]: 60
Speed [kn]: 16.6
Stability Data: Input

Natural Roll Periods Tr(Phi) [s]

Tr(10°) - calculated: 13.7
Tr(40°) - calculated: 15.7
Tr(10°) - observed: 13
Tr(40°) - observed: 16
☐ use Tr observed
☑ use Tr(40°)

Wave Parameter - Input

1st Wave: SWELL
2nd Wave: NONE

Direction [°]: 280 | Direction: 0
Period Tw[s]: ☑ 10 | Period: ☐ 0
Length L[m]: ☐ 156 | Length: ☐ 0
Height [m]: 6 | Height: 0
Enc Period TE[s]: 16.4 | Enc Period: 0.0
Interference Wave Height [m]: 0.0

Specify Result Display: All Types of Results

Result Display: Ships Natural Periods Tr(10°)=13.7 s until Tr(40°)=15.7 s

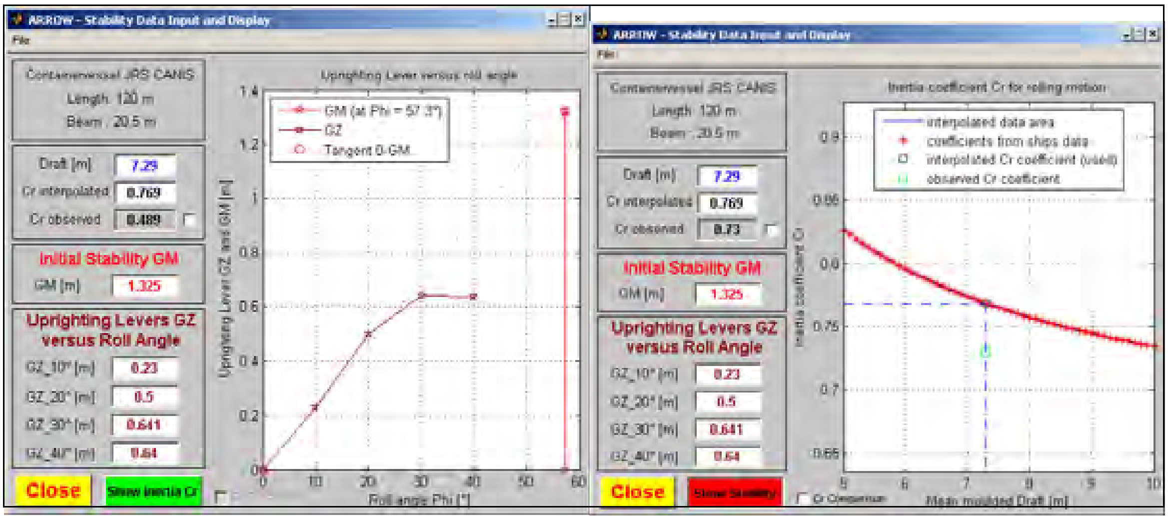
25-May-2007 10:50:54

Figure 29: ARROW program - an overview of the user interface with data from the accident situation CV JRS CANIS showing results for a endangerment assessment for Tw=10 s.

The course of the vessel and the speed can be entered into the corresponding data fields. They should then appear immediately in graphic form in the results display as a vessel contour, and the speed vector will appear in the corresponding course direction.
The vessel's natural rolling period can
a) either be calculated from the stability data or
b) entered directly from the observed roll period measurements.

a) The Stability Data Window (Fig. 30 left) can be used to enter the stability data; this window shows the inputted lever arms in the graphic display together with the tangent based on the GM value. In line with the inputted draught, the inertia coefficient Cr is calculated and shown in the right-hand window.
b) Alternatively, the roll period of the vessel can also be determined up-to-the-minute from observations and entered directly. In this case the checkbox for "calculated" or "observed" roll periods must be activated.
Up to two different wave systems are accepted for entering wave parameters, if e.g. wind sea and swell are coming from different directions. Only a few wave parameters are necessary, gained either through observations from onboard the vessel or from weather reports or forecasts. Huge benefits can be achieved by coupling ARROW with a weather routing program (in this instance e.g. "Bon Voyage" from AWT). This

combination can be excellently used for an overall assessment of the planned route, along side the stand-alone application of ARROW.


ARROW - Stability Data Input and Display

Containervessel JRS CANIS
Length 120 m
Beam 20.5 m

Draft [m] 7.29
Cr interpolated 0.769
Cr observed 0.489 ☐

Initial Stability GM
GM [m] 1.325

Uprighting Levers GZ versus Roll Angle
GZ_10° [m] 0.23
GZ_20° [m] 0.5
GZ_30° [m] 0.641
GZ_40° [m] 0.64

ARROW - Stability Data Input and Display

Containervessel JRS CANIS
Length 120 m
Beam 20.5 m

Draft [m] 7.29
Cr interpolated 0.769
Cr observed 0.73 ☐

Initial Stability GM
GM [m] 1.325

Uprighting Levers GZ versus Roll Angle
GZ_10° [m] 0.23
GZ_20° [m] 0.5
GZ_30° [m] 0.641
GZ_40° [m] 0.64

☐ Cr Observation

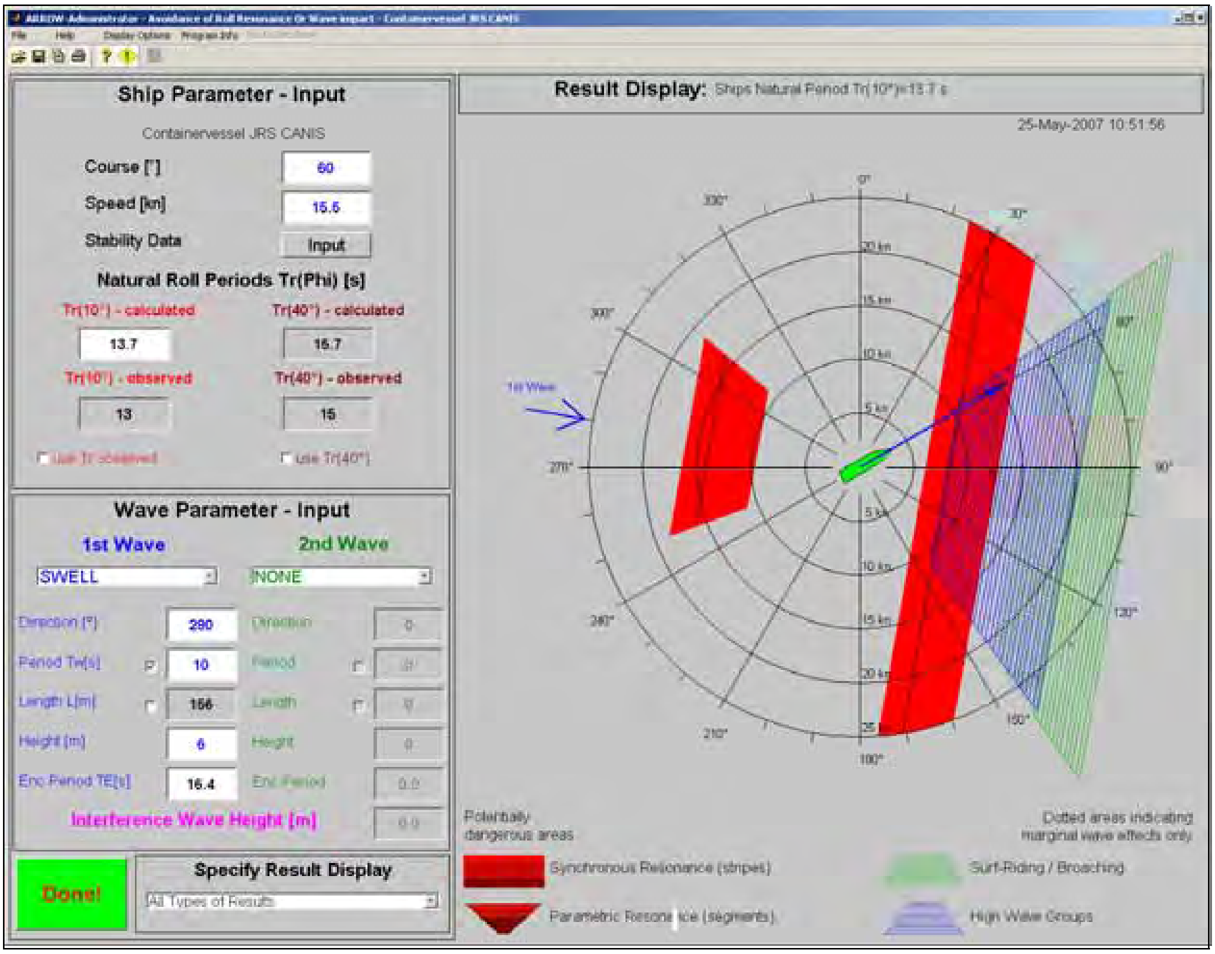
Figure 30: Stability data window – lever arm curve over the roll angle with tangents based on the GM value (left) and inertia coefficient curves CR for rolling over the draught

The polar co-ordinate diagram gives an overview of critical courses and speed ranges in the form of stripes and sectors of resonance danger and of other endangerments when sailing through high stern wave groups or while surf-riding, according to IMO guidelines. All the different types of hazards and dangers are labelled using different colours and patterns corresponding to the legend below right.
The potential resonance danger is also made explicit for large roll amplitudes. The brown areas for Tr(40°) border on the red areas for small roll angles Tr(10°) (Fig. 29). If the tip of the speed vector is located in one or several danger areas, then the vessel is potentially in a dangerous situation. In this case, either the vessel's speed or course can be altered to bring the vessel out of the dangerous situation. Alternatively, the stability can be varied. An optimum variation can be quickly identified using focused trials with the help of the software.

5.3.2.4.2 Example calculations using ARROW for the accident situation

The vessel data and sea state conditions were entered into the ARROW program to assess the time of the accident. The following will detail and discuss the results.
The stability data entries in Fig. 30 show that the lever arm curve deviates greatly from the tangent which forms the origin based on the GM value at 57.3°. The result is shown in the ship data area (Fig. 29) which indicates that the roll periods differ greatly for small and large roll angles.
Consequently this means that the potential resonance areas are larger because there is a possibility of several periods of resonance. This difference is visible when comparing the illustrations in Fig. 29 which shows all areas of roll periods Tr(10°) to Tr(40°), and Fig. 31 where only the areas for Tr(10°) are visible. It must be emphasized that for the red areas denoting resonance the amplitudes rise continually with the increase in wave excitation with smaller roll angles, whereas it is unsafe in the brown area of resonance only when there are large roll angles. This means that

resonance only comes into play when these large roll angles are reached as a result of even short-lived initial disruption!
Calculations were also carried out for wave period Tw = 11 s (Fig. 32) and wave period Tw = 12 s (Fig. 33) in addition to calculations of dangerous areas for the aforementioned period Tw = 10 s (Fig. 29 and Fig. 31).



Ship Parameter - Input

Containervessel JRS CANIS

Course [°]: 60
Speed [kn]: 15.5
Stability Data: Input

Natural Roll Periods Tr(Phi) [s]

Tr(10°) - calculated	Tr(40°) - calculated
13.7	15.7
Tr(10°) - observed	**Tr(40°) - observed**
13	15
☐ Use Tr observed	☐ Use Tr(40°)

Wave Parameter - Input

	1st Wave		2nd Wave		
	SWELL		NONE		
Direction [°]	290	Direction		0	
Period Tw[s]	☑	10	Period	☐	0
Length L[m]	☐	156	Length	☐	0
Height [m]	6	Height		0	
Enc Period TE[s]	16.4	Enc Period		0.0	
Interference Wave Height [m]				0.0	

Done!

Specify Result Display: All Types of Results

Result Display: Ships Natural Period Tr(10°)=13.7 s

25-May-2007 10:51:56

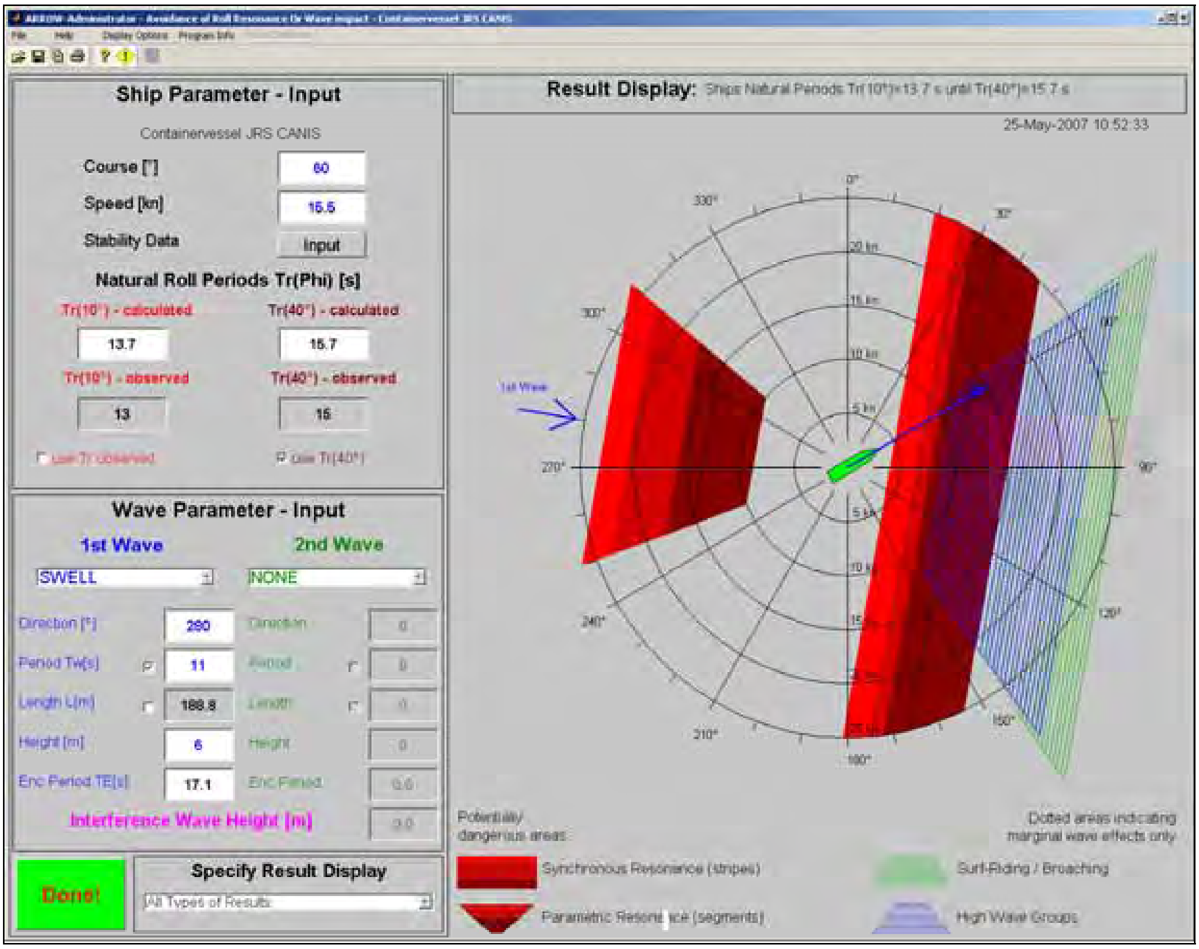
Figure 31: Results from the endangerment assessment for Tw=10 s - here without Tr(40°).

