PANAMA
MARITIME AUTHORITY

DUTCH
SAFETY BOARD

BSU
Bundesstelle für Seeunfalluntersuchung
Federal Bureau of Maritime Casualty Investigation

Loss of containers overboard from MSC ZOE

1-2 January 2019

June, 25th, 2020

CONTENT

LIST OF ACRONYMS AND ABBREVIATIONS

BSU	Federal Bureau of Maritime Casualty Investigation of Germany (*Bundesstelle für Seeunfalluntersuchung*)
CSM	Cargo Securing Manual
CSS	Code of safe practise for cargo stowage and securing
DSB	Dutch Safety Board (*Onderzoeksraad voor Veiligheid*)
DWD	German National Meteorological Service (*Deutscher Wetterdienst*)
IMO	International Maritime Organization
ISM	International Safety Management
LT	Local Time (at the time of the accident LT was UTC + 1 hour)
MSC	Mediterranean Shipping Company
MSL	Mean Sea Level
MV	Motor Vessel
PMA	Panama Maritime Authority (*Autoridad Marítima de Panamá*)
PSC	Port State Control
ROT	Rate of turn
RPM	Revolutions per minute
SOLAS	Safety of Life at Sea
STCW	Standards of Training, Certification and Watchkeeping for Seafarers
TEU	Twenty-foot Equivalent Unit
TSS	Traffic Separation Scheme
UKC	Under Keel Clearance
ULCS	Ultra Large Container Ship
UTC	Coordinated Universal Time
VDR	Voyage Data Recorder
VTS	Vessel Traffic Service

1 INTRODUCTION

1.1 The event

In the late evening of January 1, 2019 and the early morning of January 2, the containership MSC ZOE lost a total of 342 containers whilst sailing on the North Sea, in the Traffic Separation Scheme (TSS) Terschelling - German Bight. The Panamanian flagged ship was en route from Sines, Portugal to Bremerhaven, Germany. At the time of the accident the ship was sailing in conditions with north-northwesterly winds of 8 Bft and waves coming from abeam on port side. The ship was rolling constantly. The crew first detected that cargo had been lost north of the Dutch Wadden Island Schiermonnikoog, at around 01.00 hours local time[1] (LT) on January 2. North of the island Borkum, around 01.30 hours, the loss of containers overboard was witnessed by the crew. The MSC ZOE changed course to a northwesterly heading and reduced speed. The Vessel Traffic Service (VTS) German Bight Traffic was notified of the loss of containers. At 14.00 hours the voyage to the TSS German Bight Western Approach to Bremerhaven was continued and the MSC ZOE moored safely at the Eurogate Terminal at 01.00 hours on January 3.

The consequences of the accident for the Dutch and German coast were immediately visible on January 2. The fall from height and the waves destroyed most of the containers and cargo residues were washed ashore on the Dutch and German Wadden Islands and Dutch coast. No lubricants and/or bunkers of the MSC ZOE escaped and no crew members were injured. The loss of cargo and its impact on the Dutch and German coasts and environment attracted considerable public concern in the Netherlands as well as in Germany.

1.2 Investigation

The loss of containers resulted in severe damage to the environment. Based on this, the accident is classified as a very serious marine casualty as defined in the Casualty Investigation Code of the International Maritime Organization (IMO) and European Union Directive 2009/18/EC[2]. The substantially interested States for this accident are Flag State Panama and coastal States Germany and the Netherlands.

The marine safety investigation authorities of the three States involved agreed on a collaborative procedure for the safety investigation of the accident. Panama is as flag State responsible for the conduct of the marine safety investigation and therefore the Panama Maritime Authority (PMA) was in the lead regarding the investigation into the cause(s) of the container loss. The Federal Bureau of Maritime Casualty Investigation of Germany

[1] All times in the report are local times, unless stated otherwise (Local Time = UTC +1).

[2] Directive 2009/18/EC of the European Parliament and of the Council of 23 April 2009 establishing the fundamental principles governing the investigation of accidents in the maritime transport sector.

(BSU, *Bundesstelle für Seeunfalluntersuchung*) and the Dutch Safety Board (DSB, *Onderzoeksraad voor Veiligheid)* participated in the investigation.

The sole purpose of the conducted safety investigation is to prevent marine casualties and marine incidents in the future. The investigations will not be concerned with determining liability or apportioning blame.

The key question for the investigation were:

- What caused the loss of containers from the MSC Zoe on 1-2 January 2019?
- How can the risks of container loss overboard be better managed?

The investigation did not look into the incident response and crisis management following the accident.

On January 6, 2019, the safety investigators of PMA, BSU and DSB met on board the MSC ZOE in Bremerhaven and initiated the safety investigation. During the on-site investigation relevant data and information were secured, including brief statements from some crew members, VDR data, data from the loading computer and lashing program, stowage plan, stability handbook and log book extracts. In addition, damages were inspected and recorded.

In order to discuss the intermediate results and agree on the further procedure to be followed, the safety investigation authorities from Panama, Germany and The Netherlands met several times in The Hague and Hamburg and one time in Naples[3] as well as in conferences calls to collaborate in the investigation and the writing of the report.

In order to support the technical investigation, both BSU and DSB consulted domain experts regarding ship's behaviour in sea conditions and the conditions along the sailing route north of the Wadden Islands:

- The BSU engaged with the Hamburg University of Technology (TUHH, *Technische Universität Hamburg*) to perform a simulation of the ship's motions and resulting accelerations, see Appendix E.
- The DSB engaged with the research institutes Deltares and the Maritime Research Institute Netherlands (MARIN) to determine the meteorological and wave conditions along the sailing route of the MSC ZOE and the effect of these conditions on ultra large container ships such as the MSC ZOE, see Appendices C and D.

[3] The 28th Marine Accident Investigators' International Forum was held in Naples, where the three states involved in the accident: Panama, Germany and The Netherlands where present.

2 THE ACCIDENT

2.1 The journey of the MSC ZOE

On Saturday 24 November 2018, the container ship MSC ZOE sailing under Panamanian flag departed from the port of Xingang in China. The vessel visited the ports of Gwangyang (Korea), followed by Ningbo (China), Shanghai (China), Yantian (China) and Tanjung Pelepas (Malaysia), before setting course for Europe. At that time, the 22-man crew included crew members from Italy, Montenegro, Croatia, Indonesia, Samoa and Madagascar.

Following arrival at the port of Sines (Portugal), the MSC ZOE unloaded 2,173 containers and took a further 249 on board. On Sunday 30 December at 03.30 hours local time, the vessel set sail for Bremerhaven (Germany), with 8,062 containers on board (equivalent to 13,465 TEU[4] which is 70% of its full loading capacity).

On 1 January 2019, between 06.30 and 07.35 hours, the MSC ZOE sailed through the English Channel. At that time, a wind was blowing from a northwesterly direction at force 4 to 5 Beaufort (Bft) and the vessel was able to sail calmly. Following the passage of the Channel, the MSC ZOE followed the Belgian and Dutch coastlines in northerly direction. During the course of the day, wind speeds increased from 4 to 5 Bft to 8 Bft at around 18.00 hours. At around 18.50 hours (see figure 1), the vessel was approaching Texel and changed course to starboard in order to enter the southern track of the Terschelling - German Bight Traffic Separation Scheme (TSS). The chief officer was on watch at that time. At around 19.00 hours, the master took over the watch from the chief officer, and the chief officer retired to his cabin. By this time the wind was blowing at force 9 Bft and the helmsman was steering the ship manually. According to crew statements, the ship was experiencing rolling movements between 5 and 10°, with occasional 15° peaks. According to the logbook, between 16.00 hours and 20.00 hours, the lashings of the containers, the containers with hazardous substances, the hold and the bilges were inspected and found to be in good order.

According to crew statements, at 23.00 hours on the evening of 1 January 2019, the MSC ZOE suddenly started to roll violently which felt like rolling angles of 20º till 30º, for a period of around 30 seconds. These movements were so violent that the equipment in the fitness area shifted and on the bridge various items, including the printer, flew through the air. According to the crew, after this period of violent rolling, the movements of the vessel returned to the previous 5 to 10° roll. At this time, the MSC ZOE was sailing at a speed between 8 and 10 kn. The master, the third officer and the helmsman were on the bridge. The chief officer, awoken by the violent motions, checked the accommodation and the

[4] Twenty-foot equivalent unit based on the original container that was 20ft long. The TEU is a unit of cargo capacity used to describe the capacity of containers ships.

bridge for loose furniture, and then returned to his cabin. At midnight, the third officer completed his watch duty, and the second officer joined the master and the helmsman on the bridge.

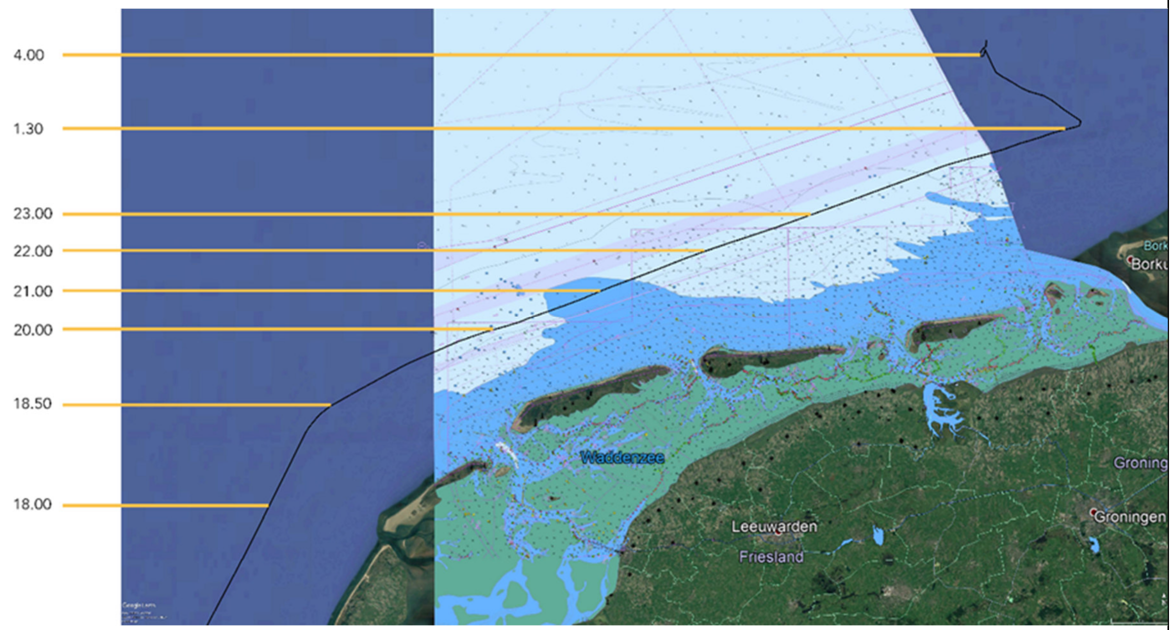


Figure 1: Track of the MSC ZOE (time indication local time). (Source: Google Earth)

At around 01.00 hours in the morning of 2 January 2019, the master walked to the back of the bridge and looked out of the bridge window at the containers behind the bridge. Because the master saw that a number of containers were no longer in the expected position, he asked the second officer to shine an Aldis lamp (a daylight signalling lamp) onto the containers. The light revealed that a number of the containers had fallen over. The master then woke the chief officer and a short time later the chief officer came on the bridge. The master also informed the head office on shore. The chief officer and the boatswain went to the main deck to check for any further damage. They observed that a number of containers were hanging overboard, but were not able to see much.

At 01.30 hours, the MSC ZOE once again experienced a short period of severe rolling which again, according to the crew, felt like rolling angels of 20º till 30º. During this period, the master observed the containers in (what subsequently proved to be) bay 26 collapse. The chief officer and boatswain were on deck and they also observed how the stacks of containers from bay 26 collapsed and fell overboard. The chief officer immediately reported this incident to the master on the bridge. The second officer informed German Bight Traffic. The master changed course from 074° to 315° and reduced speed to 2 kn, in order to direct the vessel into the wind and waves so as to stabilize the motion. The crew attempted to assess the damage, but due to the darkness and fallen containers on deck this was difficult.

The chief officer and boatswain attempted to reach the deck at several points. From the exit from the engine room, they observed that bay 58 had collapsed and that containers were hanging overboard. From the boatswain's workshop in the forecastle, they observed a similar situation in bays 10 and 26. They then returned to the bridge to report. On the bridge, the master was in contact with German Bight Traffic about the number of lost containers and whether any of them contained hazardous substances. The initial estimate suggested around 30 containers. Because their options were limited in the darkness and the risk of falling containers, debris or cargo could not be properly assessed, the master waited until it was light before sending any more people outside. The vessel continued to sail into the wind and waves to the TSS German Bight Western Approach.

When day broke, the crew started to gain a clearer picture of the situation on deck (see figures 2 and 3). The chief and second officer went in search of the hazardous substances containers and the boatswain was joined by five crew members in retightening the loose lashings. The chief and second officer identified that two of the three hazardous substances containers were missing. The third container was hanging half over the starboard side of the vessel. The crew stated that during their tours of the deck, they found various loose parts of the lashings, including the tensioners from the lashing rods, hooks and locking pins, and twistlocks that were broken in two.

Figure 2: Side view MSC ZOE. (Source: Netherlands Coastguard)

At around 14.00 hours in the afternoon of 2 January, the MSC ZOE reached the more northerly TSS German Bight Western Approach (see figure 4), and at around 15.00 hours following a turn to starboard, the vessel entered the southern lane in order to continue its journey to Bremerhaven. At 19.15 hours, the pilot came on board, to guide the ship into port. The MSC ZOE moored in Bremerhaven, at 01.00 hours in the morning of 3 January 2019.

Figure 3: Top view MSC ZOE following the loss overboard of the containers. (Source: Netherlands Coastguard)

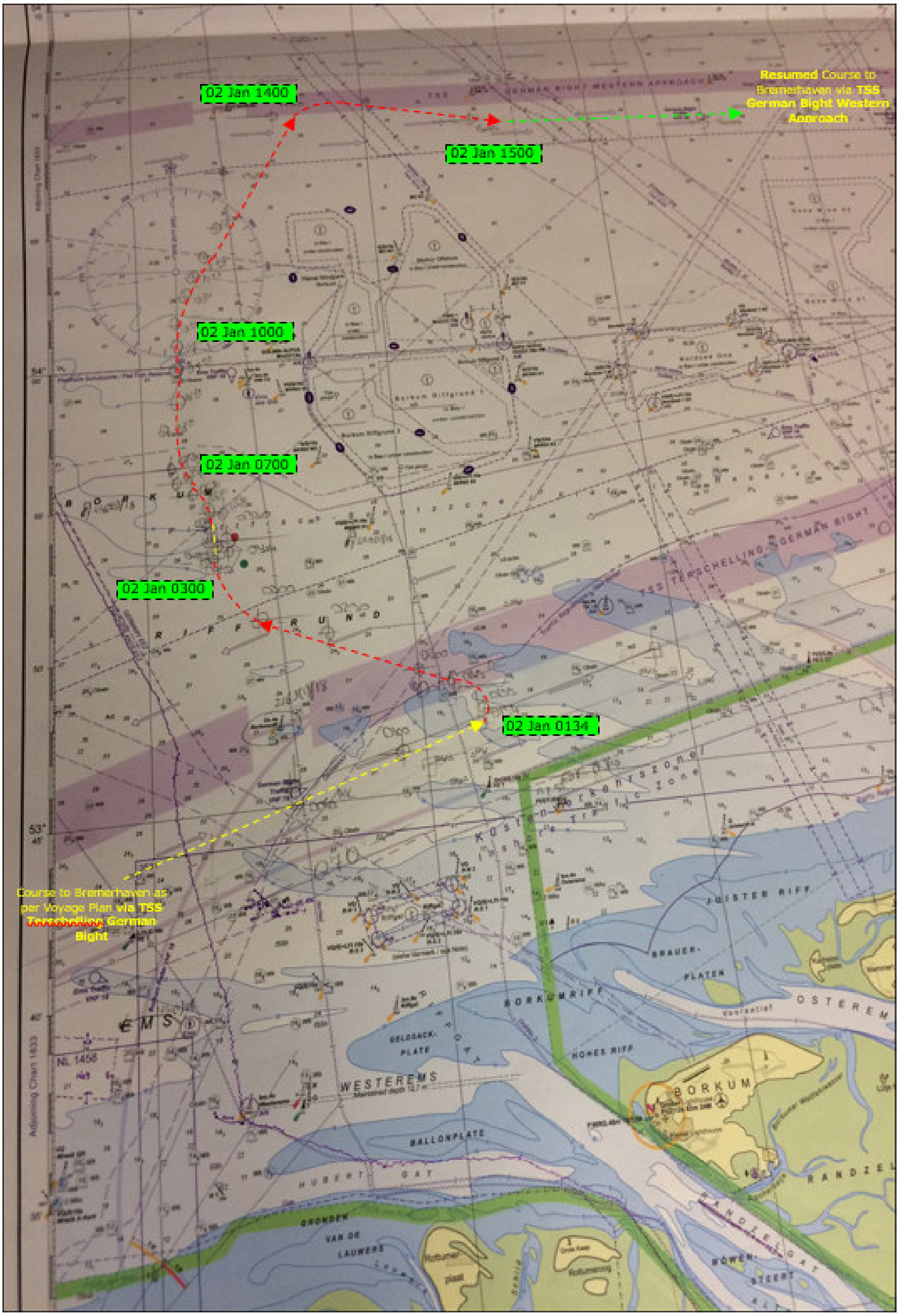
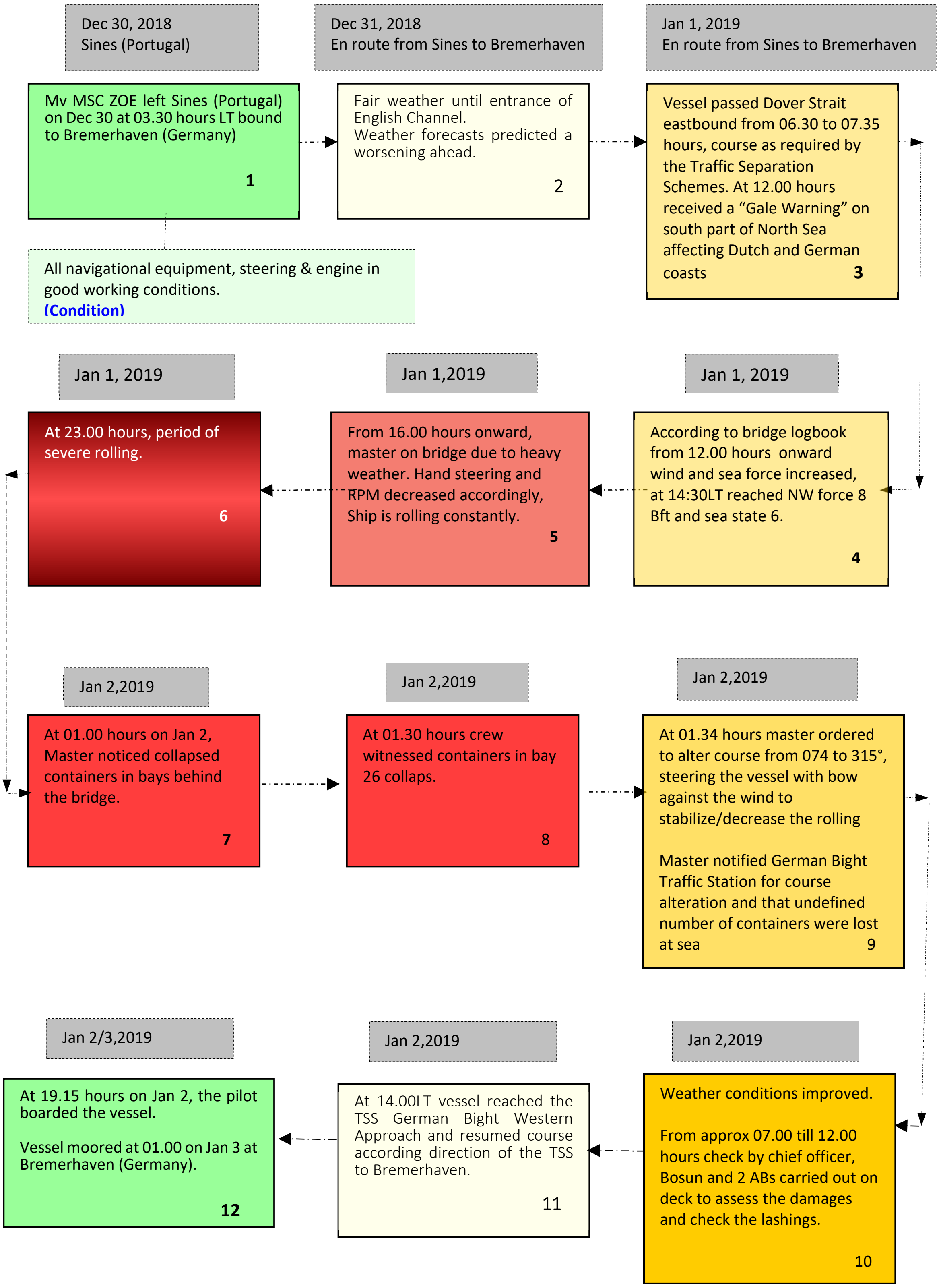


Figure 4: Track of the MSC ZOE after altering course to the north following the detection of the container loss. (Source: Paper chart MSC ZOE)

2.2 Time line

The timeline below depicts the sequence of events based on the crew statements and VDR.



2.3 Assessment of the lost containers

In the early morning of Wednesday 2 January, the second officer of the MSC ZOE informed German Bight Traffic that the vessel had lost containers during a period of severe rolling. The initial estimate was that around 30 containers had been lost overboard. Following the report by the second officer to German Bight Traffic, the Netherlands Coastguard and Rijkswaterstaat[5] incident organization were duly informed. An emergency plan existed for the loss of cargo – a generic scenario that was applied to this incident.

However, during the course of the day the number of lost containers was repeatedly upwardly adjusted and an action plan was drawn for recovering the containers. Particular attention was paid to the risk for shipping of floating containers or a pile of containers in the shipping lane. Rijkswaterstaat contacted the owners of the MSC ZOE, the Mediterranean Shipping Company (MSC), and held them liable for the recovery of the lost cargo. In response, the insurance company of MSC appointed a salvage company. In the meantime, in the Traffic Separation Scheme, the Netherlands Coastguard deployed a guard vessel to redirect shipping to the more northerly traffic separation scheme (TSS German Bight Western Approach).

In consultation with Rijkswaterstaat and the Netherlands Coastguard, the salvage company drew an action plan for recovering the containers. At this stage, the evening of Wednesday 2 January, the number of containers identified as lost had risen to 270. Within twenty-four hours, the Coastguard was in possession of the complete cargo manifest, but it took longer to determine precisely which containers had been lost.

Bay plan
In order to allocate the container on board a ship there is a bay-row-tier system, this follows a system of numerical coordinates relating to length, width and height.

The rows of containers on a ship are numbered with even numbers from the centre to port and odd numbers from the centre starboard.

[5] Rijkswaterstaat is part of the Dutch Ministry of Infrastructure and Water Management and responsible for the design, construction, management and maintenance of the main infrastructure facilities (roads, waterways and water system) in the Netherlands. Rijkswaterstaat manages and maintains the waterway network: main rivers and canals, as well as the Dutch part of the North Sea.

The tiers are numbered with even numbers, starting in the hold with 02 and then count up with 04, 06 etc. The deck cargo starts numbering with 76 or 78.

The bays are numbered from bow to stern. A bay can contain 20' and 40' containers at the same time. The odd numbers are used for the 20' containers and the even numbers for the 40' containers. For example, bay 10 consists of bay 9 and 11[6].

The assessment on board on 2 January 2019 had revealed that damage had at least occurred in bays 10(9/11), 26(25/27), 42(41/43), 50(49/51) and 58(57/59). A large number of containers was missing and many others were damaged. In total, the bays in question held approximately 1,047 containers. Particular interest was focused on the hazardous substances containers. Bay 26 housed a 20' container with 160 boxes with bags with a mixture of 50% dibenzoylperoxide and 50% dicyclohexylftalaat (50%) and 120 boxes with bags with a mixture of 34% dibenzoylperoxide and 66% dicyclohexylftalaat. Bay 26 also housed a 20' container with 467 chests with lithium-ion batteries, in total 1,400 kg. Both containers were no longer on board. A third 40' container was hanging half over the port side of the vessel (see figure 5). Due to the damage and the open top, the container lost most of its content which existed of 22,5 tons of tiny expendable polymeric beads.

Employees from Rijkswaterstaat also travelled to Bremerhaven where the MSC ZOE was still in port, to identify which containers were still present, but this procedure was made more difficult by the fact that a number of containers still on board had been completely crushed (figure 6).

After the MSC ZOE had unloaded its final containers in Gdansk, the definitive number of containers lost was established at 342.

See figure 7 to 12 for an insight in the damaged containers on deck.

[6] The picture is illustrative.

Figure 5: Container with bags with polystyrene balls hanging over the side. (Source: DSB)

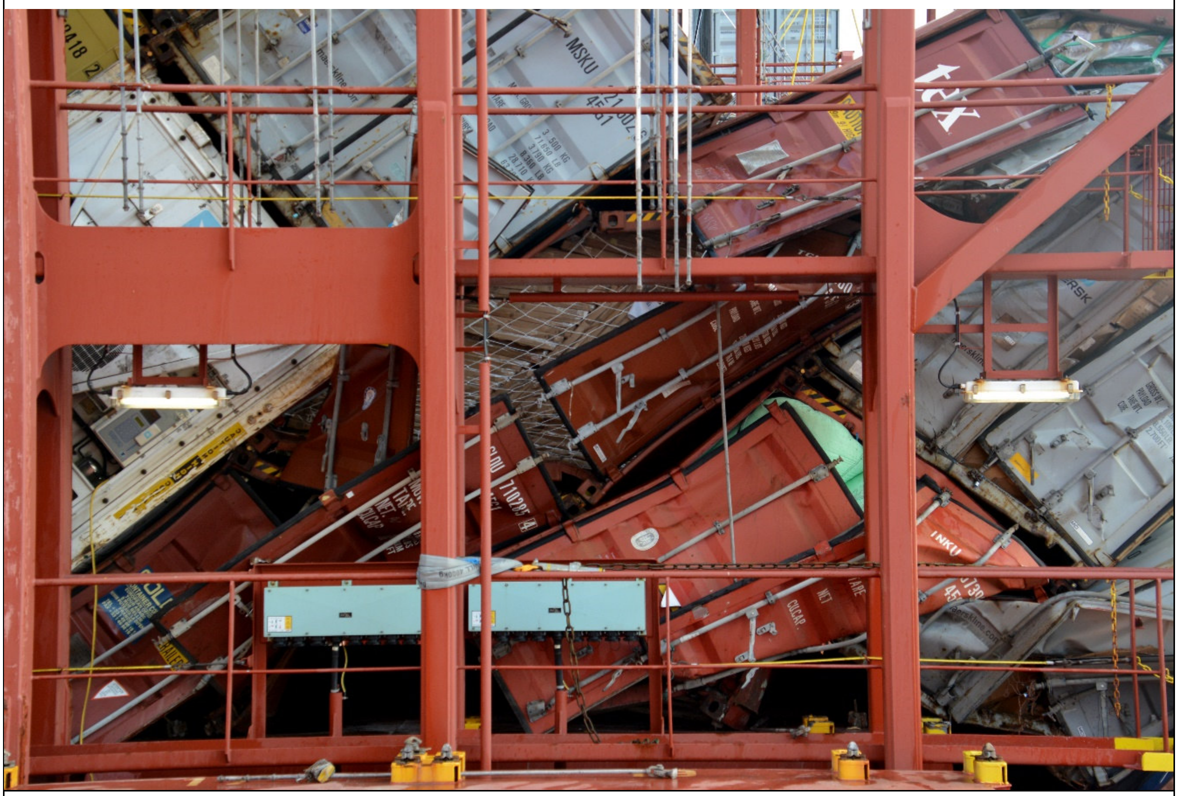


Figure 6: Crushed containers on board MSC ZOE. (Source: DSB)