(ARROW application for JRS CANIS)

The following conclusion can be drawn from the comparative evaluation of this data:
For all three periods, the vessel is located within the brown strip of resonance indicating synchronous resonance for large roll angles. There is even a virtually direct resonance for the period Tw=10 s! For periods Tw=10 and 11 s, the vessel is also simultaneously in the resonance stripe for small roll angles due to the overlapping of areas. Even with initially small roll amplitudes, such circumstances can lead to a build-up of rolling motion due to the quartering stern sea, which then really pushes it into the critical resonance range with large roll angles. It appears that this is the reason for the severe rolling motion of the vessel at the time of the accident. In addition to this, the vessel (with this course and speed) is located in the sector with blue stripe lines, which means it is in a situation where it rides for long periods on the wave crests when encountering wave groups (high wave group encounter - successive high wave attack) and consequently has only very minimal stability with low up-righting lever arms.

A description was given as to how at the time of the accident there was a slow approx. 030° change of course to port. This means a potentially dangerous passage through the direct resonance area which should in any case be done with great caution and preferably with speed and confidence.

However, this would also need a form of decision support such as an overview of the potentially dangerous areas, e.g. in the form of a polar co-ordinate diagram. If the master had had this kind of information as part of his voyage planning then he could have quickly made the appropriate decisions. Corresponding procedures are dealt with in literature and are a basis for instruction and further education at institutions for the training and qualification of ship's officers. The directive [8] also contains specific instructions on setting up these kinds of decision support tools (in this context, it is viewed as a retrograde step that the new version of the directive [9] no longer gives such specific aids to calculation and illustrations, but only contains verbal formulations).



Ship Parameter - Input

Containervessel JRS CANIS

Course [°] 60
Speed [kn] 15.5
Stability Data

Natural Roll Periods Tr(Phi) [s]

Tr(10°) - calculated 13.7
Tr(40°) - calculated 15.7
Tr(10°) - observed 13
Tr(40°) - observed 15
☐ use Tr observed
☑ use Tr(40°)

Wave Parameter - Input

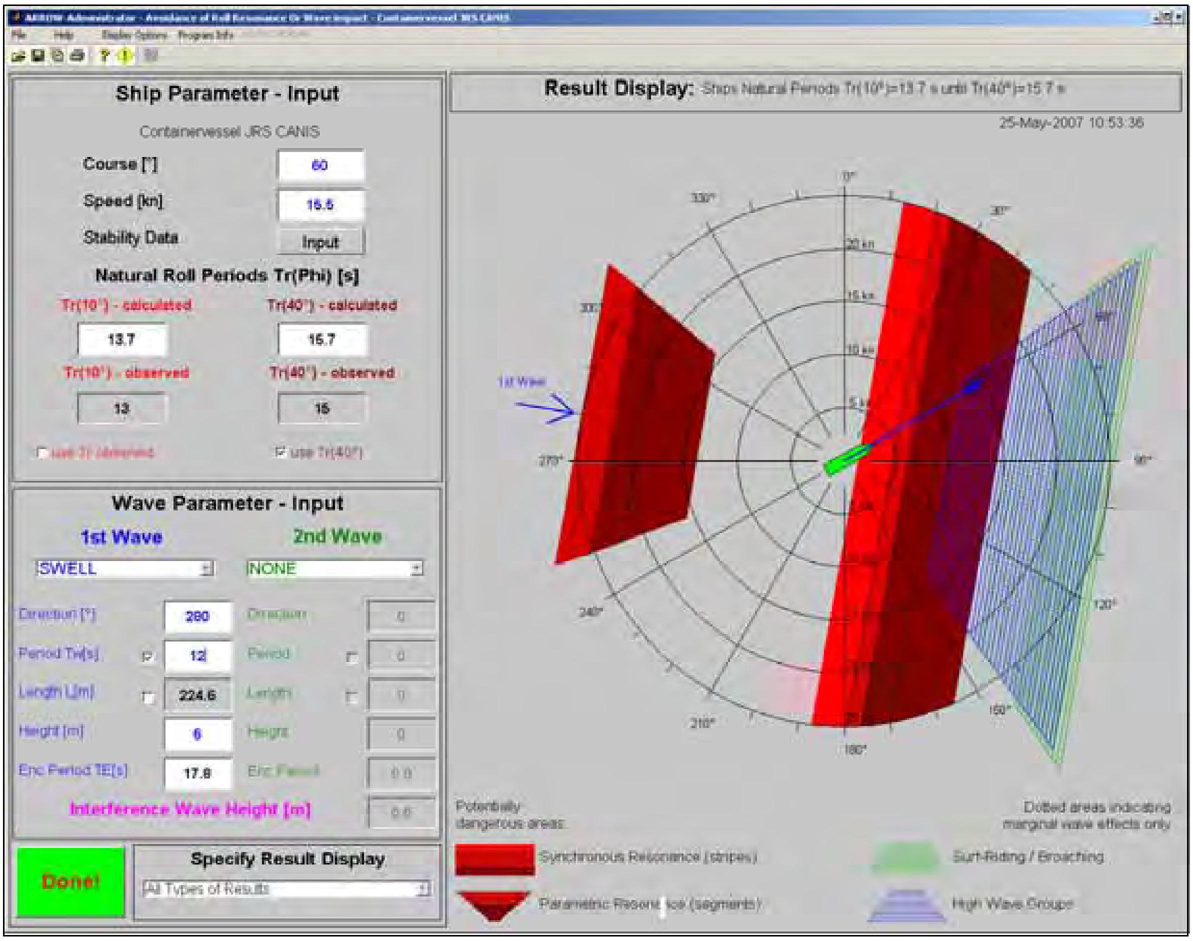
	1st Wave		2nd Wave
	SWELL		NONE
Direction [°]	290	Direction	0
Period Tw[s]	☑ 11	Period	☐ 0
Length L[m]	☐ 188.8	Length	☐ 0
Height [m]	6	Height	0
Enc Period TE[s]	17.1	Enc Period	0.0
Interference Wave Height [m]			0.0

Specify Result Display
All Types of Results

Result Display: Ships Natural Periods Tr(10°)=13.7 s until Tr(40°)=15.7 s

25-May-2007 10:52:33

Figure 32: Results of the endangerment assessment for Tw=11 s (ARROW for CV JRS CANIS)



Ship Parameter - Input

Containervessel JRS CANIS

Course [°]: 60
Speed [kn]: 15.5
Stability Data: Input

Natural Roll Periods Tr(Phi) [s]

Tr(10°) - calculated: 13.7
Tr(40°) - calculated: 15.7
Tr(10°) - observed: 13
Tr(40°) - observed: 15
☑ use Tr(40°)

Wave Parameter - Input

1st Wave: SWELL
2nd Wave: NONE

Direction [°]: 280
Period Tw[s]: ☑ 12
Length L[m]: ☐ 224.6
Height [m]: 6
Enc Period TE[s]: 17.8

Result Display: Ships Natural Periods Tr(10°)=13.7 s until Tr(40°)=15.7 s

25-May-2007 10:53:36

Figure 33: Results of the endangerment assessment for Tw=12 s (ARROW for CV JRS CANIS)

5.3.2.5 Possibility of recognising and avoiding dangers

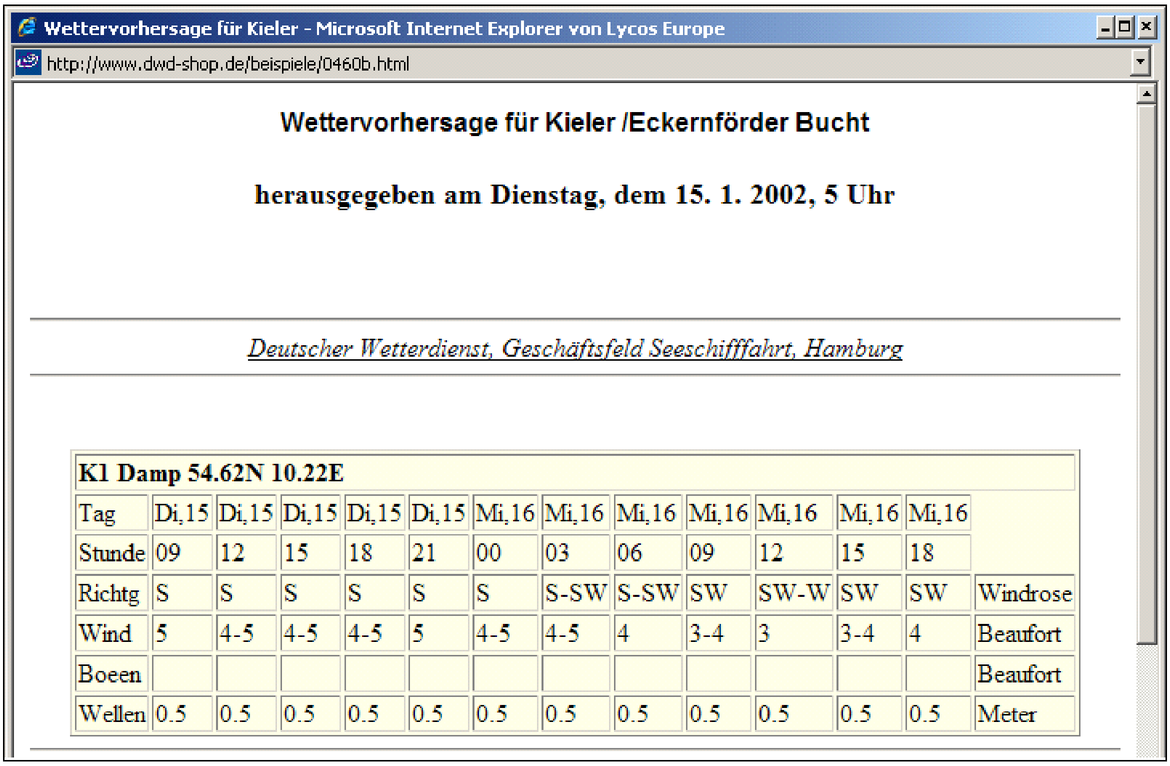
5.3.2.5.1 Possibilities for acquiring weather and sea state data

There are various options for masters to acquire information about the weather and the expected wave directions and periods either before departure of the vessel or during the voyage, especially for the German regions but also worldwide.
There are weather services such as the DWD and other globally operating weather routing companies like Applied Weather Technology (AWT), for example. As an example some information will be summarised here for two select representatives.

5.3.2.5.2 Forecasts and service of the German National Meteorological Service DWD

For example, the German National Meteorological Service provides information on the expected wave directions and periods especially for the German regions, but also worldwide. At the same time, maritime weather information received free of charge often only contains limited information; even information available at a fee from the standard "Wettershop" (weather shop) has for example no information about wave periods (Fig. 34). Specifically tailored services can be acquired directly through contracted relationships for special routes and regions, as the example for Baltic Sea ferry traffic shows (Fig. 35). Global weather routing services are also offered.

By using the maritime weather information systems as a type of self-briefing for skippers and masters, captains can individually and independently gain information before and during sailing about current and predicted wind, weather and sea conditions across Europe (Fig. 36). The maritime weather information systems, e.g. MetFERRY or SEEWIS, enable access to current weather data and forecasts in a compressed format (ZIP archive) via telephone/modem/DSL and can be viewed on a PC or laptop.



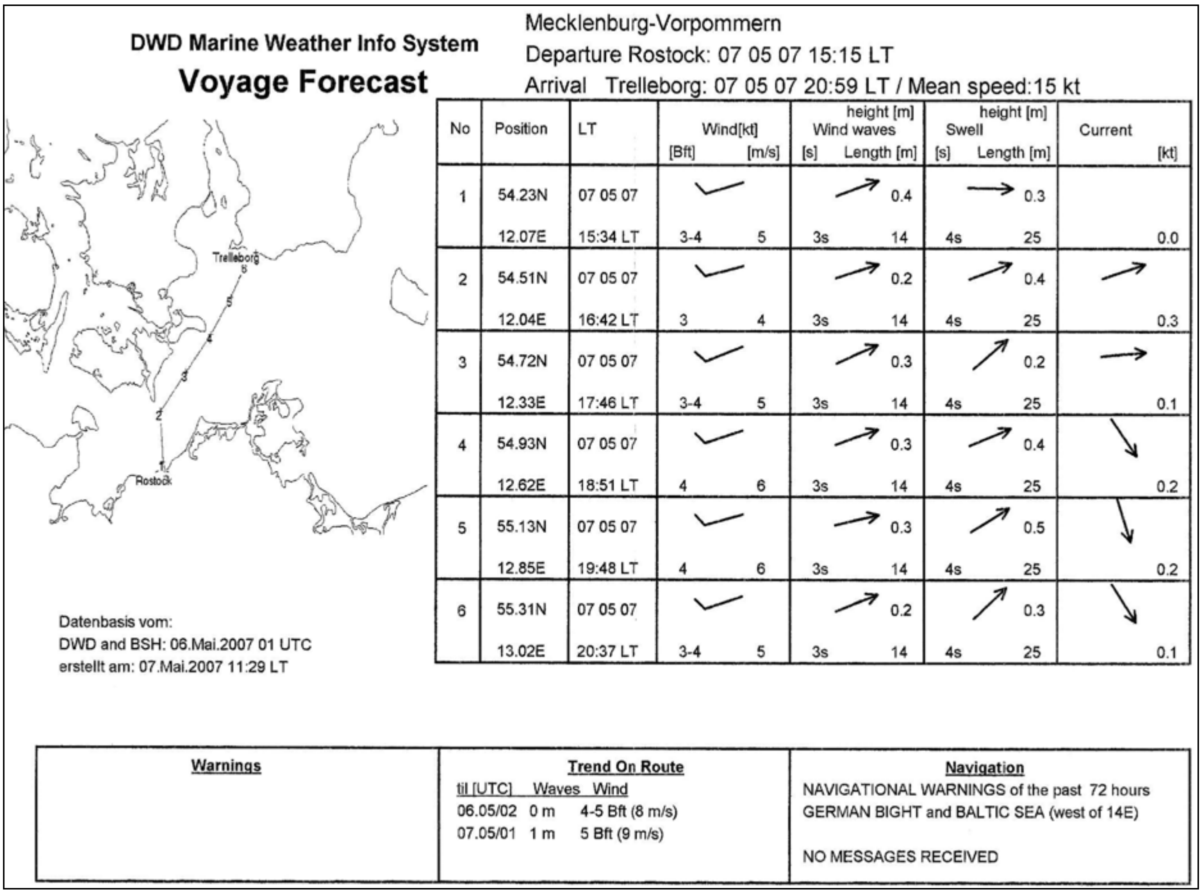
Wettervorhersage für Kieler /Eckernförder Bucht

herausgegeben am Dienstag, dem 15. 1. 2002, 5 Uhr

Deutscher Wetterdienst, Geschäftsfeld Seeschifffahrt, Hamburg

K1 Damp 54.62N 10.22E													
Tag	Di,15	Di,15	Di,15	Di,15	Di,15	Mi,16	Mi,16	Mi,16	Mi,16	Mi,16	Mi,16	Mi,16	
Stunde	09	12	15	18	21	00	03	06	09	12	15	18	
Richtg	S	S	S	S	S	S	S-SW	S-SW	SW	SW-W	SW	SW	Windrose
Wind	5	4-5	4-5	4-5	5	4-5	4-5	4	3-4	3	3-4	4	Beaufort
Boeen													Beaufort
Wellen	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	Meter

Figure 34: Example of commercial weather information of the DWD from the "Wettershop" - however, this contains no information on wave periods (http://www.dwd-shop.de/)



DWD Marine Weather Info System

Voyage Forecast

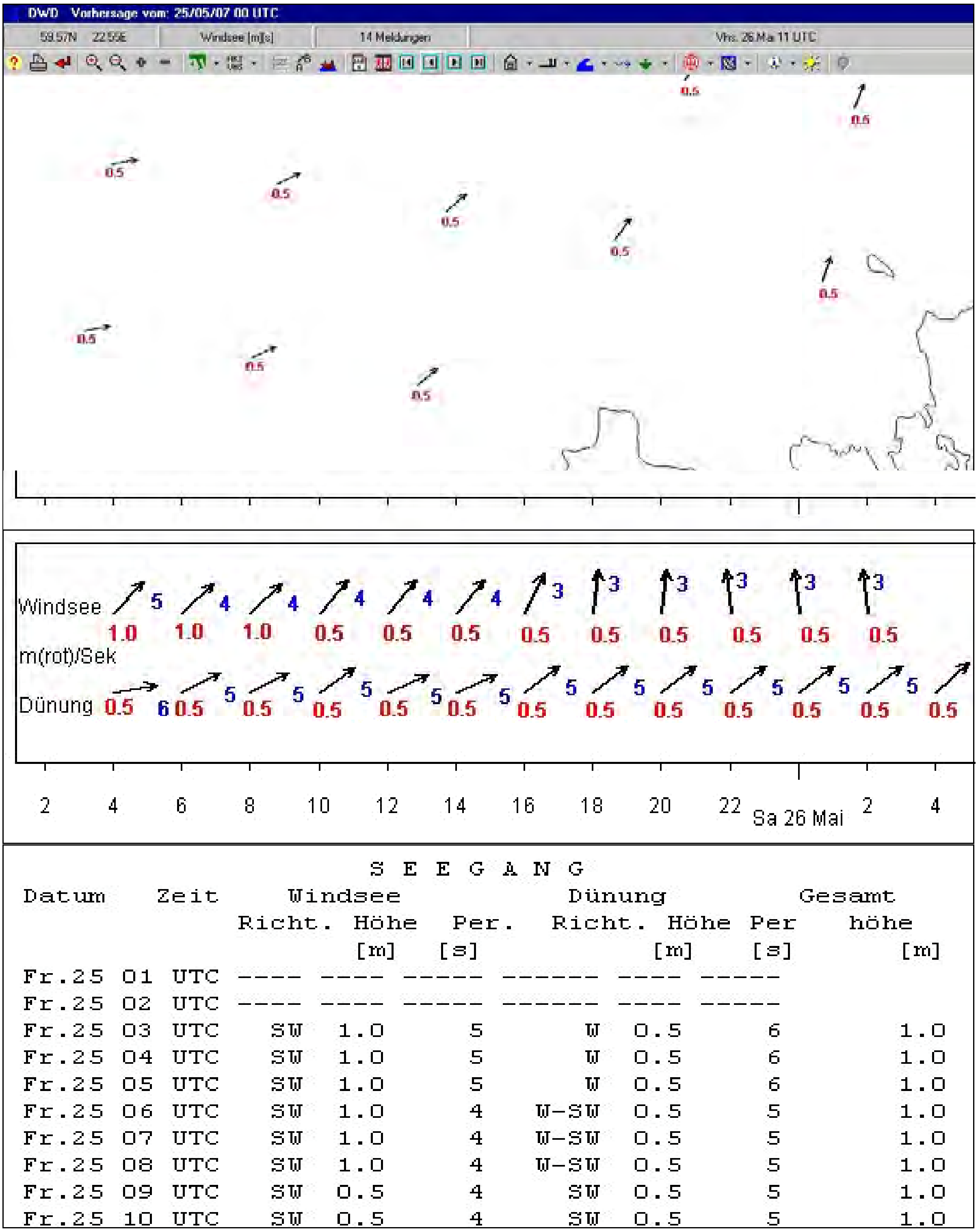
Mecklenburg-Vorpommern
Departure Rostock: 07 05 07 15:15 LT
Arrival Trelleborg: 07 05 07 20:59 LT / Mean speed:15 kt

No	Position	LT	Wind[kt] [Bft]	Wind[kt] [m/s]	Wind waves height [m]	Wind waves [s]	Wind waves Length [m]	Swell height [m]	Swell [s]	Swell Length [m]	Current [kt]
1	54.23N 12.07E	07 05 07 15:34 LT	3-4	5	0.4	3s	14	0.3	4s	25	0.0
2	54.51N 12.04E	07 05 07 16:42 LT	3	4	0.2	3s	14	0.4	4s	25	0.3
3	54.72N 12.33E	07 05 07 17:46 LT	3-4	5	0.3	3s	14	0.2	4s	25	0.1
4	54.93N 12.62E	07 05 07 18:51 LT	4	6	0.3	3s	14	0.4	4s	25	0.2
5	55.13N 12.85E	07 05 07 19:48 LT	4	6	0.3	3s	14	0.5	4s	25	0.2
6	55.31N 13.02E	07 05 07 20:37 LT	3-4	5	0.2	3s	14	0.3	4s	25	0.1

Datenbasis vom:
DWD and BSH: 06.Mai.2007 01 UTC
erstellt am: 07.Mai.2007 11:29 LT

Warnings	Trend On Route	Navigation
	til [UTC] Waves Wind 06.05/02 0 m 4-5 Bft (8 m/s) 07.05/01 1 m 5 Bft (9 m/s)	NAVIGATIONAL WARNINGS of the past 72 hours GERMAN BIGHT and BALTIC SEA (west of 14E) NO MESSAGES RECEIVED

Figure 35: Example of commercial weather information of the DWD from specific, individualised routing advice for ferry traffic in the Baltic Sea



```
                    S E E G A N G
Datum     Zeit     Windsee            Dünung          Gesamt
                 Richt.  Höhe   Per.   Richt.  Höhe  Per    höhe
                         [m]    [s]            [m]   [s]     [m]
Fr.25  01  UTC  ----  ----  -----  ------  ----  -----
Fr.25  02  UTC  ----  ----  -----  ------  ----  -----
Fr.25  03  UTC    SW   1.0      5       W   0.5      6       1.0
Fr.25  04  UTC    SW   1.0      5       W   0.5      6       1.0
Fr.25  05  UTC    SW   1.0      5       W   0.5      6       1.0
Fr.25  06  UTC    SW   1.0      4    W-SW   0.5      5       1.0
Fr.25  07  UTC    SW   1.0      4    W-SW   0.5      5       1.0
Fr.25  08  UTC    SW   1.0      4    W-SW   0.5      5       1.0
Fr.25  09  UTC    SW   0.5      4      SW   0.5      5       1.0
Fr.25  10  UTC    SW   0.5      4      SW   0.5      5       1.0
```

Figure 36: Screenshots of professional maritime forecasts in maritime weather information systems of the DWD

5.3.2.5.3 Weather routing advice and onboard supported routing program from Applied Weather Technology (AWT)

As a globally active weather routing company, AWT provides

- both shore-based advice for shipping via its central routing offices: Routing recommendations are prepared specifically on shore and then sent to the ships.
- as well as onboard based route processing: Based on the weather data transmitted to the ship, software packages such as "Bon Voyage" enable route processing and optimisation onboard, carried out by the crew themselves.

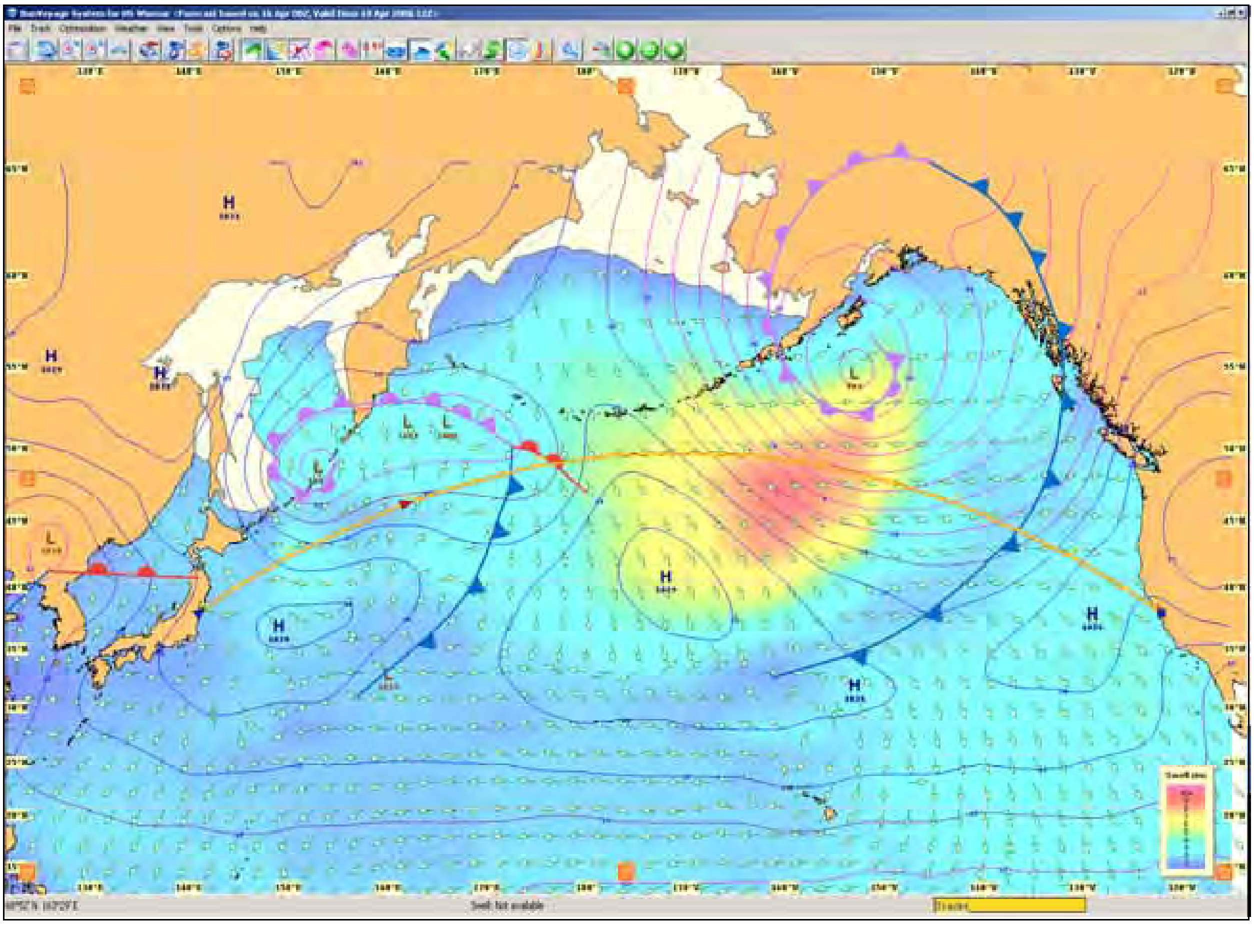


Figure 37: Screenshot of onboard based route processing with professional weather and maritime forecasts in the routing software "Bon Voyage" from AWT

5.3.2.5.4 Assessment of current sea state information onboard

On the one hand there is the conventional method of e.g. using a stop watch to measure wave periods or of assessing the wave length compared to the ship length: To calculate the wave periods TW, you measure several times e.g. with a stop watch the time taken for an area of foam caused by breaking waves to move through a full upwards and downwards motion, i.e. between two consecutive 'up' positions.
On the other hand, there are also up-and-coming technologies where measurement by radar is followed by data processing to determine wave parameters (e.g. WaMoS Wave and Surface Current Monitoring System see http://www.sea-image.com/wamos_intro.htm).