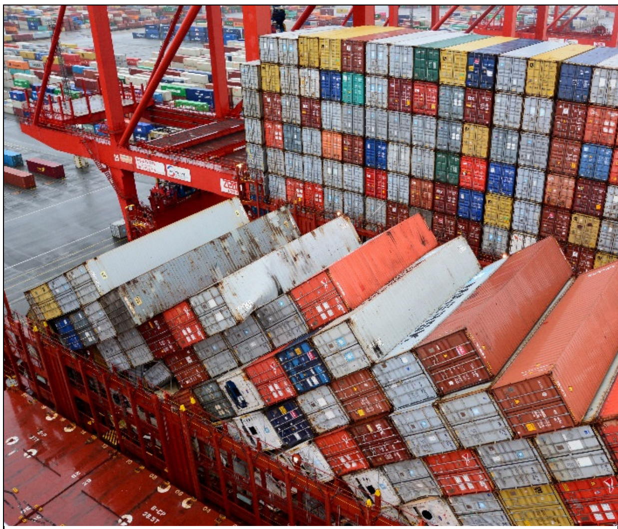


Figure 7: View on bay 26 (Source: DSB)

Figure 8: Collapsed containers in bay 26. (Source: BSU)

Figure 9: Collapsed rows in bay 42 and 50. (Source: BSU)

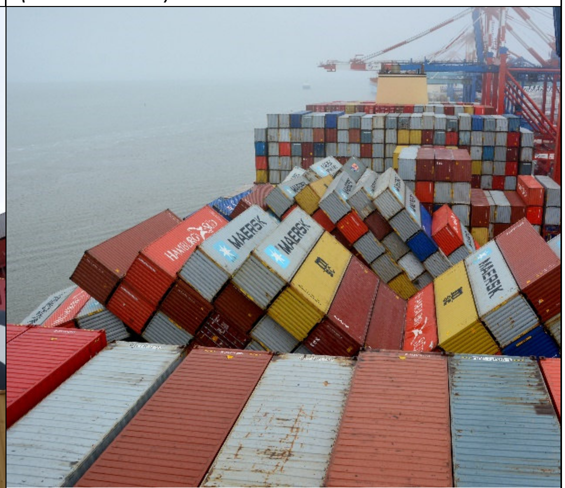


Figure 10: View on bay 42, 50 and 54 (Source: DSB)

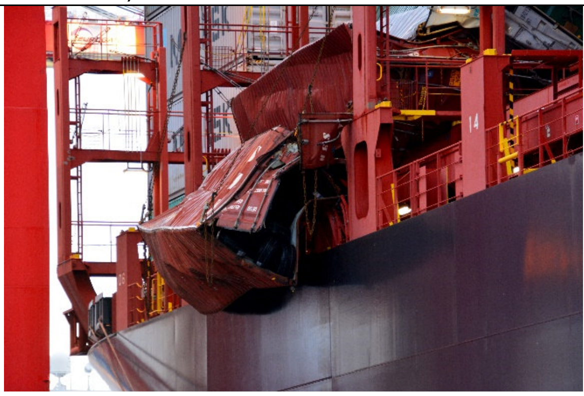


Figure 11: View on bay 10, port side. (Source: DSB)

Figure 12: View on bay 10, starboard side. (Source: Netherlands Coastguard)

2.4 Damage to the vessel

Following arrival in Bremerhaven on 3 January 2019, the MSC ZOE underwent a series of inspections and examinations by various parties. Among others, the vessel underwent a Port State Control inspection. This inspection process resulted in a *condition of class* by the Classification Society; for the MSC ZOE the classification society is DNV GL SE. A *condition of class* means that repairs have to be carried out under the supervision of a classification society. The repairs must then be signed off by a surveyor from the classification society and reported back to Port State Control. In Bremerhaven they also started to off load containers.

The Port State Control inspection resulted in an inventory of the damage suffered. Both on deck and on the lashing bridges, a number of handrails had been bent or broken. Also the lashing bridges themselves and the fire valves and ventilation openings were damaged. A number of hatches[7] were damaged too. Bays 10 (9/11), 26 (25/27), 50(49/51) and 54(53/55) were so severely damaged that they were temporarily decommissioned. The vessel also suffered a series of minor dents in the hull above the waterline. None of the damage influenced the seaworthiness of the vessel enough to prevent the vessel from sailing to its subsequent port of destination.

The classification society granted the MSC ZOE permission to sail to Gdansk to unload the remaining containers. The ship departed on 16 January 2019. During the crossing, the ballast tanks in the double bottom had to be permanently monitored, to ensure that no water was taken on board, because of the possibility that during the period of severe rolling, the MSC ZOE came in contact with the seabed. Moreover, Port State Control decided that due to potential damage to the bottom of the vessel, it needed to be inspected in Gdansk.

In Gdansk, the MSC ZOE unloaded the remaining containers. At this point, the definitive extent of the damage could be determined. In the port of Gdansk, divers carried out an underwater inspection of all the ship’s bottom and bilge areas (the transition from the ship’s bottom to the side). The survey statement of the classification society DNV-GL states that the divers found *no damage caused by grounding*.

[7] Hatches 3-CS, 3-CP, 3-P, 3-S, 7-P, 7-S, 7-CS, 13-P, 13-S, 13-CS, 13-CP, 14-S

Figure 13: Bent turnbuckle (Source: German Waterway Police)

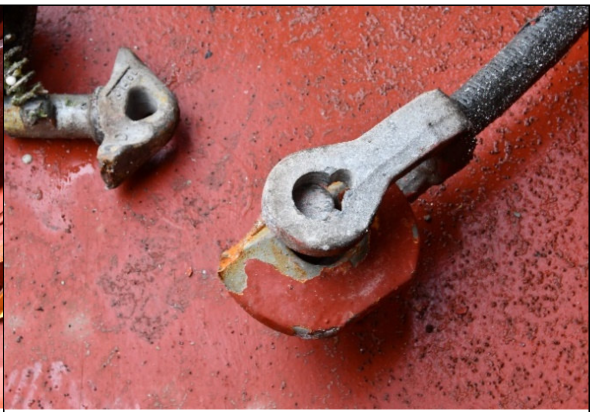


Figure 14: Broken mount from lashing bridge (Source: German Waterway Police)

Figure 15: Broken twistlock in a bent deck fitting (Source: German Waterway Police)

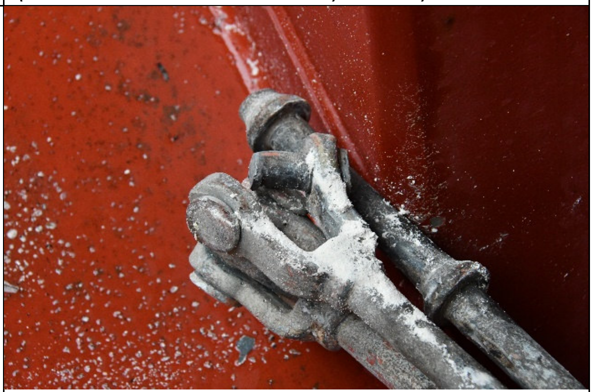


Figure 16: Broken turnbuckle (Source: German Waterway Police)

Figure 17: Broken twistlock in deck fitting (Source: German Waterway Police)

Figure 18: Broken twistlock (Source: German Waterway Police)

Figures 13 to 18 show evidences of the damages to lashing material and deck fittings. Some container stacks remained, even on their side, securely fastened to each other with twistlocks. In the bays with damaged or lost containers, broken twistlocks were found. Also bent or deformed lashing rods and turnbuckles were found, as well as broken mounts from the lashing bridges with the turnbuckle still attached.

2.5 Damage to the environment

The MSC ZOE lost its containers north of the Dutch and German Wadden Islands. It was estimated that around 3,257 tons (containers and its content) fell into the sea. The majority of the content of the containers lost overboard consisted of consumables and associated packaging materials. Above all plastic objects washed ashore the coast of the Wadden Islands the days following the accident.

Two of the lost containers contained hazardous materials. One container contained 160 boxes with bags with a mixture of 50% dibenzoylperoxide and 50% dicyclohexylftalaat(50%) and 120 boxes with bags with a mixture of 34% dibenzoylperoxide and 66% dicyclohexylftalaat[8][9]. The second container contained 467 chests with lithium-ion batteries[10], in total 1,400 kg. In addition, there was a lot of damage due to the loss of raw materials for the plastic industry, in the form of millions of small particles of plastic. One container contained 22.5 tons of tiny expendable polymeric beads[11]. Tiny balls of polyethylene with a diameter of 4 millimeters, washed up on the beaches immediately after the event[12]. The wind continued to disperse these plastic particles, which are difficult to remove from the environment due to their small dimensions.

Large-scale coastal clean-ups and salvage operations at sea have been successful to the extent that the bulk of the lost cargo has been recovered. Mid-November 2019, 87% of the containers and 75% of the cargo were found and removed. It is expected that the majority of the remaining lost content can no longer be traced and cleaned up. Floating objects spread with wind and sea currents, others end up on the seabed.

Plastic pollution of seas and oceans is a worldwide problem. It is estimated that 13 to 35 thousand tons of plastic disappear into the sea every day, 4 to 10 times the lost cargo of MSC ZOE. Because plastic breaks down very slowly, plastic pollution in the oceans is increasing rapidly. On a global scale, MSC ZOE's contribution to the plastic problem appears to be of minor importance. However, placed within the regional context a completely different picture emerges: not only the amount of the cargo that fell overboard determined the severity of the consequences, the place where it happened is also of great importance. MSC ZOE lost its cargo in the vicinity of the Wadden Sea, the special nature reserve that has been placed on the World Heritage List by the United Nations.

Wadden Sea

The Wadden Sea extends along the coasts of Denmark, Germany and the Netherlands and is the largest tidal flats system in the world. Due to the special ecological conditions, the Wadden Sea is a habitat of an extremely diverse flora and fauna. The inhabitants include

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[8] UN3106 CLASS 5,2

[9] WUR, *Mogelijke ecologische gevolgen containerramp MSC Zoe voor Waddenzee en Noordzee – Een quickscan*, maart 2019.

[10] UN3480, CLASS 9

[11] UN2211, Polymeric Beads EXPANDABLE(-) CLASS9(-) PG III

[12] NIOZ & WUR, *Notitie over de status van het onderzoek naar ecologische effecten van het MSC ZOE incident met focus op microplastics,* 30 januari 2020.

marine mammals such as the harbor seal, the gray seal and the porpoise. Ten to twelve million birds go to the Wadden region every year to forage, breed and hibernate[13].

A complex ecosystem with such great diversity is vulnerable. Environmental and nature conservation organizations therefore make great efforts to preserve the natural habitat of the Wadden region and to protect its flora and fauna. Also governments have implemented policies to preserve the Wadden Sea. The international status of the Wadden Sea is expressed by the following:

- The area is included in the list of Natura 2000 sites[14] established by the European Commission. The relevant Member States must ensure that the sites are managed in a sustainable manner, both ecologically and economically, and therefore establish appropriate conservation measures and management plans.
- The vulnerability of the Wadden Sea was officially recognized in 2002 by the IMO by the designation of the Wadden Sea in Denmark, Germany and the Netherlands as a *Particularly Sensitive Sea Area* (PSSA). International recognition of this kind of area as a PSSA offers the possibility of adopting additional protective measures within the mandate of the IMO, such as routeing measures.
- As of 2009, the Wadden Sea is listed by UNESCO[15] as World Heritage. This status obliges the States of Denmark, Germany and the Netherlands to collaboratively ensure the protection and conservation of this natural heritage.[16]

[13] UNESCO World Heritage Centre (2014)
[14] Natura 2000 is a network of core breeding and resting sites for rare and threatened species, and some rare natural habitat types which are protected in their own right. It stretches across all 27 EU countries, both on land and at sea. The aim of the network is to ensure the long-term survival of Europe's most valuable and threatened species and habitats, listed under both the Birds Directive and the Habitats Directive. https://ec.europa.eu/environment/nature/natura2000/index_en.htm
[15] United Nations Educational, Scientific and Cultural Organisation
[16] Convention concerning the protection of the world cultural and natural heritage (1972)

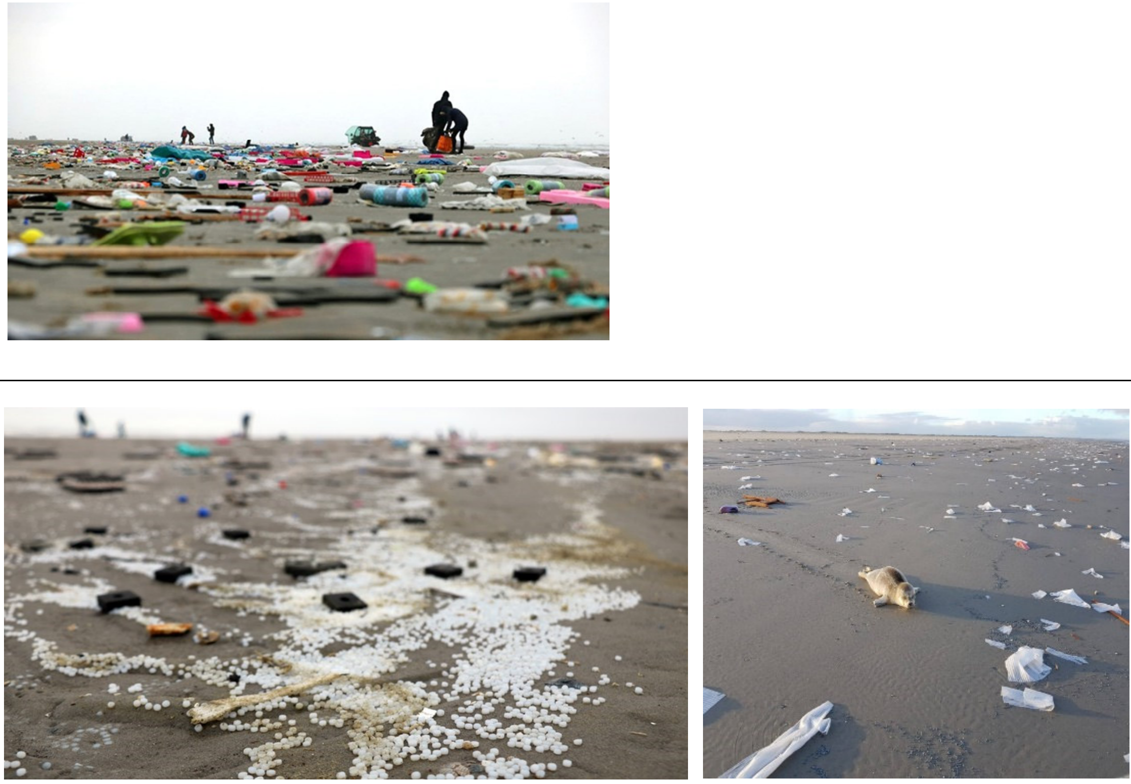


Figure 19. Polluted beaches on the Dutch Wadden Islands. Washed up items from the MSC ZOE (Source: left pictures: Arnold van der Wal - Natuurmonumenten, right picture: Jeroen Berkenbosch - RTV-Noord.)

2.6 Recovery of the lost containers

Following the accident, Dutch and German authorities Rijkswaterstaat and Wasserstraßen- und Schifffahrtsamt Emden, together with the ship operator and his P&I Club, immediately co-operated and started organising the recovery without delay. During the recovery of the containers, use was made of various specialist equipment, including crane ships, a barge to dispose of the waste, a ship for collecting floating waste and vessels equipped for surveying the seabed.

The area to be surveyed was considerable. In total around 4,200 km² was screened. First the southern shipping lane of the TSS Terschelling - German Bight was investigated, followed by the area between the shipping lane and the coastline. The decision to temporarily close the shipping lane was considered, but when it became clear that no serious shallows had been created by stacks of fallen containers, it was decided that this measure was not necessary. During the seabed survey, more than six thousand objects were identified. These were plotted for each km^2. The recovered container residues were transported by the salvage company to a central collection point. A recovery report was drawn up for each individual identifiable component.

On the basis of the identified parts (whether or not recovered from the seabed), Rijkswaterstaat identified which objects had been carried in which containers, and where they had been placed on board the MSC ZOE, by comparing the recovery reports with cargo manifests.

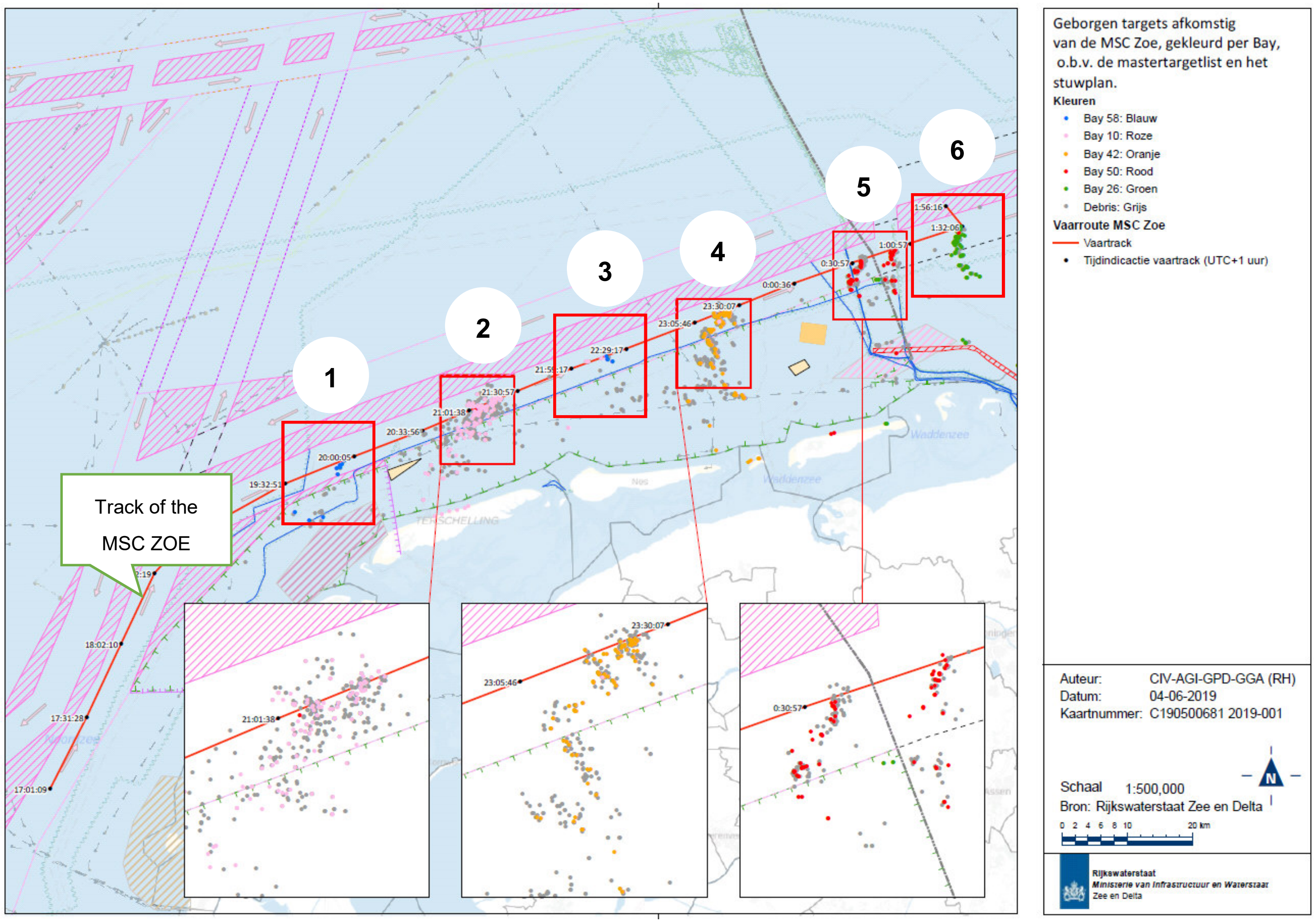


Figure 20. Recovery locations of lost containers. Six main locations can be identified. Colours indicate bay number on board the ship: blue=bay58, pink=bay10, orange=bay42, red=bay50, green=bay26, grey=debris. Track of the MSC ZOE is indicate in red. (Source: Rijkswaterstaat, the six locations added by the investigation team)

Figure 20 shows that large numbers of containers were recovered at six locations. Combining this with the sailing route of the MSC ZOE, it was possible to reconstruct where and when which containers fell overboard. The MSC ZOE lost containers from the bays 10 (9/11) (pink), 26 (green), 42 (orange), 50 (red) and 58 (blue). Bays 46 and 54 also contained damaged containers, but they didn't fall overboard (see chapter 4).

The first containers were lost shortly before 20.00 hours (blue dots in figure 20). At that time, the MSC ZOE was located to the north of the most easterly point of Vlieland. These containers originated from bay 58, in the middle of the ship (see figure 21). The most notable element of this initial loss moment was that all the containers fell over the starboard side (see figure 22).

The second loss of containers occurred between 21.05 and 21.20 hours (pink dots in figure 20). At that time the MSC ZOE was located to the north of Terschelling. These containers originated from bay 10 at the bow of the vessel (see figure 21). Approximately the same number of containers fell overboard from both sides of the vessel (see figure 22).

The third loss occurred at around 22.20 hours. A number of additional containers fell overboard from bays 58 and 10. In total 21 containers were lost from bay 58, both at the first and third loss. It is impossible to determine exactly how many containers from this bay were lost at the first or third loss. Only the cumulative number of containers lost from bay 58 at those two points is known. The same holds for containers from bay 10 (9/11), which were lost during the second and third loss. In total 93 containers were lost from bay 10 (9/11) (see figure 22).

The fourth loss of containers took place at around 23.20 hours (orange dots in figure 20). At that time, the MSC ZOE was located to the north of the most easterly point of Ameland. These containers originated from bay 42, situated behind the bridge (see figure 20). Slightly more containers fell overboard from the starboard side, than from the portside. A number of containers from the middle of the bay also went overboard. Eventually 65 containers from bay 42 fell overboard (see figure 22).

The fifth loss of containers took place at around 00.35 and 00.50 hours (red dots in figure 20). At that time, the MSC ZOE was located to the north of the eastern tip of Schiermonnikoog. These containers originated from bay 50, in the middle of the ship (see figure 21). Slightly more containers fell overboard from the starboard side than from the portside. In total 80 containers from bay 50 fell overboard (see figure 22).

The sixth and final loss of containers took place at around 01.30 hours (green dots in figure 20). At that time, the MSC ZOE was located to the north of Rottumerplaat and Rottumeroog. These containers originated from bay 26, just in front of the vessel's bridge (see figure 21). Here, too, slightly more containers fell from the starboard side than from the port side; eventually 83 containers from bay 26 fell overboard. This loss also contained two containers with hazardous substances. Unlike the previous losses, this loss of containers was witnessed by the captain and some crew members.

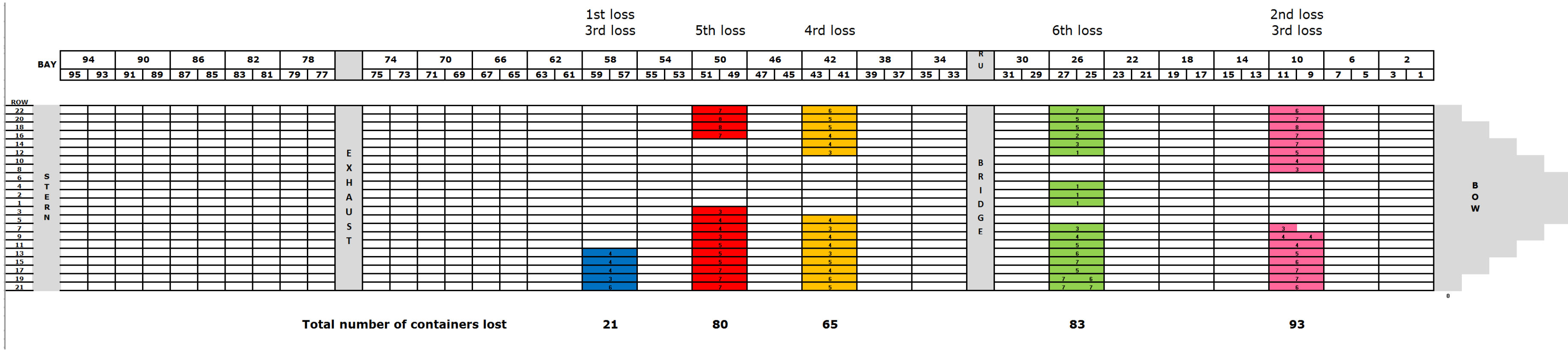


Figure 21: Top view of the MSC ZOE with lost containers per bay. (Source: Based on data provided by Rijkswaterstaat)

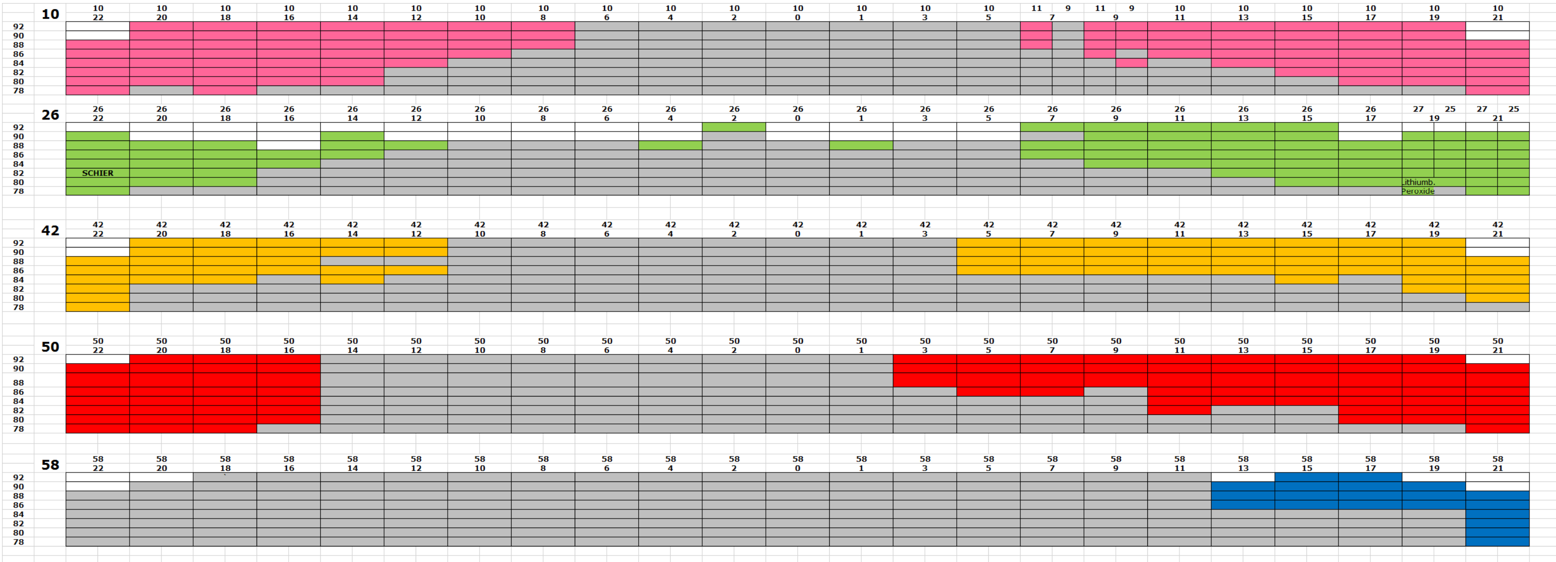


Figure 22: Cross section view of lost containers per bay. (Source: Based on data provided by Rijkswaterstaat).