5.3.2.6 Methods of calculation to identify dangers or make preparatory decisions to avoid danger

5.3.2.6.1 Fundamental methods of calculation

A risk assessment benefits from both calculations and representations of the situation in a polar co-ordinate diagram. There are two possibilities for this, as follows:

A) Calculation of potentially dangerous areas for resonance and other dangers such as stability endangerment due to high stern waves and surf-riding as a qualitative illustration:
This procedure is used as a basis for the assessment in this survey report. **It has the advantage of only requiring a small amount of representative data for simplified modelling of the sea state and ship dynamics. However, no concrete figures are forecast for expected amplitudes, instead they are only given for potentially dangerous areas.** However, these are based on the reliable fact that these dangers (for example) occur if the natural roll period of the ship and the encounter periods are in specific relationship to each other, thus leading to resonance. **However, this method makes it possible to assess tendencies and derive a direction for altering course or speed which is especially useful when combined with the experience that ship officers have of the behaviour of their particular ship at certain wave heights.**

Due to its simplicity, a great advantage of this method is that you can manually prepare diagrams in preparation for the voyage from forecast data or from current data for assessing the situation and use it onboard. You can chiefly draw such polar co-ordinate diagrams using procedures like those described in detail in Chp. 5.4.3 and [10] [12], or you can use alternative methods for preparing several diagrams for different roll periods of the ship, as described in the guidelines [8].

Software, as e.g. ARROW, are required for more complex tasks, such as voyage planning and weather routing over longer periods of sailing, but especially for optimum results when calculating several versions.
B) Calculation of roll amplitudes by simulating the movement of the ship at sea or based on the transfer functions as a quantitative illustration:
This method is applied in complex tools such as the OCTOPUS system from AMARCON with the "Ship Routing Assistant" (SRA) from Germanischer Lloyd GL or

also the SeaSENSE system from FORCE Technology, which even calculates the loads of a seagoing ship within the context of its power spectrum.
Such forecasting results for amplitude calculations do however come with uncertainties and the reliability is consequently limited. Apart from which, these systems are associated with high costs (in particular when combined with wave radar) and require comprehensive data processing for the sea and vessel data.

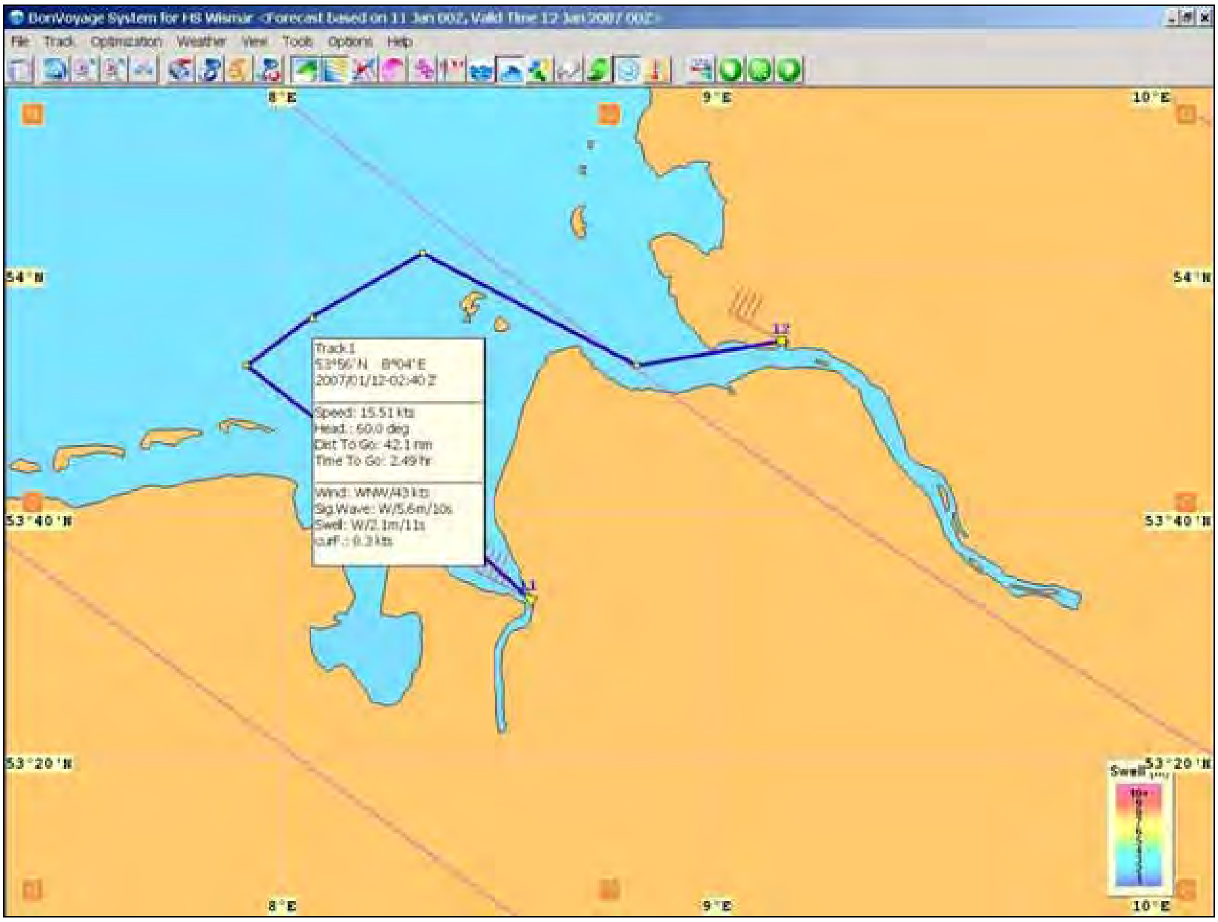
5.3.2.6.2 Concrete possibility for the crew to identify danger (calculating polar co-ordinate diagrams to clarify avoidance tactics)

Two points will be set out here as to what options would have been available with low-level equipment and with professional software:

1) Basically the crew would have had to determine the roll period simply, based on the given stability data of the vessel or by measuring the ship. Then they could have assessed the potential sea data based on weather information. This would have given a simple evaluation of the risk situation when planning the voyage:
    - Calculation of the roll period for small and large roll amplitudes could have been carried out as described in Chapter 5.4.1.2.
    - Based on weather forecasts predicting strong winds, we can assume wave periods of approx. $T_w \approx 10$ -12 s in the North Sea.
    - If you then use this data and apply the procedure for evaluating the situation in a polar co-ordinate diagram as shown in Chapter 5.4.3, we can deduce that the ship was in danger of resonance on the affected sections of the voyage. Decisions can be made on this basis, e.g. to secure the cargo better or to take measures for changing the roll period by altering the stability through varying the GM (as far as possible). Such variant calculations can be made manually with a pocket calculator, but take time and effort.
2) If the ship is better equipped, such decisions can be made more easily as is apparent from applying voyage planning tools such as "Bon Voyage" from AWT and ARROW.
    - The voyage is roughly planned from Bremerhaven to Brunsbüttel in Fig. 38. The weather and sea data are allocated along the voyage for the individual way points, according to the weather forecast data for that time. The only thing relevant for this point is the route segments at sea and not the voyage segments on the Weser or Elbe Rivers - they are only entered here for completeness' sake.
    - The situation for each route section can be assessed by using the ARROW program. The data from the time of the accident has been used in Fig. 39 in compliance with the information from the information box at the position of the accident (small information box in Fig. 38). The ship is in resonance, both for the first main sea wave system with a wave height of 5.6 m as well as for smaller swells from 263° and a 2.1 m wave height corresponding to the second wave system.
    - If you wish to make stability changes to escape the potential danger zone, then variant calculations can be made. Below is a hypothetical example to illustrate the advantage of using such programs (precise loading and possibilities for change, e.g. through ballast, are not known).
        i) For example, we can see in Fig. 40 that for GM = 0.8 m (=GMmin) and therefore Tr=17.8 s, there is no longer any real resonance danger from the

first main sea wave system on a critical course of 60°. The arrow for the speed vector is already at the edge of the stripe; speed reduction or a change of course to port would be helpful.

ii) If you look at both wave systems, you can see in Fig. 41 that there is resonance danger for the second wave system here (however, with considerably smaller waves); the course change to port would have to be undertaken with great confidence to traverse the critical sector quickly.



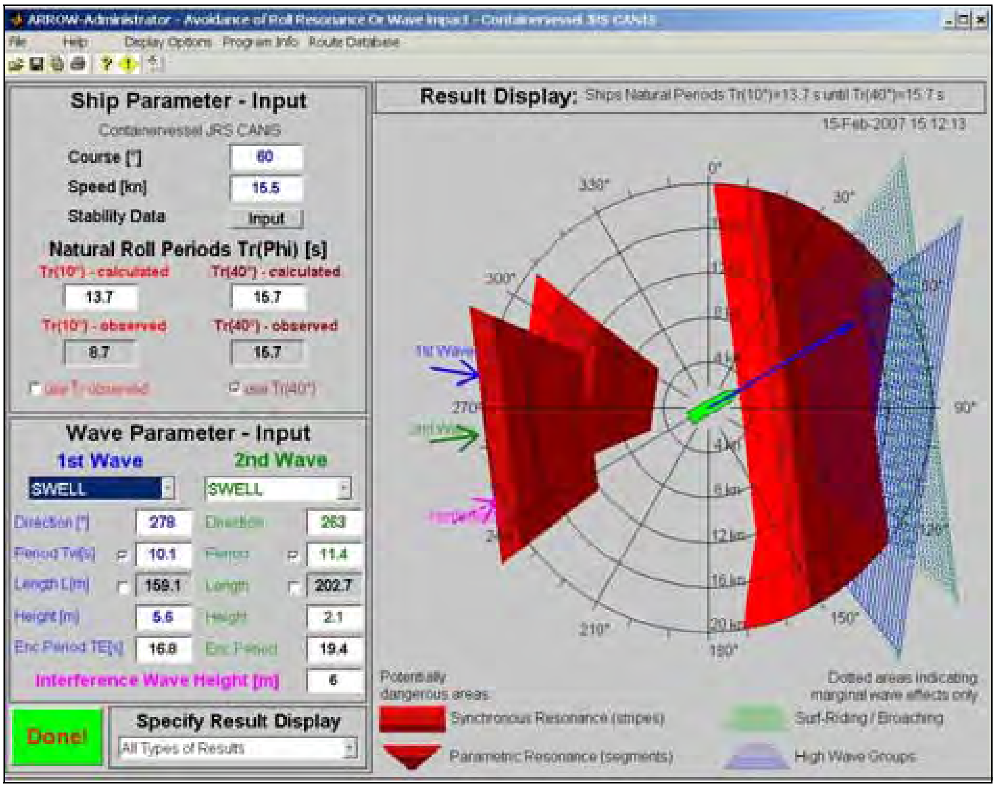
BonVoyage System for HS Wismar <Forecast based on 11 Jan 00Z, Valid Time 12 Jan 2007 00Z>

Track1
53°56'N 8°04'E
2007/01/12-02:40 Z

Speed: 15.51 kts
Head.: 60.0 deg
Dist To Go: 42.1 nm
Time To Go: 2.49 hr

Wind: WNW/43 kts
Sig.Wave: W/5.6m/10s
Swell: W/2.1m/11s
CurF.: 0.3 kts

Figure 38: Screenshot of the weather routing software "Bon Voyage" from AWT for the estimated route of the JRS CANIS using the weather forecasting data for that time


ARROW-Administrator - Avoidance of Roll Resonance Or Wave Impact - Containervessel JRS CANIS

Ship Parameter - Input

Containervessel JRS CANIS

Course [°]: 60
Speed [kn]: 15.5
Stability Data: Input

Natural Roll Periods Tr(Phi) [s]

Tr(10°) - calculated: 13.7
Tr(40°) - calculated: 15.7
Tr(10°) - observed: 8.7
Tr(40°) - observed: 15.7
☐ use Tr observed
☑ use Tr(40°)

Wave Parameter - Input

	1st Wave		2nd Wave
	SWELL		SWELL
Direction [°]	278	Direction	263
Period Tw[s]	☑ 10.1	Period	☑ 11.4
Length L[m]	☐ 159.1	Length	☐ 202.7
Height [m]	5.6	Height	2.1
Enc.Period TE[s]	16.8	Enc.Period	19.4

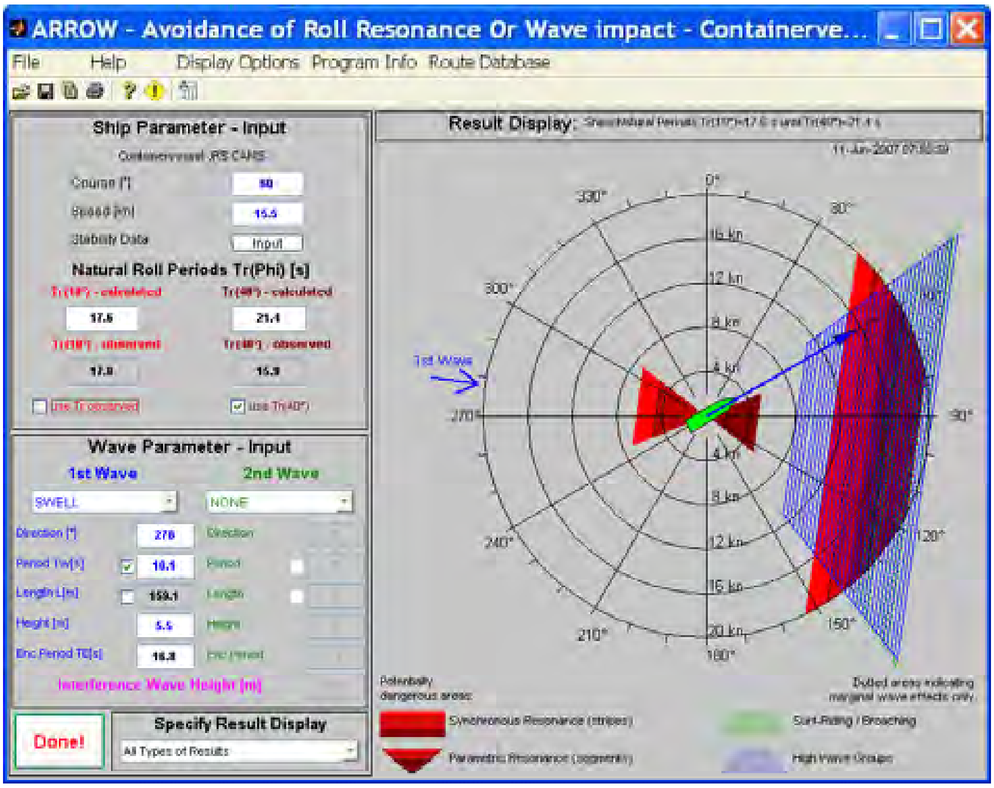
Interference Wave Height [m]: 6

Specify Result Display: All Types of Results

Result Display: Ships Natural Periods Tr(10°)=13.7 s until Tr(40°)=15.7 s

15-Feb-2007 15:12:13

Figure 39: ARROW screenshot showing data for the current situation from the routing software "Bon Voyage" Fig. 38 corresponding to the two wave systems


ARROW - Avoidance of Roll Resonance Or Wave impact - Containerve...