2.7 Data from the VDR

The MSC ZOE was equipped with a Voyage Data Recorder (VDR)[17] which recorded several parameters and audio, including for the passage through the TSS Terschelling – German Bight. The data from the VDR was available for the safety investigation.

Figure 23 displays relevant parameters of the VDR from 17.10 hours LT on January 1, 2019 until 02.53 hours on January 2, 2019.

At approximately 18.50 hours, when the MSC ZOE entered the TSS Terschelling – German Bight, the ROT (rate of turn or swinging port/starboard) started to increase. The ship was at that time sailing with a speed of approximately 13-14 knots. The ship started to roll continuously: whenever a ship starts to heel, it will also start to turn.

At around 20.08 hours, the engine RPM (revolutions per minute) decreased, followed by a decrease of the ship's speed to around 9 knots. At around the same time it can be seen that both rudder control and rudder angle suddenly increased, as a result of switching from automatic to manual steering. As a result the ROT increased further.

The VDR also recorded the UKC (under keel clearance) as measured by the echo sounders. The MSC ZOE has two echo sounders installed, one at 4.40 m starboard of the centre line in the aft of the vessel and one on the centre line in the front of the vessel. The echo sounders indicate the depth measured from the echo sounder to the seabed, and also gives the offset between the echo sounder and the water surface. The latter has to be set manually. Data shown is the measured depth from the echo sounder to the seabed. The data shows that the measured UKC varied from 11 to 19 m. As from 20.00 hours until 21.00 hours, the UKC decreased and values as low as 5 m are recorded. As of 21.30 hours the data shows again all recorded UKC values over 10 m. Around 01.30 hours values of 6 m UKC are recorded. Following the change of heading at 01.34 hours, the measured UKC also starts to increase. The data shows some non-realistic displacements in short time and can therefore be considered as signal noise as explained below.

Echo sounders and noise

An echo sounder measures the depth of the water by transmitting a sound (a 'ping') towards the bottom of the water and then listening for the reflection (echo) of the sound through the receiver. The time between transmitting the sound and receiving the sound times the speed of sound in water divided by two (the sound goes down and back up again) gives the depth of the water. While this is straightforward, there are several kinds of noise that can occur in the measurement of water depth. Noise is an unwanted change in a signal that causes errors of the measurement.

The following is a list of some examples that can cause noise in echo sounder measurements[18] [19]. It is not an exhaustive list:

---

[17] The VDR was a Consilium F2 VDR and received its annual performance test on July 25, 2018.

[18] EA640 Hydrographic single beam echo sounder Installation Manual, Kongsberg, 2018

[19] FE-800 Operator's Manual Navigational Echo Sounder, Furuno, 2014

- Water and bottom characteristics. The speed of sound changes with different water temperatures, salinity and pressure. The reflection of the echo sounder's ping changes based the type of bottom, such as rock versus mud and the slope of the bottom.
- Electronic interference. Other electronic equipment nearby the echo sounder cabling can cause noise.
- Ship's noise. The ship itself makes noise such as the propeller and vibrations of the hull, which can interfere with the echo sounder's measurements.
- An earlier 'ping' reflecting multiple times before getting back to the receiver can interfere with the next 'ping'.
- Pitch and roll of the ship. If the angle of the roll of the ship gets too high, the ping may no longer go straight down, and instead may measure the bottom of the water at an angle, wrongly increasing the water depth measured (outliers)[20].

Some noise can be reduced through software, but this is not always possible. In figure 23 the measurement of the echo sounder is shown. It also shows several peaks at 50 or even 100 meters. These are considered noise, since such water depths are not present at that location of the MSC ZOE. Because these peaks start to show up during the time where the roll motion is also increased, it is likely noise (outliers) caused by the roll of the ship or due to the ship's noise which is increased during this part of the voyage.

[20] The error due to roll and pitch is recognized by the manufactures and depending on the manufacturer is corrected by data reduction methods.

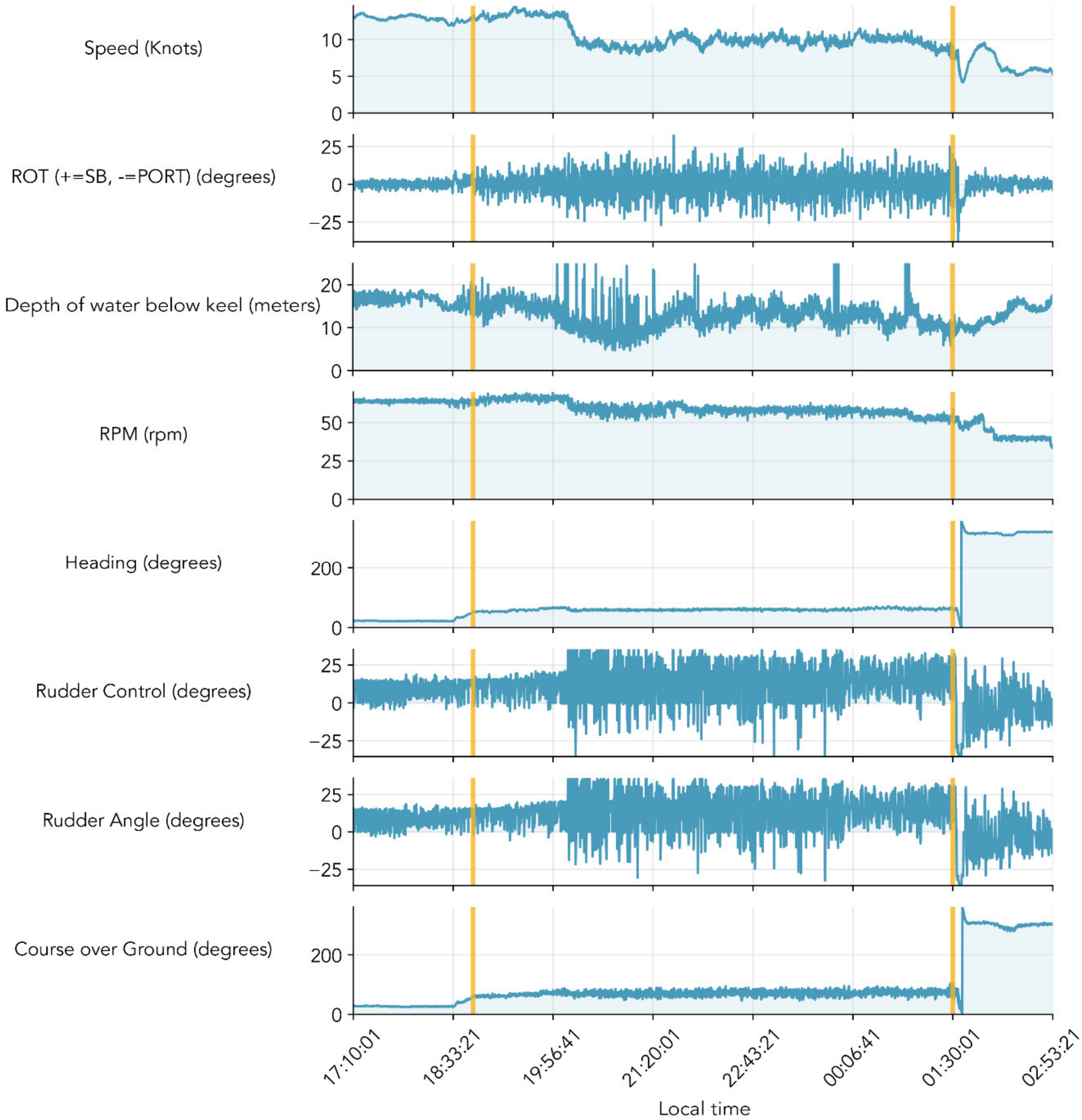


Figure 23: Selected parameters from the Voyage Data recorder (VDR) in local time.

2.8 Sequence of events

Comparing the crew statements with the container recovery data indicates that during the passage at least at six moments serious amounts of containers were lost, but that five of these losses were not noticed by the crew. At 01.00 hours the master observed collapsed container stacks behind the bridge. Only the sixth loss of containers at 01.30 hours was actually witnessed by the crew. The ship's size, the constant motions of the ship, noises on the bridge due to wind and shifting objects and the night conditions probably have contributed to the unnoticing of the losses.

The first container loss only involved containers on the starboard side. The other five events all involved container loss from both sides of the ship.

Figure 24 summarizes the sequence of events and combines the data from the VDR, the information based on crew statements regarding the perceived ship motions and the major container loss moments based on the container recovery data.

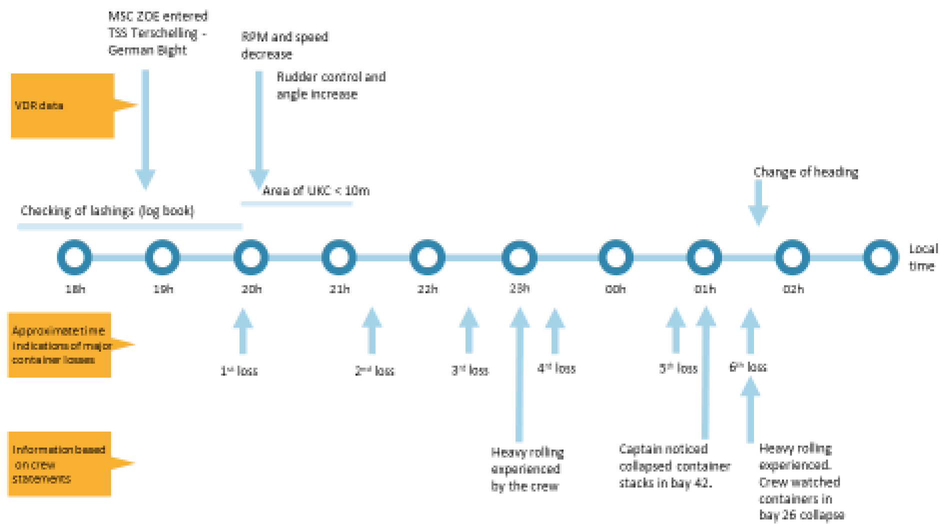


Figure 24: Sequence of events

According to crew statements, the MSC ZOE experienced in the TSS Terschelling – German Bight continuous rolling movements of 5 and 10°with occasional moments of heavier rolling of15° up till 30° peaks. The VDR data confirms that when the MSC ZOE entered the TSS Terschelling – German Bight the ship started to roll continuously.

The MSC ZOE's first loss of containers occurred around 20.00 hours LT on January 1. In total at least at six moments containers were lost. The crew on board did not detect the loss or the collapse of containers until 01.00 hours on January 2. The last loss, bay 26, occurred half an hour later, around 01:30 hours, and was witnessed by the crew.

In the bays with damaged or lost containers, broken twistlocks, broken or bent turnbuckles and broken mounts from the lashing bridges were found.

No crew members were injured but in total 342 containers were lost overboard. The containers and content severely polluted the Wadden Sea region in The Netherlands and Germany.

3 SHIP AND CREW

3.1 Ultra Large Container Ship MSC ZOE

The Panamanian flagged container carrier MSC ZOE is a DNV GL SE modern new generation container ship. It was built in 2014 in the Republic of Korea by Daewoo Shipbuilding & Marine Engineering Co. and delivered to MSC in 2015. The ship has a total theoretical container capacity of 19,224 TEU, corresponding to a deadweight of almost 200K tons. The ship has an overall length of 395.4 m and breadth of 59 m. It has 24 40' container bays on deck (two 20' containers fit in one 40' bay), numbered 2 to 94. The company MSC engages the ship in a liner service between Europe and the Far East. The ship's particulars are listed in Appendix A.

3.2 Information on the crew

The MSC ZOE had a crew of 22. The composition of the crew was in accordance with the Minimum Safe Manning Certificate and the officers were appropriately qualified. Hours of rest records indicate that the bridge watch keeping officers and the master had all received rest in excess of the statutory minimum requirement according to the Maritime Labor Convention (MLC).

The master, 64 years old at the time of the accident, joined the vessel in Singapore on November 5, 2018 and is holder of an Italian STCW class II/2 certificate. He was enrolled with the company in 1973 as deck cadet, was promoted, became chief officer in 1986 and master since 1997. He has sailed on bulk carriers, general cargo vessels and container vessels. It was his first contract on the MSC ZOE, but fourth contract on similar vessel size and type.

The chief officer, 33 years old, joined the vessel at Singapore on November 2, 2018 and is holder of a STCW class II/2 certificate from Montenegro. He enrolled with the company in 2004 as deck cadet, since 2006 and 2008 as respectively third and second officer, and since 2012 as chief officer.

The second officer, 24 years old, joined the vessel at Singapore on November 2, 2018 and is holder of a STCW class II/1 certificate from Montenegro. He was enrolled with the company in 2013 as deck cadet, has been promoted in 2015 as third officer, since 2017 as second officer. He was on his third contract with the company MSC.

The third officer, 31 years old, joined the vessel in Singapore on November 2, 2018. He started his career in 2010 as deck cadet and is a third officer since 2016. He is holder of an Italian STCW class II/1 certificate and was on 1st contract on the MSC ZOE, but has been on the MSC ERICA with similar dimensions.

The scheme for the manning of the bridge is presented in the table below. The bridge was manned by the designated Officer On Watch and the helmsman/lookout. In the standard scheme, the master was not a watch keeping officer. He had the flexibility to work and be on call when required. Due to the worsening of weather conditions, on January 1 from around 16.00 onwards, also the master was on bridge and from of 19.00 hours onwards in command, see table 1.