Ship Parameter - Input

Containervessel JRS CANIS

Course [°]: 60
Speed [kn]: 15.5
Stability Data: Input

Natural Roll Periods Tr(Phi) [s]

Tr(10°) - calculated: 17.6
Tr(40°) - calculated: 21.4
Tr(10°) - observed: 17.8
Tr(40°) - observed: 15.9
☐ use Tr observed
☑ use Tr(40°)

Wave Parameter - Input

	1st Wave		2nd Wave
	SWELL		NONE
Direction [°]	278	Direction	
Period Tw[s]	☑ 10.1	Period	☐
Length L[m]	☐ 159.1	Length	☐
Height [m]	5.5	Height	
Enc.Period TE[s]	16.8	Enc.Period	

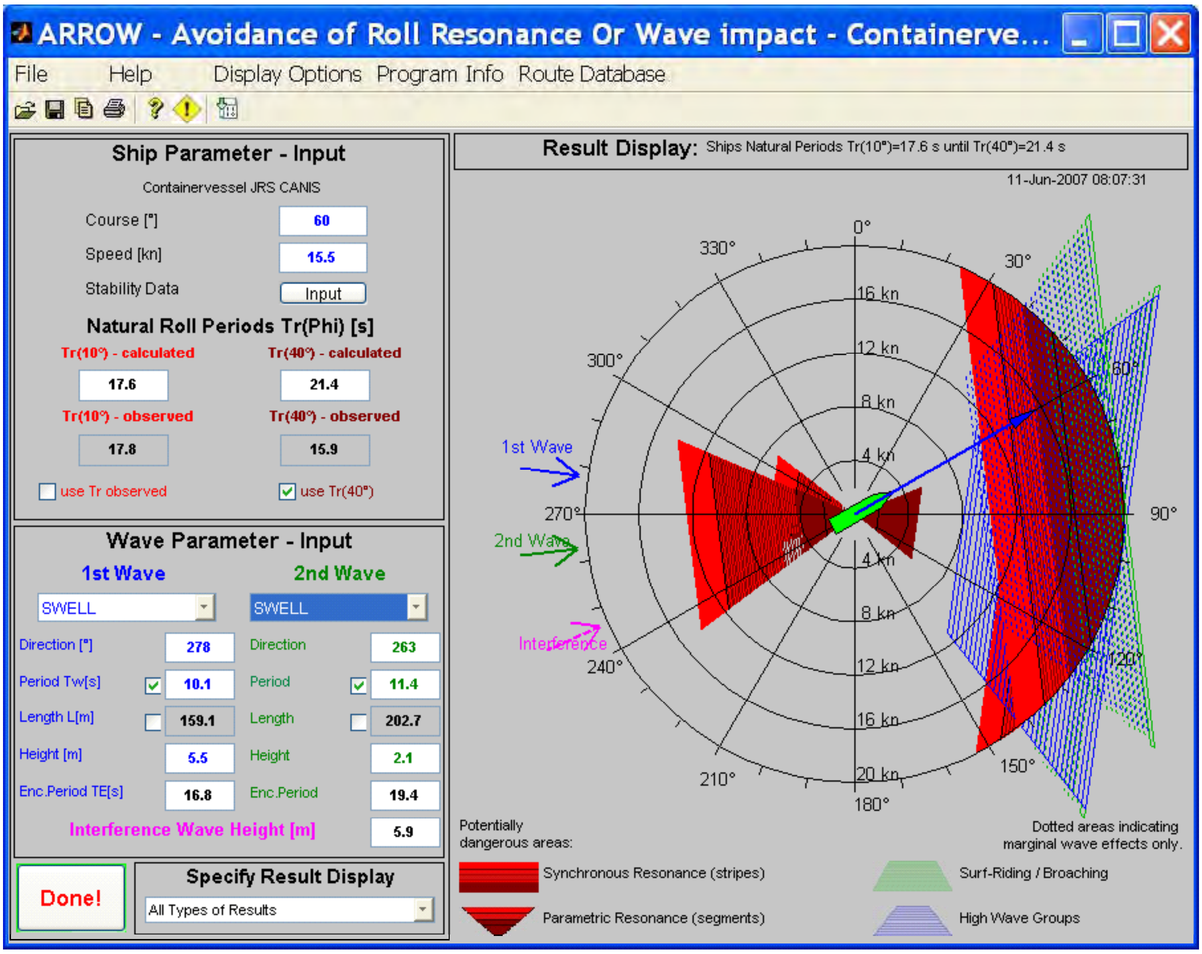
Interference Wave Height [m]

Specify Result Display: All Types of Results

Result Display: Ships Natural Periods Tr(10°)=17.6 s until Tr(40°)=21.4 s

11-Jun-2007 07:50:59

Figure 40: ARROW screenshot showing data for the alternative situation with Tr=17.8 s only for the first main sea wave system: there is hardly any resonance danger left from this wave system, especially with a further course change to port



Ship Parameter - Input

Containervessel JRS CANIS

Course [°] 60
Speed [kn] 15.5
Stability Data Input

Natural Roll Periods Tr(Phi) [s]

Tr(10°) - calculated	Tr(40°) - calculated
17.6	21.4
Tr(10°) - observed	Tr(40°) - observed
17.8	15.9
☐ use Tr observed	☑ use Tr(40°)

Wave Parameter - Input

	1st Wave		2nd Wave
	SWELL		SWELL
Direction [°]	278	Direction	263
Period Tw[s]	☑ 10.1	Period	☑ 11.4
Length L[m]	☐ 159.1	Length	☐ 202.7
Height [m]	5.5	Height	2.1
Enc.Period TE[s]	16.8	Enc.Period	19.4

Interference Wave Height [m] 5.9

Specify Result Display
All Types of Results

Result Display: Ships Natural Periods Tr(10°)=17.6 s until Tr(40°)=21.4 s

11-Jun-2007 08:07:31

Potentially dangerous areas:

Dotted areas indicating marginal wave effects only.

🟥 Synchronous Resonance (stripes)
🟥 Parametric Resonance (segments)
🟩 Surf-Riding / Broaching
🟦 High Wave Groups

Figure 41: ARROW screenshot showing data for the alternative situation with Tr=17.8 s for both wave systems: there is still a danger of resonance which would be avoidable with a course change to port by approx. 15°

5.3.2.7 Summary assessment

At the time of the accident, the ship was located **in a resonance area of synchronous resonance with large roll angles** for the assumed range of wave periods of 10 and 11 s.
There is even a virtually **direct resonance** for the period 10 s.
For the 10 and 11 s periods, the vessel is also simultaneously in the resonance stripe for small roll angles due to the overlapping of areas.
Even with initially small roll amplitudes, it can lead under such circumstances to **a build-up of rolling motion** due to the quartering stern sea, which then really enters the **critical resonance range** with large roll angles.
This can be viewed as the probable reason for **the severe rolling motion** of the ship at the time of the accident.

In order to make the right decisions in this situation, decision-making support would have been necessary for the vessel's command in the form of a general overview of the potentially dangerous areas.
These kinds of decision-making aids could have been available to the vessel's command whether as low-level equipment or in the form of professional software.

If the master had already had this kind of information as part of his voyage planning then he could have quickly made the appropriate decisions.

It is finally the view of the expert, that the loss of cargo in this case would have been preventable if wave and surface current monitoring software (supporting by weather routing) had been onboard.

5.4 Investigation of the lashing material

Shortly after the incident, parts of the lashing material were secured. These parts were subjected to a material examination to clarify whether pre-existing material faults could have contributed to the loss of the containers.
The following were examined in particular: a fragment of a lashing bar, a turnbuckle with a lug fracture, the fragment of another lug (probably of a turnbuckle), the fragment of a bolt for unlocking the lashing bar and an automatic twistlock.

5.4.1 Lashing bar

The lashing bar showed a rupture approx. 150 mm near the end fitting. Figure 42 shows an overview of the fragment. The fractured surface can be seen in Figure 43. This is covered with corrosion products. We are dealing here with a non-deformed forced rupture which has a correspondingly coarse break structure. A sample was taken from the rupture area and a micro-section created from this. It showed a predominantly pearlitic structure with narrow seams of ferrite on the grain boundaries. Apart from this, the significant appearance of cleavage fractures due to a brittle rupture was identified (see Fig. 44).
There did not seem to be any point in doing a tension test as there was a weld seam about 30 mm away from the fracture point.
A hardness test from the micro-section showed a hardness of 272 HV 10. This allows us to estimate a tensile strength for the lashing bar of approx. 870 N/mm^2.

Figure 42: Fragment of a lashing bar

Figure 43: Corroded fracture surface of the lashing bar

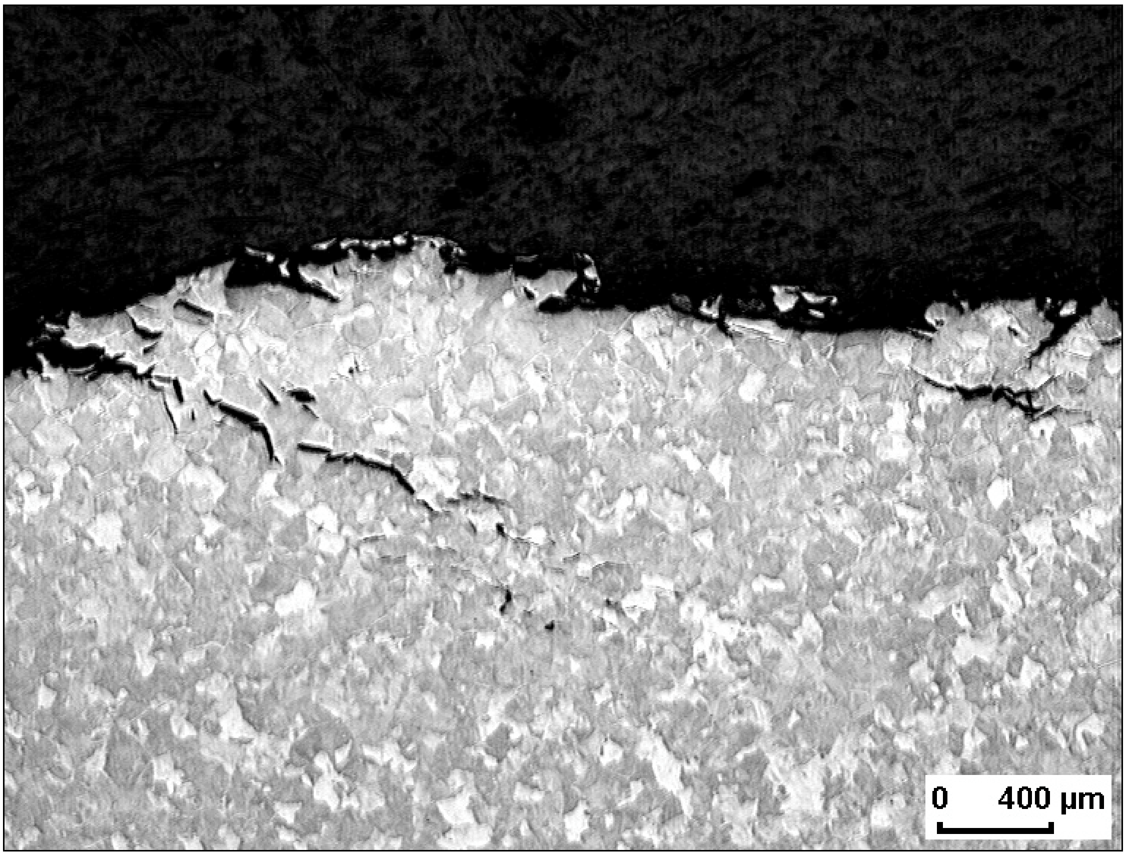


Figure 44: Cleavage fracture structures of the lashing bar

5.4.2 Turnbuckle with broken lug

As shown in Figure 45, the end of the turnbuckle is forked with lugs. The fracture is next to a lug in the side of the fork. The fracture was non-deformed and the fracture area is covered with corrosion products which means that no additional information can be taken from the fracture image (Fig. 46). The micro-section taken from the fracture area shows that the material is cast steel with low micro-porosity. The structure corresponds to a hardened and tempered material (Fig. 45). A hardness test gave an average value from three measurements of 309 HV 10. The subsequently calculated tensile strength is 995 N/mm$^{2.}$

Figure 45: Turnbuckle fork

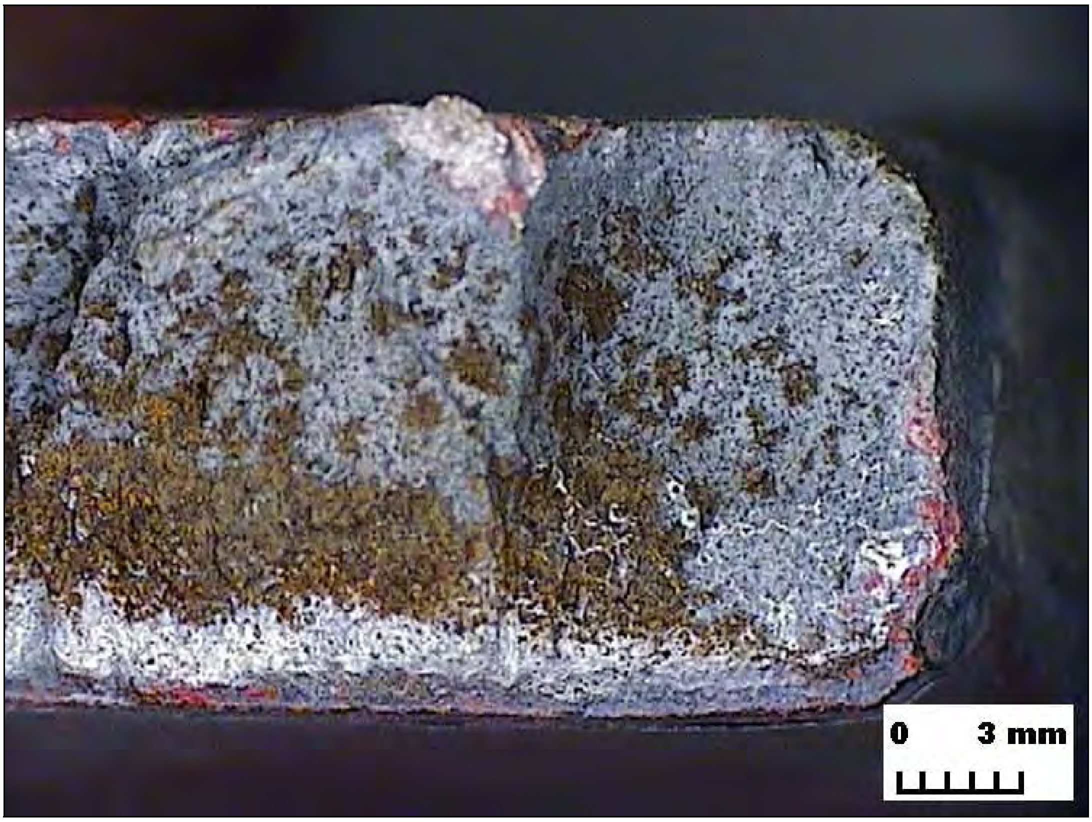


Figure 46: Fracture surface of the turnbuckle

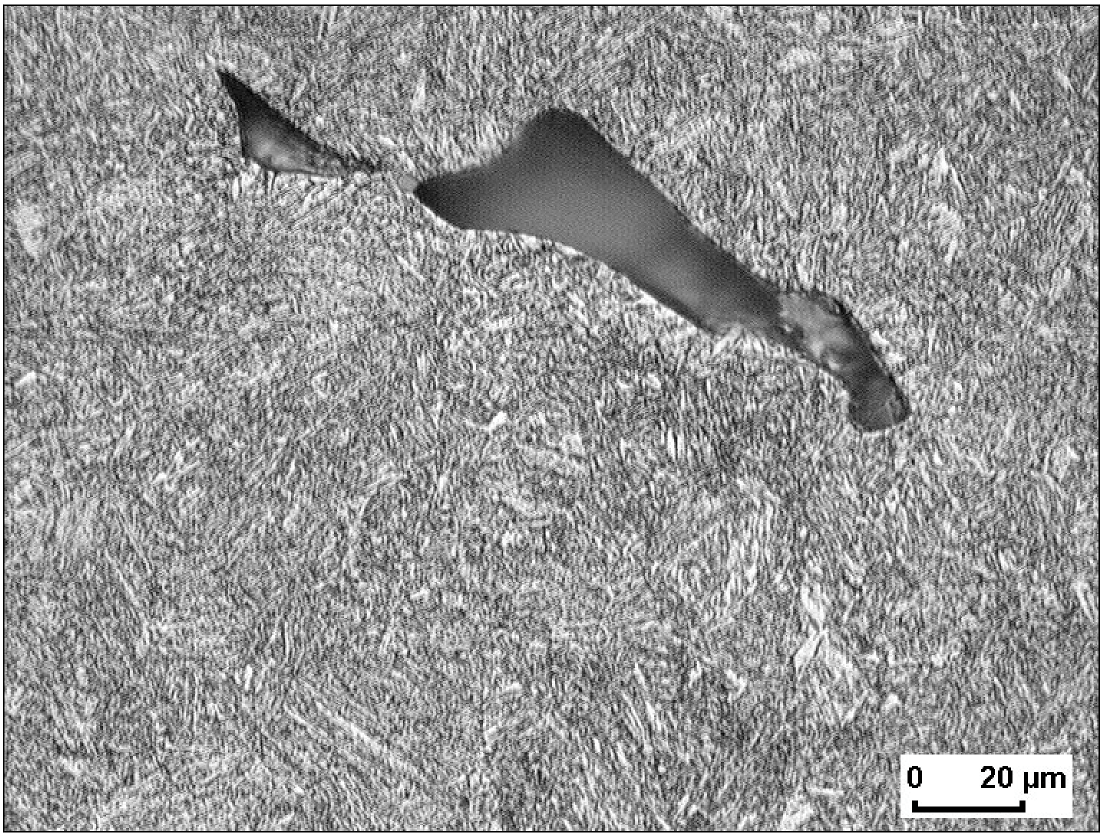


Figure 47: Turnbuckle grain structure

5.4.3 Broken lug

The shape of the fragment allows us to draw the conclusion that it is part of a turnbuckle (see Fig. 48). The fracture surface is very similar to those of other parts. The micro-section taken has a similar look to the micro-section taken from the turnbuckle. This is cast steel with a low micro-porosity and a grain structure that corresponds to tempered and hardened material (Fig. 49).

The hardness test showed an average value from three measurements of 326 HV 10. Accordingly the tensile strength must be estimated as 1040 N/mm^2 .

Figure 48: Lug fragment

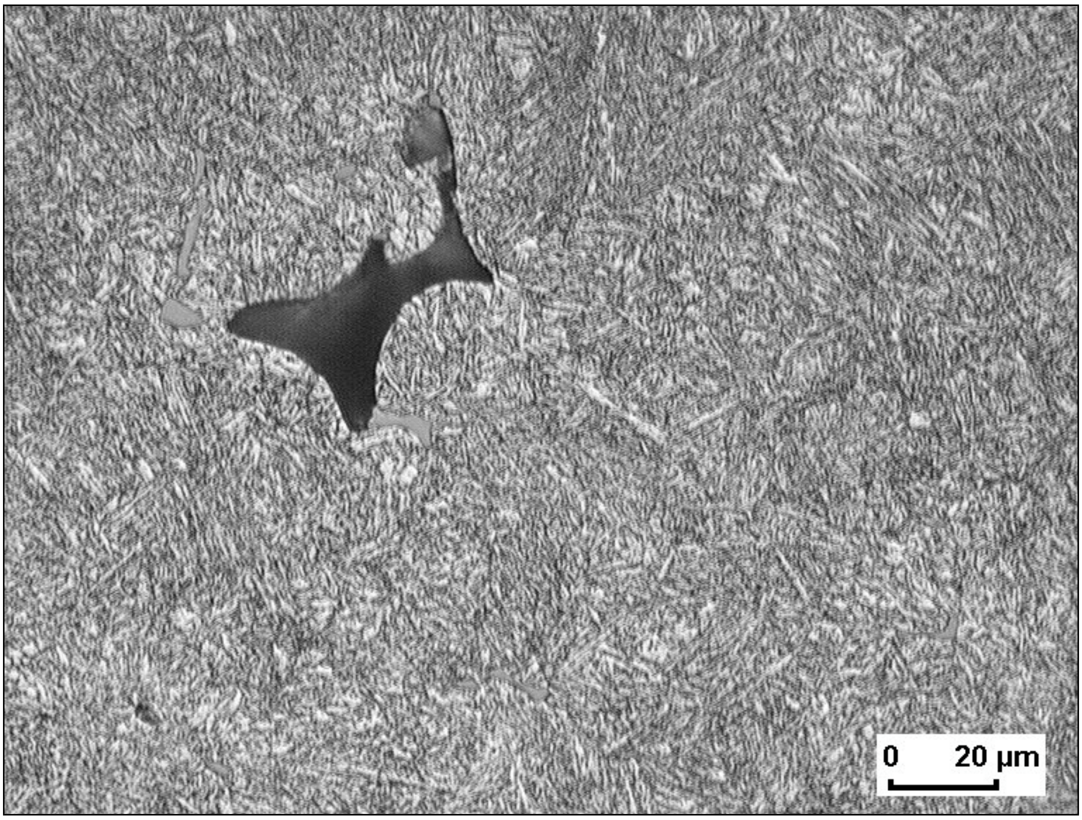


Figure 49: Lug grain structure

5.4.4 Bolt

The bolt is a narrow strip of material broken with a shear fracture (see Fig. 50). The micro-section showed that the bolt was manufactured from a sheet using cold forming. The material is low-carbon steel with a structure predominantly comprising ferrite (Fig. 51).

Figure 50: Bolt

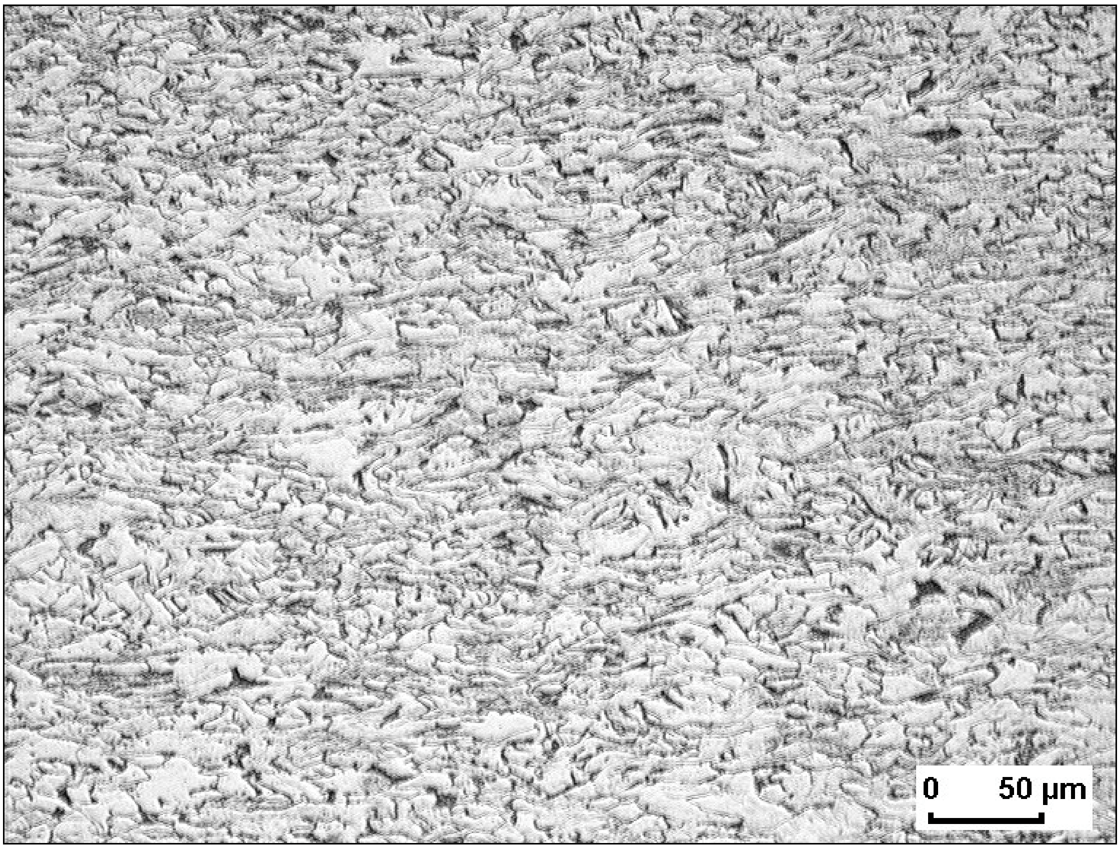


Figure 51: Bolt grain structure

5.4.5 Twistlock

In contrast to the parts examined so far, the twistlock is not broken (see Fig. 52). This is an automatic twistlock from the manufacturer SEC. These kinds of twistlocks are used to connect containers. This is done by first inserting the twistlocks into the bottom corners of the top containers to be loaded. When this container is placed down on the pre-stowed container, the twistlocks push into the so-called corner castings of the bottom container and automatically lock together. This locking function is engaged using slanted surfaces on the underside of the twistlock.

A function check showed no signs of faulty functioning. In Figure 53, you can clearly see the slanted surface which sat in the corner casting of the bottom container. This slanted surface shows considerable signs of wear which indicates that the twistlock was pulled with some force out of the bottom container.