Manning scheme on the bridge 1st January		Additional information
00h - 04h	Second Officer + helmsman/lookout	
04h - 08h	Chief Officer + helmsman/lookout	
08h - 12h	Third Officer + helmsman/lookout	
12h - 16h	Second Officer + helmsman/lookout	
16h - 19h	Chief Officer + helmsman/lookout	*Master on the bridge, but not in command*
19h - 24h	Third Officer + helmsman/lookout	*Master on the bridge and in command*
00h - 04h	Second Officer + helmsman/lookout	*Master on the bridge and in command*

Table 1. Scheme for manning on bridge.

On January 1, the chief officer on bridge watch reported in the deck log book that from 16.00 hours to 20.00 hours the lashing of containers, dangerous cargo, reefers, cargo holds and bilges were checked and reported "all in order". Due to the continuous worsening of weather conditions, the master ordered to proceed on hand steering and the RPM was also reduced resulting in a decrease of the speed.

The MSC ZOE is an ultra large container ship with a theoretical container capacity of 19,224 TEU. The ship is engaged in a liner service between Europe and the Far East. For the voyage from Sines, Portugal to Bremerhaven, Germany, there was a crew of 22 on board. The officers on board were appropriately qualified.

Due to the worsening of weather on the 1st of January 2019, the master stayed on the bridge and ordered hand steering and reduction of speed.

4 CONTAINER STOWAGE AND SECURING

4.1 General Information on the cargo

From Sines to Bremerhaven, the MSC ZOE was carrying 8,062 containers[21], see table 2. On the MSC ZOE, the containers on deck were stacked seven to eight high on the hatch covers.

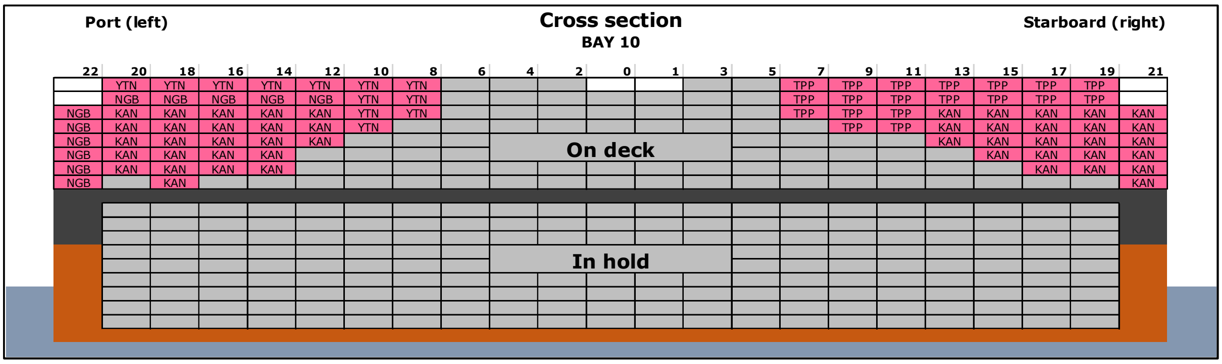
	Hold	On deck	Total
20'	2,392	267	2,659
40'/45'	2,090	3,313	5,403[22]
Total	4,482	3,580	8,062

Table 2. Overview of number of containers

The containers were loaded in ports in China: Xingang (TXG), Ningbo (NGB), Shanghai (SHA) and Yantian (YTN). The vessel also loaded containers in Malaysia: Tanjung Pelepas (TPP) and in Korea: Gwangyang (KAN). The containers were destined for Sines (Portugal), Bremerhaven (Germany) and Gdansk (Poland).

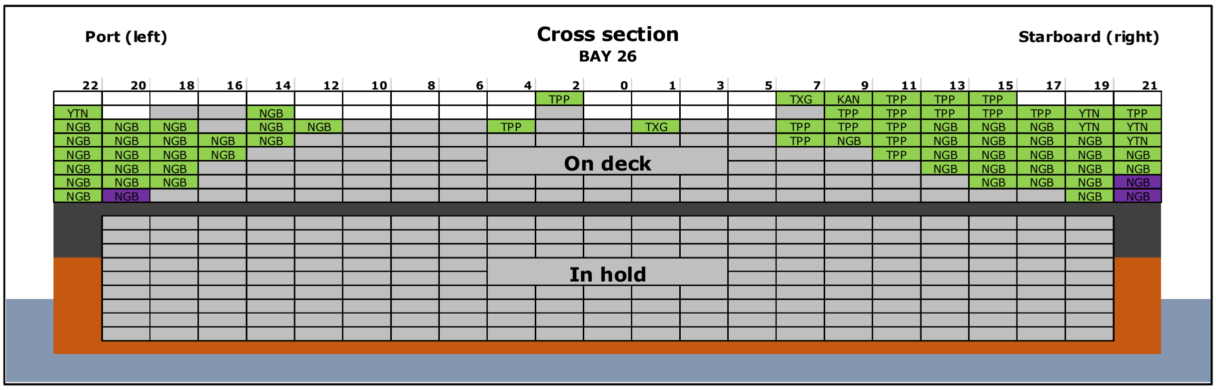
In the following bay plans, the lost containers are coloured per bay, based on where the containers, or parts of the containers were found. The MSC ZOE lost containers from the bays 10 (9/11) (pink), 26 (green), 42 (orange), 50 (red) and 58 (blue). The containers that remained on board in the respective bays are coloured grey[23].

The containers lost from bay 10[24] were loaded in all Asian ports except Xinyang and Shanghai and were destined for Gdansk.

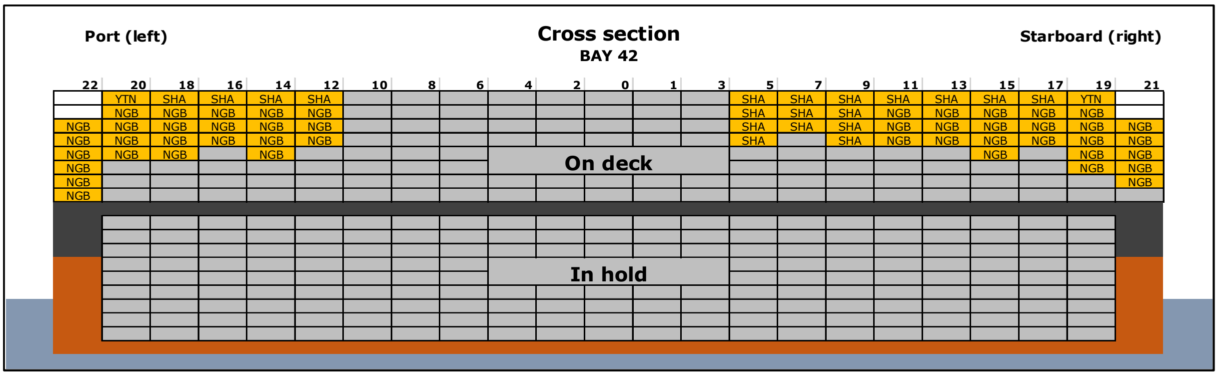


[21] See Appendix B
[22] Of which 2,656 45 foot containers
[23] The containers displayed in the hold do not fully represent the true situation.
[24] Bays 9 and 11

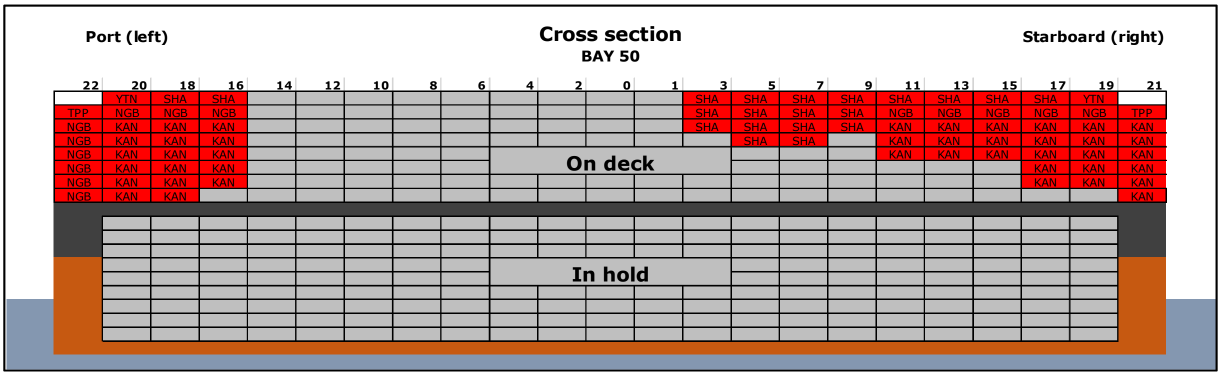
The containers lost from bay 26 were loaded in all Asian ports except Shanghai and destined for Gdansk. Bay 26 contained 3 containers with dangerous goods, coloured purple. The two containers on starboard were lost; the one on port side remained on board but lost some of its content.



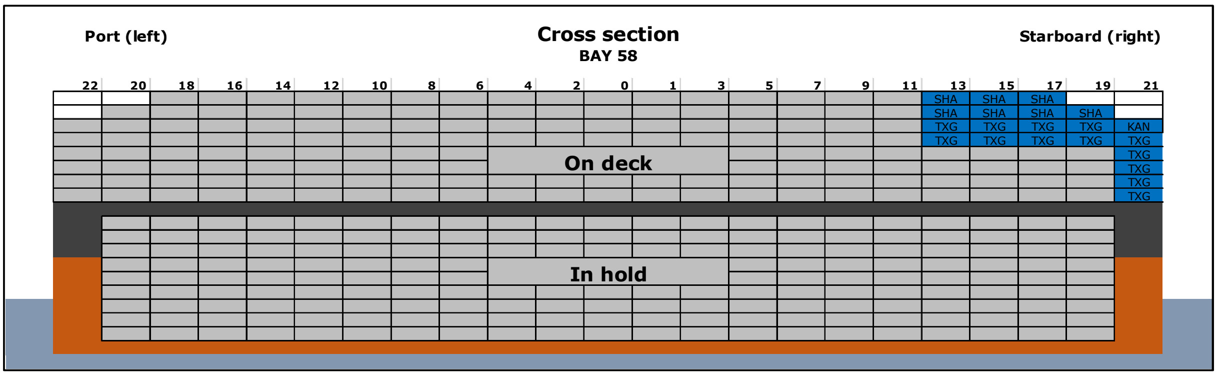
The containers lost from bay 42 were loaded in Ningbo, Shanghai and Yantian and were destined for Gdansk.



The containers lost from bay 50 were loaded in all Asian ports except Gwangyang and Shanghai and were destined for Gdansk.

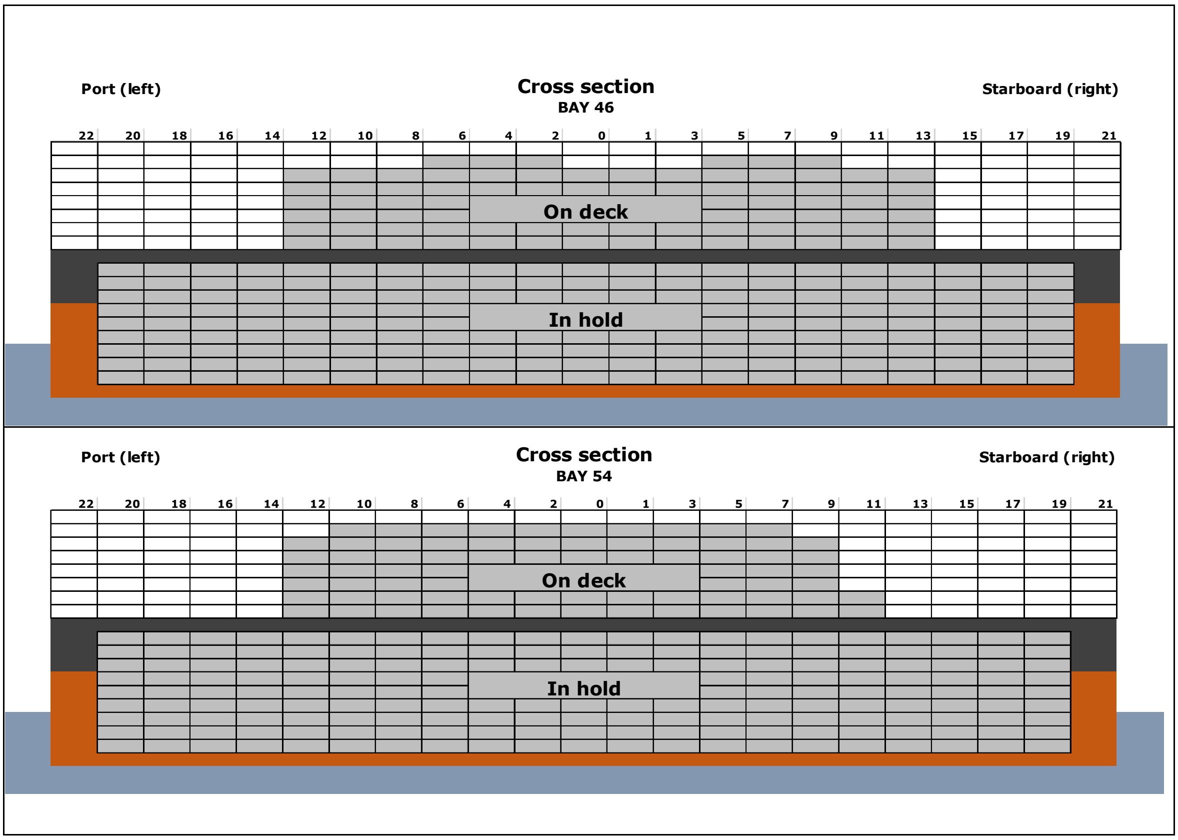


The containers lost from bay 58 were loaded in Xinyang, Gwanyang and Shanghai and destined for Gdansk.



There were no containers lost from bay 46 and bay 54, but they are situated between bays that did loose containers. From the bay plans from bay 46 and bay 54, it can be seen that they didn't contain containers close to the sides of the vessel.

Figure 25: Top view of the bays with lost containers. (Source: The Netherlands Coast guard)



The lost containers were loaded with a wide variety of goods. From auto parts to furniture, handbags, tools, baskets, lamps and lighting fixtures, televisions, tyres, sport goods, toys and batteries. The MSC ZOE also carried reefer containers, but none of them went overboard.

4.2 The securing of cargo

The International Convention for the Safety of Life at Sea (SOLAS) regulations indicate that cargo shall be loaded, stowed and secured throughout the voyage in accordance with the Code of Safe Practice for Cargo Stowage and Securing (CSS code[25]). This code provides guidance on proper stowage and securing of cargo and should be used as the basis for the Cargo Securing Manual (CSM). The CSM is specifically tailored to the ship and describes the containers stowage and lashing equipment. The cargo securing arrangements detailed in the vessel's CSM, should be based on the forces expected to affect the cargo carried by the ship, calculated in accordance with the method described in Annex 13 of the CSS or with a method accepted by the Administration or approved by a classification society.

The containers are stowed in a bay-row-tier system which follows a system of numerical coordinates (see also paragraph 2.3). Stowage and securing of cargo aim to absorb forces. Transverse forces increase amongst others with the height of the stow. The transverse forces exerted increase directly with the GM (stability) of the ship.

[25] IMO Res. A.714(17) (MSC/Circ.1026)

Most container vessels secure containers in their hold with vertical cell guides and stow them on deck in stacks on the hatch covers. Securing containers for carriage on deck is based on locking containers on deck fittings, interconnecting containers with twistlocks and a system of lashing bars. The containers in the first tier on top of the hatch cover are positioned on fixed twistlock foundations. The containers in the following tiers are stacked one on top of the other, connected with twistlocks. Up till the third tier lashings are fitted, although this may vary per vessel. The lashings are put diagonally, so that the container and the lashings work together to resist racking. No stack is connected with any other stack to keep cargo handling flexible.

The general information given in de CSS code provides handling and safety instructions for the securing of cargo, heavy weather and cargo checks. The CSS code includes guidance in the event of the vessel entering heavy weather. The following measures are listed to avoid excessive accelerations:

- Alteration of course or speed;
- Heave to[26];
- Avoidance of areas of adverse weather and sea conditions;
- Timely (de)ballasting to improve the behaviour of the ship.

The CSS code also states that through supervision of the loading operations improper stowage should be prevented. Through the voyage, cargo should be regularly inspected.

4.3 Lashing

The MSC ZOE was, as almost all modern container vessels, fitted with a lashing bridge (see figure 26), a steel structure running athwart ships between each 40’ container bay. This allows the fourth and fifth tiers of containers to be secured to the bridge using lashing rods and turnbuckles besides the use of twistlocks. At the time of the accident, the MSC ZOE had a maximum of eight (out of eleven) tiers stowed on deck.

The lashing rods, which are put diagonally (external-lashing or cross-lashing), reduce the tipping moments acting on a stack when a vessel is rolling. The fitting of the bridges between 40’ bays means that the 20’ foot containers can only be lashed on the bridges at one end up till the fourth or fifth tier and on the other end to the hatch covers until the second or third tier.

The use of the lashing computer together with the CSM supported the lashing plan, which fits to the cargo. Stevedores are performing the lashing and de-lashing in port. The deck crew, coordinated by the chief officer, is responsible for the correct execution thereof and checks this operation.

Lashing and locking materials should be properly maintained. Annex 1 of the CSM contains the record book of inspections and maintenance regarding all the lashing equipment. The last inspection before the incident was done at sea on 15 December 2018 and written in the

[26] Heave to: to stop forward movement, esp. by bringing the vessel's head into the wind.

record book: *"Inspection of all lashing material carried out: All turnbuckles greased where needed, damaged lashing materials repaired with new ones."*

Locking by twistlocks

The first tier of containers of the MSC ZOE was locked on to fixed deck fittings which are welded on the hatch covers. The containers in the following tiers are stacked one on top of the other, connected with twistlocks. A twistlock and corner casting together form a standardized rotating connector for securing shipping containers. The twistlocks used on the MSC ZOE were provided by German Lashing and their specifications are described in the CSM.

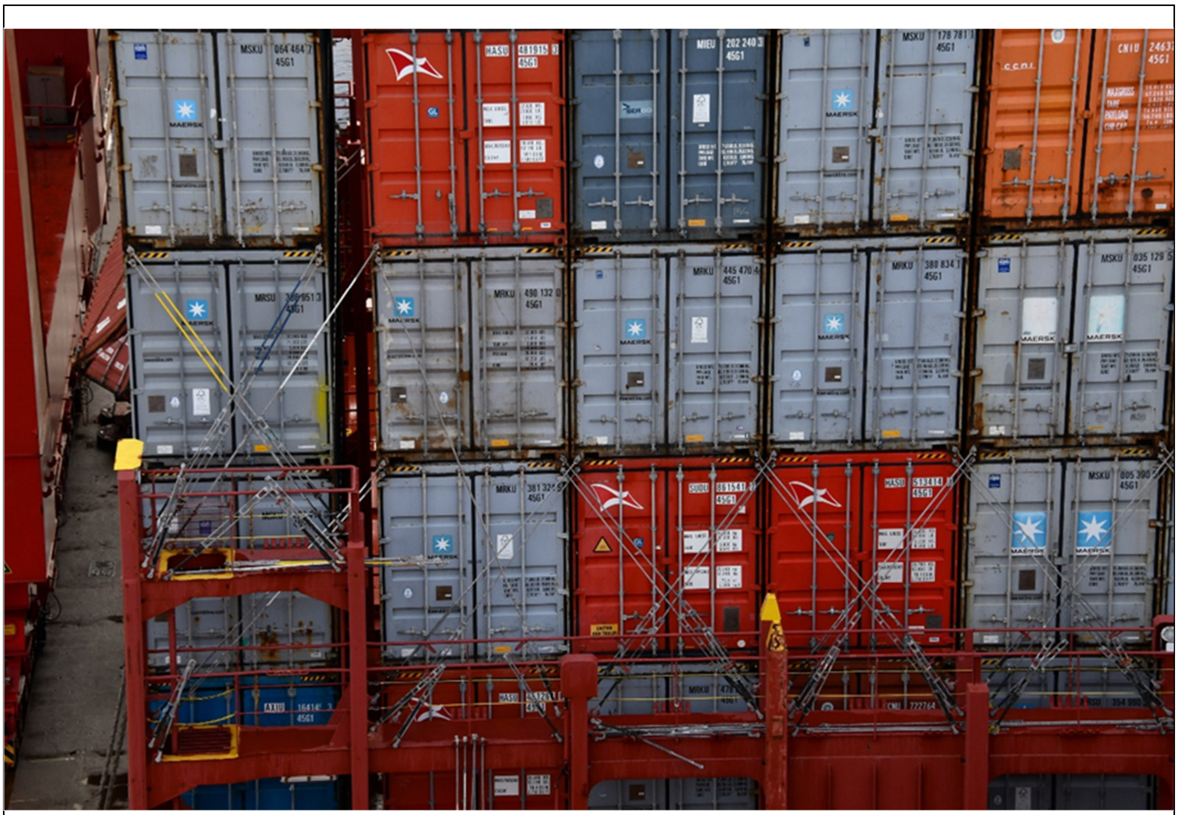


Figure 26: Lashing bridge on MSC ZOE (Source: DSB)

Records on board the MSC ZOE indicated that inspections of the lashing material and the quality of the lashing were in accordance with the procedures. No systematic deviations of the international requirements were identified.

4.4 Cargo Securing Manual

The MSC ZOE has an approved Cargo Securing Manual (CSM) which was compiled by the manufacturer of the lashing material (German Lashing co.) The CSM conformed with the guidelines for the preparation as indicated by the Code of Safe Practice for Cargo Stowage and Securing (CSS code) and was approved by the class society DNV GL SE.

The CSM of the MSC ZOE contains a chapter about the stowage and securing of containers. The chapter contains paragraphs on handling and safety instructions, stowage and securing instructions, other stowage patterns, forces acting on cargo units and the container securing arrangement plan. The forces acting on containers and securing devices in each stack originate from external forces. The transverse component of the three-dimensional force spectrum is the predominant one.

The magnitude and distribution of these forces depend on:

- total stack mass,
- vertical sequence of masses in stack,
- exposure to wind attack,
- application of securing devices,
- value of GM and the movement of the ship due to wave patterns.

The container stowage and lashing equipment on board the MSC ZOE is delivered by German lashing and certified by DNV GL SE.

The strength ratings of fixed and loose container lashing equipment are standardized. The limitations[27] (see table 3) are set by the safe working load (SWL). Permissible forces for container securing devices shall be taken as the provided safe working load. Also the maximum allowable forces on containers are standardized (see table 3).

[27] These limits are set under static conditions.

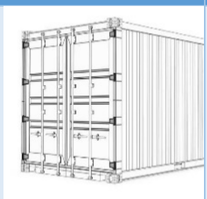
Securing device	Figure	Safe Working Load (SWL)	Proof Load (PL)	Minimum Tension Breaking Load		
Lashing rod[28]		245kN	306kN	490kN		
Turnbuckle		245kN	306kN	490kN		
Twistlock		250kN	313kN	500kN		
Container	**Figure**	**Transverse Racking force**	**Longitudinal Racking force**	**Corner post compression**	**Corner post compression 45ft on top of 40ft**	**Maximum payload standard 20 ft**
ISO Container		150kN	125kN	848kN	270kN	approx. 28.000kg

Table 3: Typical SWL values for container securing device and maximum forces on containers (Source: DNV GL SE)

The container stowage and lashing parts on board the MSC ZOE had a Certificate of test and examination. When new and replacement securing devices are placed on board, they should be provided with an appropriate certificate which should be retained with the CSM manual. Existing securing equipment which has proven satisfactory in service is not subject to examinations providing it is properly maintained and used for the purpose for which it is intended.

For existing fixed fittings applies that where there is any doubt over the capability of existing fixed securing equipment, including the supporting structure, the fixed fitting should be proof tested at loads equal to the maximum specified securing load + 25%. The proof loading is to be applied at both the mean and extreme angles of the operation.

In extreme cases, the excess of strength ratings of the lashing system may lead to collapse of container stacks or loss of containers over board.

In designing and calculating the individual lashing configuration for each stack not only the strength of securing devices but also the strength capacities of containers are taken into account. The CSM states in a clear diagrammatic form for each bay:

[28] The lashing rods for external lashings for the vessel have a SWL of 200 kN. The internal lashings are certified for a SWL of 245 kN.

- The maximum permissible number of containers in each stack;
- The maximum permissible weight of each stack;
- The lashing configuration for each bay.

The chapter in the CSM about the stowage and securing of containers describes situations which may result in the damage or loss of containers and contains the following warnings:

- exceeding the permissible stack mass;
- neglecting permissible sequences of masses in stacks;
- failing to properly lock twistlocks;
- failing to apply lashings as lined out in relevant bay plans;
- exceeding recommended pre tension of 5 kN in lashings;
- extreme partial loading situations;
- exceeding of the maximum GM-value in the stowage plan.

The CSM of the MSC ZOE states that the stowage and securing system as described in the manual is designed under the conditions of GM≤2.08 m. It notes that if the ship is operated with larger GM-values, the expected accelerations will increase accordingly. It mentions that if a GM-value greater than 2.08 m cannot be avoided, a reduction of stack masses or stack heights or a shifting of masses to lower tiers in the stack should be effected. The CSM also states that in light of the complexity of the problem of proper stowage and securing of containers with varying gross masses and vessel's GM value, the actual loading and securing have to be checked with the loading and lashing software on board. The exceedance of the forces caused by previously mentioned reasons will be made visible in such software to enable ship's staff to keep the securing of individual loading situations under control.

ULCS design accelerations according to CSM
The CSM for standardized container ships specifies a lashing arrangement that is assumed to be sufficient for all operationally occurring loads. It is not designed for specific weights of cargo, but for a fixed max allowable load as a result of accelerations, stack weights, wind and waves. For each voyage, the maximum allowable stack weight and distribution is matched with the maximum allowable loads in the gear such that the fixed load ratings are not exceeded. This is done by combining expected accelerations with specified cargo weights.

The only explicit reference to estimate acceleration levels in the CSM is provided for non-standardized cargo. The CSM defers to the loading computer for calculations for container cargo. The acceleration levels for non-standardized cargo are reviewed nevertheless since accelerations are ship specific and not related to particular cargo.

The base table for design accelerations (see figure 27) can be obtained from the table in the CSS code. The table consist of transverse, longitudinal and vertical accelerations.