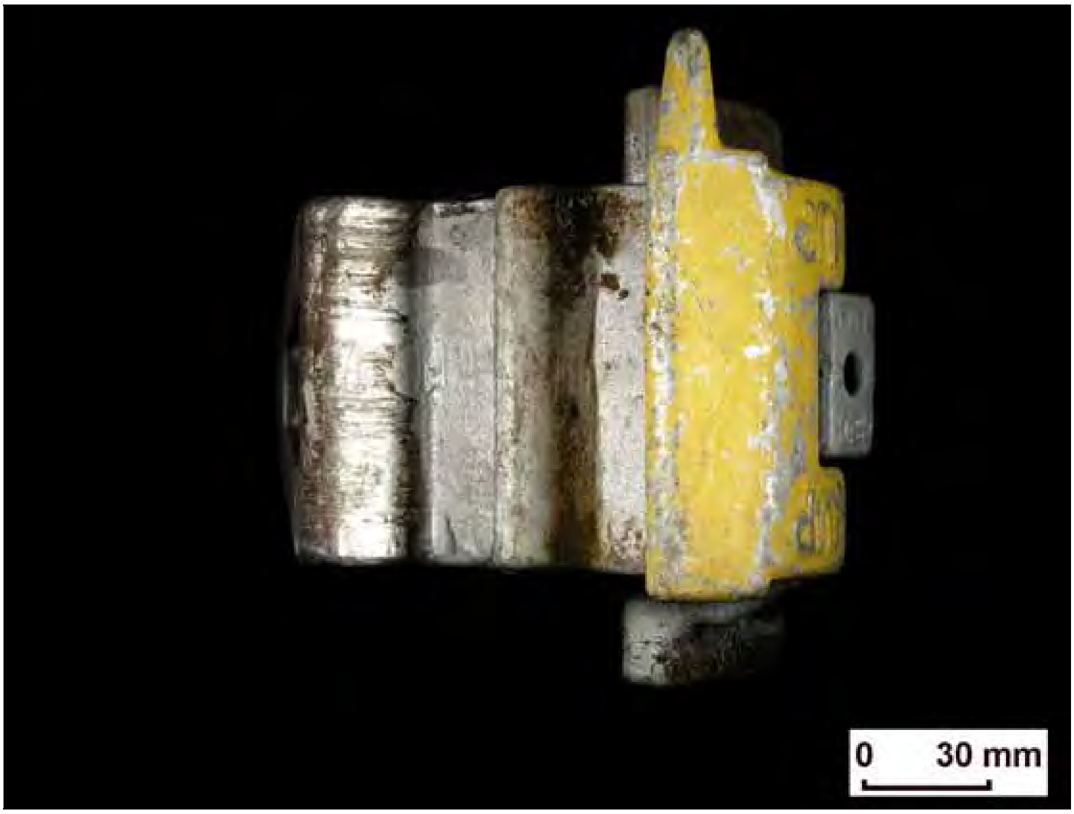


Figure 52: Twistlock

Figure 53: Signs of wear on the bearing surface of the twistlock

6 Analysis

By investigating this marine casualty, the BSU wanted to illustrate the current status of scientific knowledge and technology. As expected, the results showed differing statements. The questions listed at the beginning

1. Was the loss of cargo due to resonance effects caused by sea conditions?
2. Did the crew have the opportunity to recognise this beforehand? In this respect, we should also address the question of whether the use of so-called wave and surface current monitoring software could have prevented the loss of cargo.

were processed by the Institute of Ship Design and Ship Theory[13] as well as the Warnemünde Department for Maritime Studies of the Wismar University of Technology, Business and Design.

The question

3. What role did the lashing material play? (Twistlocks)

was addressed by the Institute for Materials Science and Welding Service GmbH in Hamburg.

6.1 Assessment by the TU Hamburg Harburg

In the opinion of the TU Hamburg-Harburg expert, calculations for the seagoing behaviour of JRS CANIS under the conditions prevailing at the time of the accident have clearly shown that the roll angle of 20° (as stated by the crew) was indeed very probably achieved. Furthermore, the calculations have shown that this roll angles of about 20° were not only achieved in this situation but also in many other, neighbouring situations. A loss of cargo as a consequence of resonance can therefore be practically excluded as there is no indication that the situation at the time of the accident was more dangerous than neighbouring situations. **A moderate change of course or speed would have probably also led to a loss of cargo.**

In any case, the stability of the ship was sufficient and it was not overloaded.

Calculations of the accelerations affecting the container stacks have shown vertical acceleration values for the accident situation that were so low that any unintentional release of the automatic twistlocks due to vertical accelerations can be practically excluded. The calculated transversal accelerations for the container stack are somewhat lower than the theoretically supportable limit value. However, in the expert's opinion, it is possible with high container weights or with less than optimal lashing that the bottom lashing could have experienced a forced rupture under the conditions of the accident.

The calculation of accelerations on the container stack, under the conditions preceding the actual accident with slow speed in a head sea, have shown

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[13] at the TUHH – Technical University of Hamburg Harbug

considerably higher vertical accelerations with the same transversal accelerations. This indicates possible prior damage to the lashing under these conditions followed by a subsequent forced rupture and failure. Moreover, the expert believes that sailing with both inside rows empty had a negative effect on the cargo security and therefore an influence on the damages that occurred. However, this cannot be quantitatively proven.

Furthermore, the expert concludes that the loss of cargo as such could not have been predicted by the crew. Calculations were unable to identify either a resonance or any incident where acceleration limit values were exceeded.

Finally, the expert substantiates the view that the loss of cargo would have not been prevented by using currently available wave and surface current monitoring software. This is due to the fact that these systems simplify the complex physics of a vessel during large rolls at sea for practical onboard use to such a degree that the decisions made using such systems must in many cases by incorrect. Even if such a system had been onboard, then the crew (in the opinion of the expert) would have most likely not trusted the system because the reliability of such systems at the present time is insufficient. The formal consequence of this is that no such system is actually approved for onboard use.

6.2 Evaluation of the Warnemünde Maritime Studies Department at Wismar University

In the opinion of the expert from the Maritime Studies Department, the comparative analysis of data from the accident allows us to draw the following conclusion:
For the accepted wave period range of Tw=10-11 s, the ship is located in the resonance range for synchronous resonance for large roll angles; and for the period Tw=10 s it is even located in virtually direct resonance! For periods Tw=10 and 11 s, the ship is also simultaneously in the resonance stripe for small roll angles due to the overlapping of areas. Even with initially small roll amplitudes it can lead under such circumstances to a build-up of roll vibrations due to the quartering stern sea, which then really pushes it into the critical resonance range with large roll angles. It appears that this is the reason for the severe rolling motion of the ship at the time of the accident. In addition to this, the ship (with this course and speed) is in a situation where it rides for very long periods on the wave crests of wave groups it encounters (high wave group encounter - successive high wave attack) and consequently has only very minimal stability with low righting lever arms.
A description was given as to how, at the time of the accident, there was a slow approx. 030° change of course to port. This means a potentially dangerous passage through the direct, synchronous resonance area (Tr/TE=1), which should in any case be done with great caution and preferably with speed and confidence.
However, this would also need a form of decision support such as an overview of the potentially dangerous areas, e.g. in the form of a polar co-ordinate diagram. If the master had had this kind of information as part of his voyage planning then he could have quickly made the appropriate decisions. Corresponding procedures are dealt with in literature and are a basis for instruction and further education at institutions for the training and qualification of ship's officers. The directive [8] also contained specific instructions on setting up these kinds of decision support tools (in this context, it is viewed as a retrograde step that the new version of the directive [9] no

longer gives such specific aids to calculation and illustrations, but only contains verbal formulations).

In order to assess how the crew could recognise the danger, two points were considered which covered the options of low-level equipment and having professional software.
In principle, the crew would have had to determine the roll period using simple methods based on the given stability data of the vessel or by measuring the ship. They could then have assessed the potential sea data based on weather information. This would have given a simple analysis of the risk situation when planning the voyage. Decisions can be made on this basis, e.g. to secure the cargo better or to take measures for changing the roll period by altering the stability through varying the GM (as far as this is feasible from a load-related perspective).
Such variant calculations can be made manually with a pocket calculator, but take time and effort. Higher level equipment means that such decisions can be made more easily, as shown in the example of using voyage planning tools and resonance program(s).

6.3 Summary by the BSU on the hydrodynamic findings

Both survey reports can be well substantiated. On the one hand, the TU Hamburg-Harburg thinks that the sea state and stability conditions of the vessel must be quantitatively known with as much accuracy as possible in order to then receive flawless computer-based results. At the same time it is recognised that there are currently no technical options either for precisely recording the sea state at a vessel, or for continually updating the stability conditions of the vessel. This includes both the actual cargo (in particular on a container ship) as well as measuring the vessel's consumables.
These difficulties are common points raised by the TU Hamburg-Harburg and the Warnemünde Maritime Studies Department. These difficulties are perceived similarly there but simultaneously form the starting basis for simplifying wave conditions data, so that a simple comparison of natural roll periods and wave periods can give a result. This result is then only to be understood as a tendency or trend. Absolute figures are not stated by Warnemünde, as all the basic data is too imprecise. However, an area is shown which could at least give suggestions of support for the vessel's command.
At this point it is worth mentioning that other institutions and companies are also occupied with this issue. For example, Germanischer Lloyd in Hamburg is working on its own wave radar which, when combined with a database comprising pre-calculated sea state and stability conditions, is to show dangerous resonance for the vessel.
On 2 November 2007, the company of SAM Elektronics presented their system for avoiding resonance at the VDR symposium in Hamburg. The basic idea for this is to use the own vessel as a "measuring buoy" in order to deduce the state of the sea from the measured natural motion of the vessel, and to illustrate the dangerous areas for the vessel.[14]
The company of OceanWaveS GmbH[15] has for a long time now been marketing wave radars, in particular on platforms anchored to the seabed. However, vessels are also being equipped with this system. Although the inadequacy of the system is

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[14] see http://www.sam-electronics.de/dateien/automation/seasense.html
[15] see also http://www.oceanwaves.de/

known with regard to the fact that there is a spatial different between the measured area and the vessel which can only be interpolated with difficulty.

The Institute for Maritime Studies at the FH OOW[16] in Elsfleth worked in collaboration with the company of Interschalt in Hamburg to develop a stochastic procedure as a decision-making aid for vessel commands. An attempt has also been made here to circumnavigate the aforementioned disadvantages by measuring and statistically evaluating the rolling motions onboard in order to gain a basis for representing the sea state spectrum.[17]

Finally, we can say that in practice (in particular onboard large container ships) there is a need to have access to a tool that can be used easily and clearly to avoid dangerous sea conditions.

This is a recognised need and is being worked on by numerous institutions. Research and development should be intensively expedited in order to be able to provide a reliable tool to vessel commands as soon as possible.

6.4 Container storage and lashing

According to the Germanischer Lloyd accredited "Cargo Securing Manual", the JRS CANIS was permitted a maximum of 6 containers on deck, stacked on top of each other, in Bay 28 (see Fig. 54). To secure the lowest layer on deck, manual twistlocks are to be used between deck and container. Apart from this, the lower container layer is to be secured with lashing rods and turnbuckles. Other lashing rods must be arranged between the second container layer and the deck. The containers are to be further secured only using automatic twistlocks. In the case of this accident, 10 containers were lost overboard which were stored in the third, fourth and fifth layers directly in front of the vessel superstructure. These containers were secured as intended just using twistlocks.

The turnbuckle parts and lashing rod examined were not used to secure the lost containers. In spite of this, they suffered stress during the voyage which led to breakage. There is no direct connection between the failure of these parts and the loss of the containers. However, an indirect influence cannot be excluded.

The automatic twistlock examined had obviously opened under considerable strain. Consequently it can be assumed that the loss of the 10 containers is due to the automatic twistlocks giving way. This was very probably facilitated by the breaking of different lashing rods and turnbuckles (indirect influence) which could no longer withstand the exceptional strain of the ship's motion.

On the other hand, the exceptional strain can be explained by the fact that all container weights lay far above the permitted values. This points to a lack of communication between the loader and the vessel's command. As already established in other investigations, the unloading and loading process in container ports is carried out so quickly that the crew hardly has any time to check the cargo before the ship leaves the port again.[18] At the same time, it is also becoming increasingly apparent that the containers are loaded differently to instructions.

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[16] FH OOW – Oldenburg/Ostfriesland/Wilhelmshaven Advanced Technical College

[17] Published in Schiff & Hafen - April 2008 Page 88 ff.

[18] See also the BSU report 537-06 – Page 28; BSU report 187-05 Page 40; MAIB report on the MSC NAPOLI at http://www.maib.dft.gov.uk/cms_resources/MSC%20Napoli.pdf and the BEAmer report on the CMA CGM OTELLO at http://www.beamer-france.org/english/inquieries/inquieries.htm

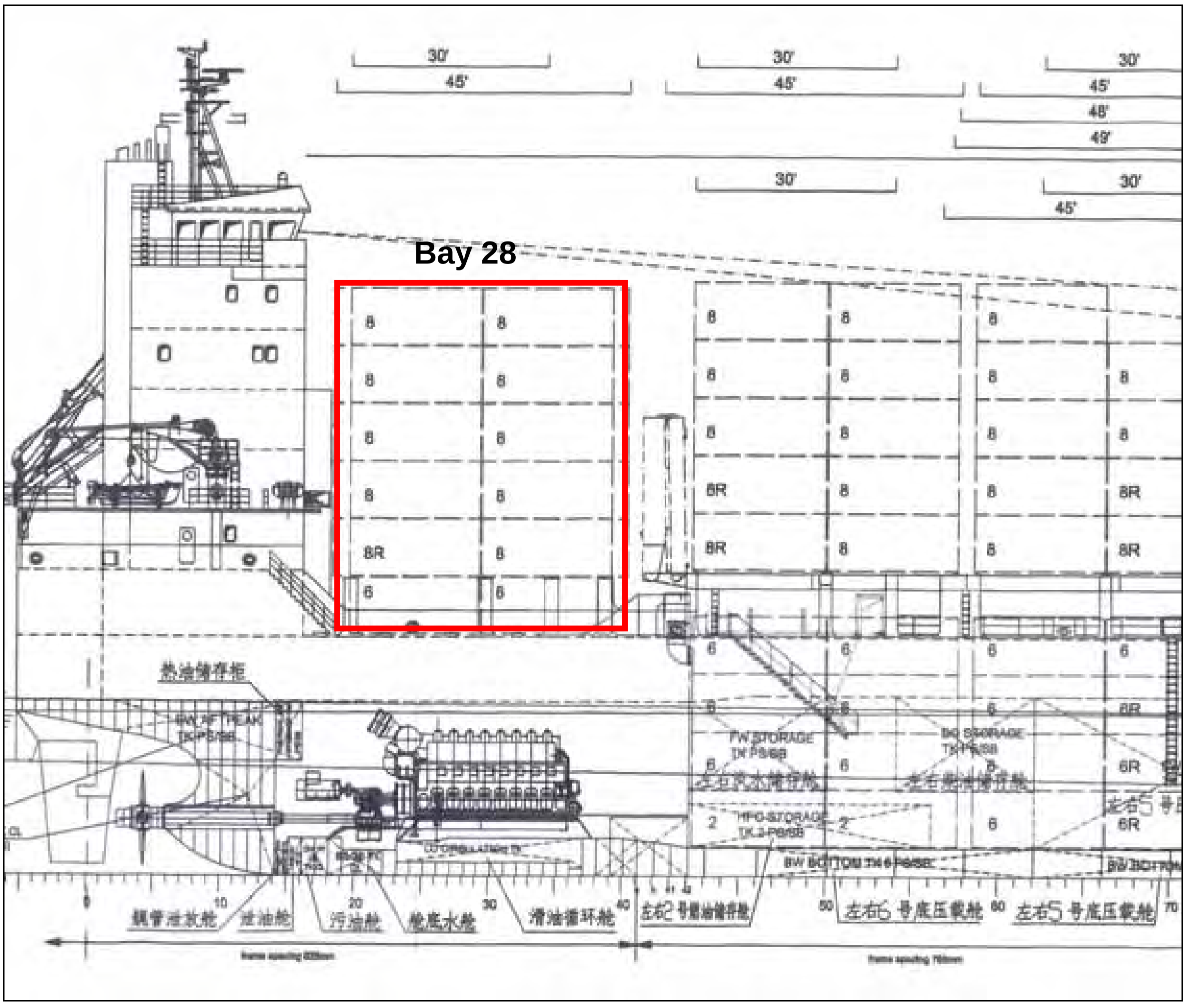

Figure 54: Section of the general arrangement plan - side view

7 Safety recommendations

The following safety recommendations shall not create a presumption of blame or liability, neither by form, number nor order.

7.1 Operators of seagoing vessels, vessel's command and operators of port transshipment companies

The Federal Bureau of Maritime Casualty Investigation recommends that **operators of container ships** co-operate with port transshipment companies to take precautions that will enable the **vessel's command** to effectively monitor loading of the vessel. This refers in particular to the positions of the containers and their weights.
The Federal Bureau of Maritime Casualty Investigation recommends in particular creating possibilities to weigh containers before loading onto a vessel in order to further increase the safety for crew and vessel.

In this context, the Federal Bureau of Maritime Casualty Investigation likewise refers to the investigation report of the British Marine Accident Investigation Branch (MAIB) regarding the structural failure of the hull on the MSC Napoli[19]. In section 4.2 of the report regarding measures already carried out, the MAIB refers to a safety recommendation from an earlier report. This report recommended that the International Chamber of Shipping (ICS) prepare a Code of Best Practice together with the container ship industry. This code of practice should be finished by the end of 2008 when it will be presented to the International Maritime Organisation (IMO) for approval. In section 5 of the report on the MSC Napoli, the MAIB actively refers to this older safety recommendation and also recommends that the code should deal with the following:

- The necessity to determine the actual weights of containers before they are loaded onto a vessel
- The significance of safe speed and good seamanship when sailing under severe weather conditions.

7.2 Scientific institutions and shipping related companies, Marine Insurance and Safety Association and Federal Ministry of Transport, Building and Urban Affairs

The Federal Bureau of Maritime Casualty Investigation recommends to **maritime science institutions and shipping companies** to further expedite research and development of systems that enable the vessel's command to monitor and correctly assess sea-related vessel motions, in order for them to take necessary measures promptly to avoid vessel motions and manoeuvres that jeopardise safety.
The Federal Bureau of Maritime Casualty Investigation recommends to the **Marine Insurance and Safety Association** to continue to lend critical support to the development of these systems and if necessary to update guidelines for the use of these systems.
The Federal Bureau of Maritime Casualty Investigation recommends to the **Federal Ministry of Transport, Building and Urban Affairs** to support the research and development of these systems.

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[19] See http://www.maib.gov.uk/cms_resources/MSC%20Napoli.pdf

8 Sources

- Investigations of Waterway Police (WSP)

- Written statements

  - Vessel's command
  - Shipping company/owner:
  - Classification society
- Witness accounts

- Section of the nautical chart INT 1413 of the Federal Maritime and Hydrographic Agency (BSH) as well as vessel data

- Official weather expertise by the German National Meteorological Service (DWD)

- Radar plots by Vessel Traffic Services (VTS)/Vessel Traffic Centres

- Gutachten zur Werkstoffuntersuchung an Laschmaterial der JRS CANIS (survey report on the material investigation of the lashing material from the JRS CANIS) written by Prof. Happ of the Institute for Materials Science and Welding (IWS) at the college for applied sciences, Hamburg

- Gutachten zum Ladungsverlust der JRS CANIS (survey report regarding the loss of cargo on the JRS CANIS)
  written by Prof. (Eng.) S. Krüger, head of the Institute of Ship Design and Ship Safety at the TU Hamburg-Harburg

- Gutachten zum Ladungsverlust der JRS CANIS (survey report regarding the loss of cargo on the JRS CANIS)

written by Prof. (Eng. habil.) Knud Benedict from the Wismar University of Technology, Business and Design, Warnemünde Department for Maritime Studies

This refers to:

[1] France & William a.o. 2001. An Investigation of Head-Sea Parametric Rolling and Its Influence on Container Lashing Systems. SNAME, Annual Meeting 2001.
[2] IMO 1993. Code on intact stability for all types of ships, Resolution. A.749 (18) Nov 1993
[3] Code über Intaktstabilität aller in IMO-Regelwerken behandelten Schiffstypen (Code über Intaktstabilität); [code on intact stability of all types of ships dealt with in IMO legislature] came into effect on 1.1.2000, CD-ROM 06-2004 See-BG
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9 Appendix

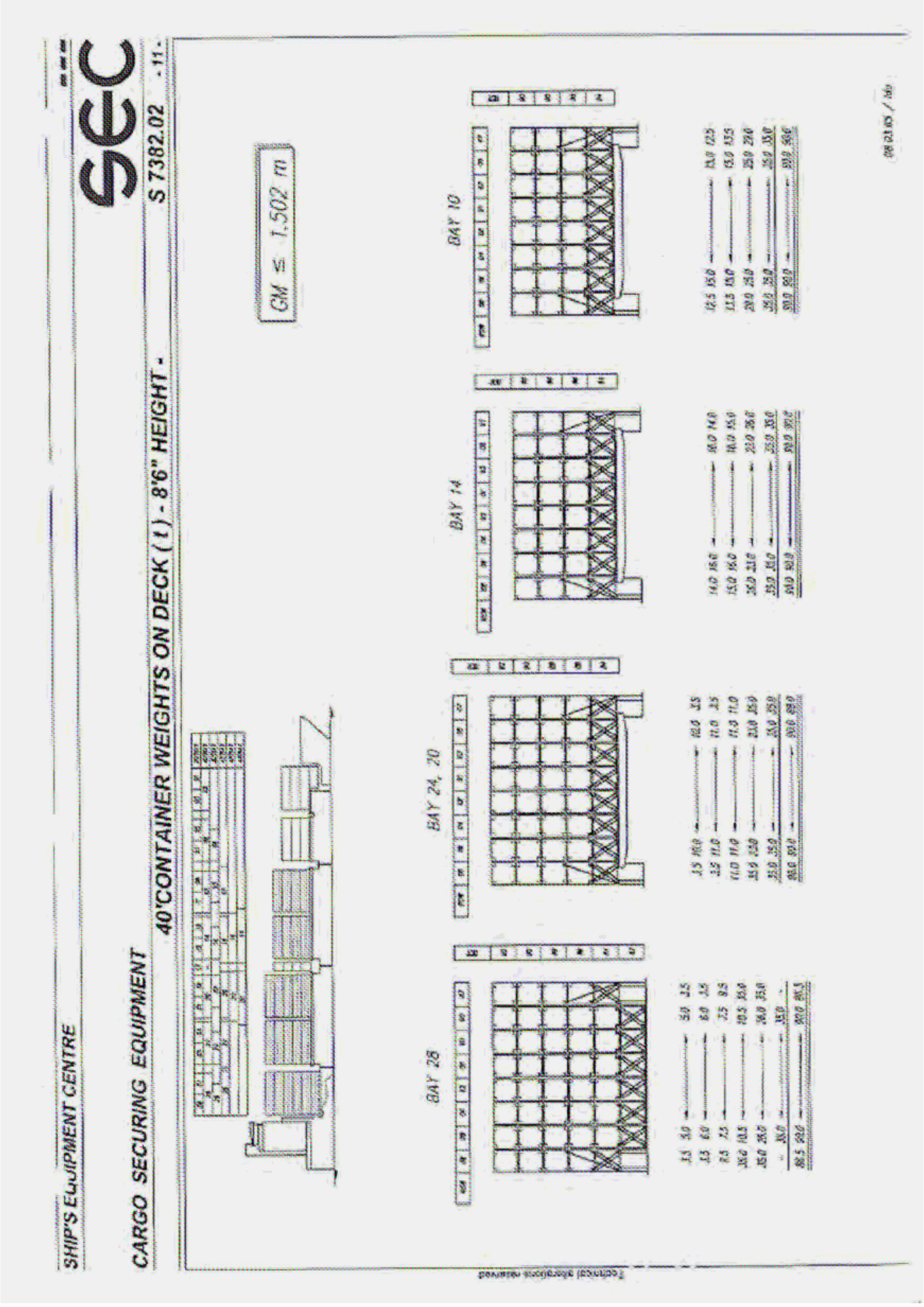

Figure 55: Cargo securing manual - stack weights

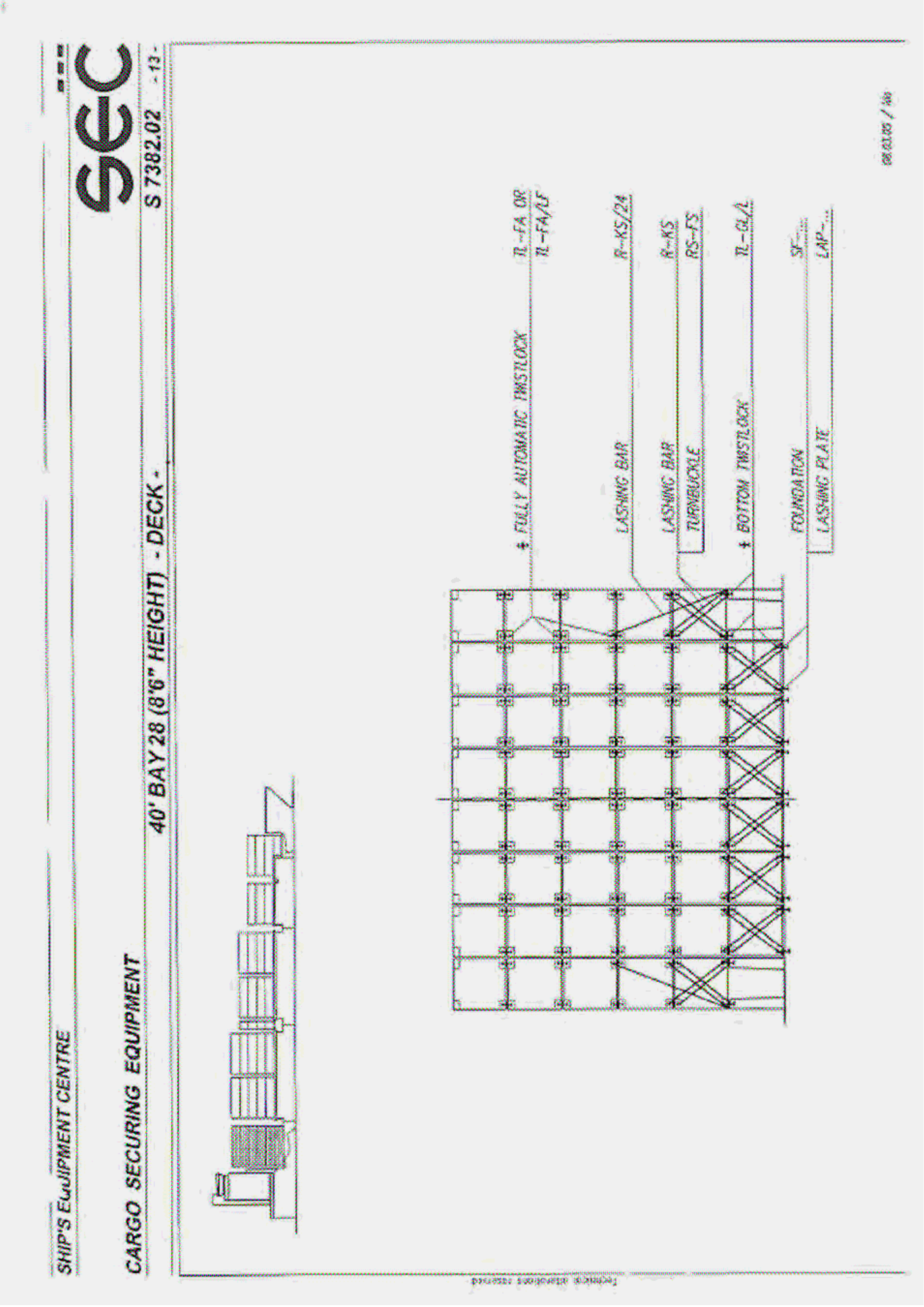

Figure 56: Cargo securing manual - lashings