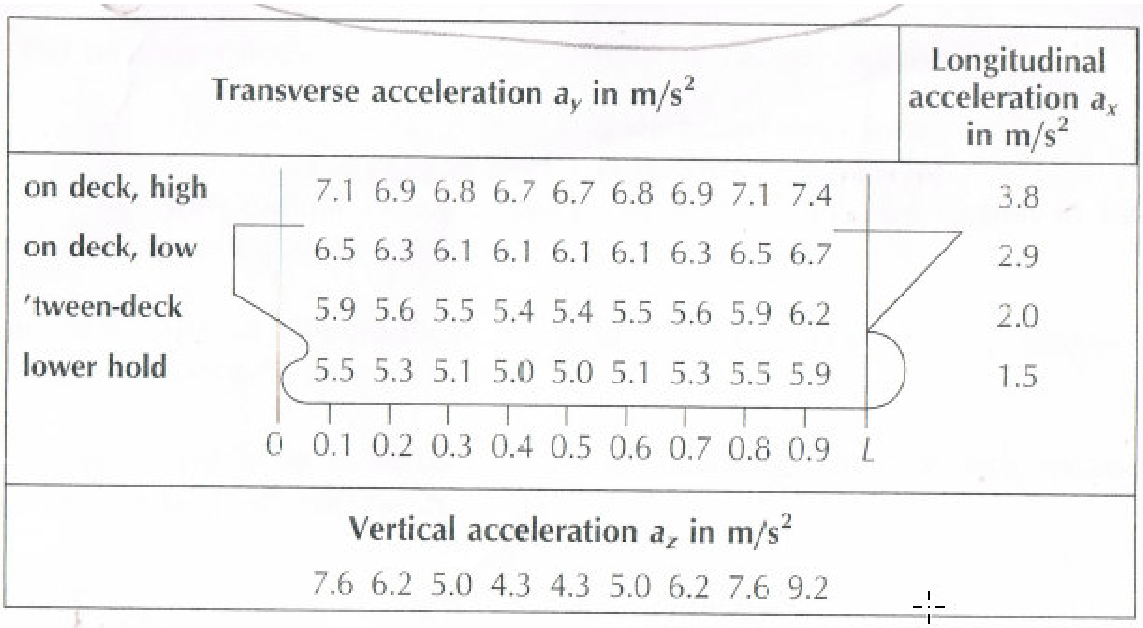


Figure 27: Basic acceleration data according the CSS code. (Source: CSS code)

These design accelerations need to be corrected by application of the correction factor formula in the CSS code for ships, where L is the length between perpendiculars in metres and v is the vessels service speed in knots. For the MSC ZOE Lpp = 379 m and v = 22.8 knots.

$$correction\ factor = \left(0.345 * {}^{v}/_{\sqrt{L}}\right) + \frac{(58.62\,L - 1035.5)}{L^2} = 0.55$$

This leads to the following values for the MSC ZOE as mentioned in the CSM of the MSC ZOE, see figure 28.

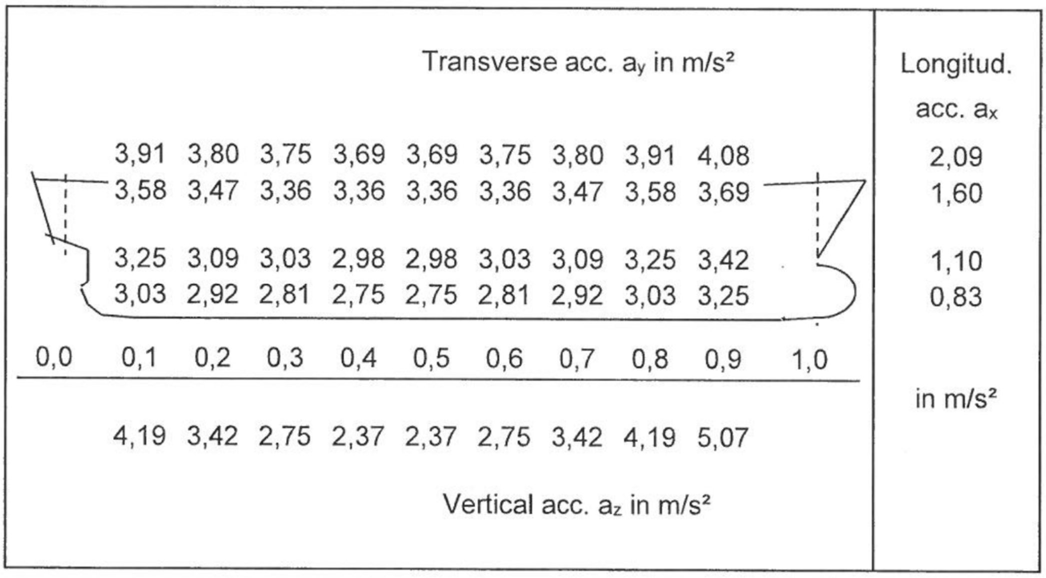


Figure 28: Basic acceleration data for 22,8 kn and GM≤ 4.538 m. (Source: CSM MSC ZOE)

The given acceleration values in figure 29 need to be corrected if the GM ≥ 4.538 m. The CSS code contains a correction table[29] for values of B/GM=7 to 13⁺ (see table 4). For a 59 meter beam this corresponds to GM[30] range of 4.5 to 8.4 m.

B/GM	7	8	9	10	11	12	13+
deck high	1.56	1.40	1.27	1.19	1.11	1.05	1.00
deck low	1.42	1.30	1.21	1.14	1.09	1.04	1.00
hold high	1.26	1.19	1.14	1.09	1.06	1.03	1.00
hold low	1.15	1.12	1.09	1.06	1.04	1.02	1.00

Table 4: Correction factors for B/GM<13. (Source: CSS code)

	Aft	Mid	Fwd	Long. acc
	Transverse accelerations (m/s²)			
deck high	6.1	5.76	6.33	2.09
deck low	5.08	4.77	5.24	1.6
hold high	4.10	3.75	4.31	1.1
hold low	3.48	3.16	3.74	0.8
Vertical acc.	4.19	2.37	4.19	

Table 5: Calculated accelerations in m/s² for the MSC ZOE at GM between 4.5 and 8.4m. (Source: MARIN)

Summarizing the results (see table 5), the deck cargo should be secured to withstand transverse accelerations of 5 m/s² at deck level up to 6.33 m/s² higher in the tiers. Vertical accelerations should be limited to 4.2 m/s² at bow and transom.

However, it has to be noted that:

- the length of the MSC ZOE (397 m) exceeds the application range of the correction factor formula (50 – 300 m),
- the operational GM of 10.23 m exceeds the valid range of the GM correction table,
- the methods described should be applied to non-standardized cargoes, but not to containers on containerships.
- The accelerations in CSS-Code Annex 13 have never been applied in container lashing calculations[31] on container vessels as the design acceleration approach in class rules needs to be applied consistently in conjunction with the lashing force calculation algorithm.

This means that this part of the CSS code is not to be used to calculate the design accelerations for the MSC ZOE or other ULCS with a Lpp >300 m.

[29] This table is also stated in the CSM of the MSC ZOE.
[30] The relevant GM for the accelerations is actually the SOLID GM.
[31] According to the statement of DNV GL SE.

In the bays with damaged or lost containers, broken twistlocks were found. Also bent or deformed lashing rods and turnbuckles were found, as well as broken mounts from the lashing bridges with the turnbuckle still attached. The damages found are an indication for overstress fractures.

Parts of the CSS code are not applicable for ULCSs like the MSC ZOE. Although containerships experience similar accelerations, according to the CSS code the method to calculate the design accelerations should not be applied to containers on containerships. Besides this, the length of the vessel exceeds the applicable range of the correction formula. Also the operational GM of the MSC ZOE exceeds the valid range of the GM correction table.

The acceleration and lashing force calculations are performed with the lashing software in the loading computer by means of an algorithm. Therefore it's not always clear for the crew which maximum accelerations the system of containers and lashing equipment needs to withstand.

4.5 Loading computer

Due to the range of GM values and stack configurations, the calculations needed to determine securing loads are too complex to do manually. The loading computer on board the MSC ZOE had to offer guidelines on loading, stowage control, operational functions, ballast distribution and stability (software Total Soft Bank CASP). The lashing software, being a module of the loading computer, calculates the actual loading condition.

The software uses the actual stow configuration and relevant GM and the vessel dimensions to determine securing loads. The loading computer displays clear warnings if certain loading limitations are exceeded.

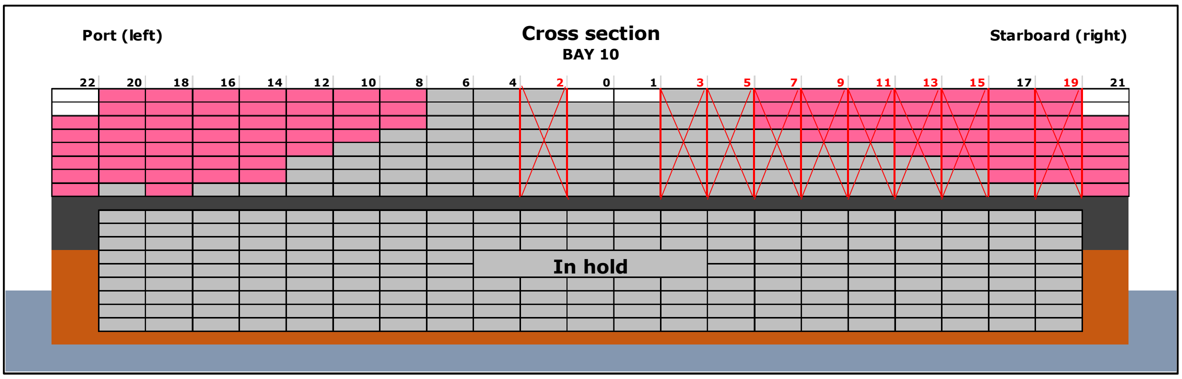
In the manual of the lashing software on board the MSC ZOE, six possible reasons are mentioned in case warnings appear. The warnings are displayed as red boxes in the bay plan:

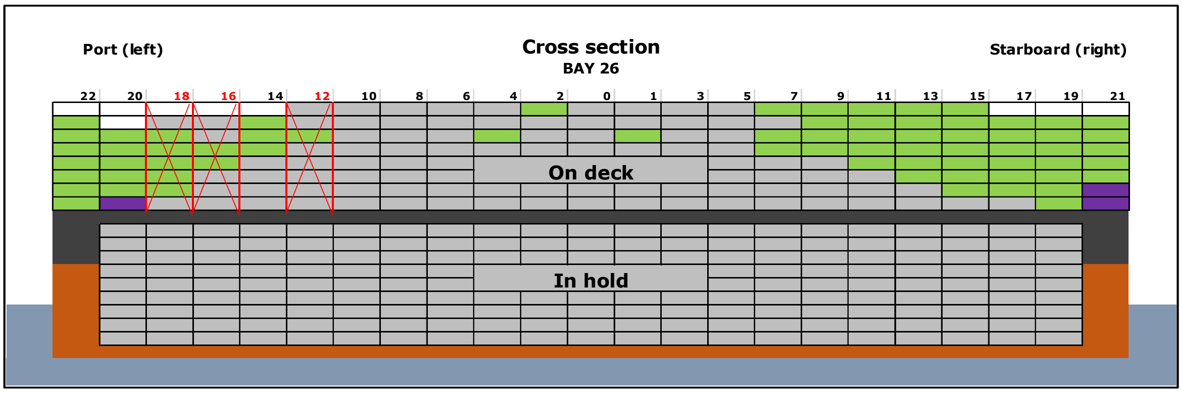
- Racking force
- Side wall racking force
- Vertical tension
- Vertical compression
- Corner post load
- Shearing force at twistlock

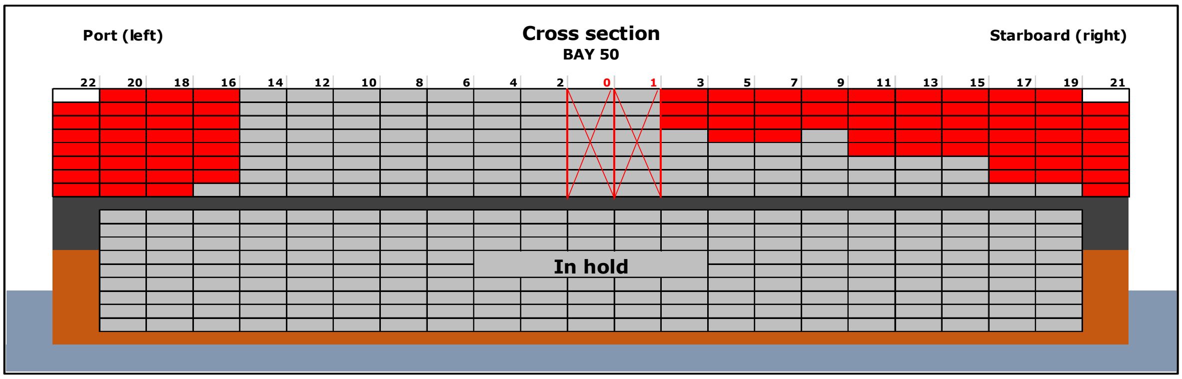
The loading computer was tested and approved by classification society DNV GL SE. During approval of the loading computer by the classification society, they accept a deviation of calculation results of 1%. The most loading computers alert the user as soon as the above mentioned strength ratings are exceeded. The utilisation of the strength ratings implemented in the lashing computer software is shown in either numerical values or percentage. The printed report shows numerical values whereby limits are noted in the header. In addition, the lashing condition check gives an overview of exceeded forces of each strength rating in percent per bay. According to DNV GL SE, the classification society bases the software on pre-described design limits from motion analysis which has been carried out for different container vessel designs for over 20 years and on overall design accelerations. In extreme cases, excess of strength ratings may lead to collapse of container stacks or loss of containers over board. The calculation method of how accelerations and other external forces are translated into lashing forces is described in DNV GL SE rules. Details of the loading computer and lashing software modules, however, are due to the complexity of the calculations not fully transparent. It is not referenced how the inertia and wind loads are translated into securing loads, stack tipping, racking and compression forces etc..

Red warning boxes

During the on-site investigation in Bremerhaven the loading computer on board the MSC ZOE indicated, for the accident voyage, red warning boxes in bays 10 (9/11), 18, 26, 30, 50, 62 and 70. A red warning box indicates an exceedance of any of the tolerance limit of one of the six possible reasons listed above. The exceedance of the tolerance limits where, however, not further specified. From bay 10 (9/11), 26 and 50, which showed red warning boxes based on the information retrieved in Bremerhaven, containers fell overboard. But bays 42 and 58, where containers also have been lost, did not have any red warning boxes.







The standard practice for loading plans on board MSC operated vessels is that the vessel's crew first checks the pre-stowage plans (these are the provisional plans which are sent to the vessel prior to arrival in port) for ship stresses (bending moments, shear forces and torsion forces), calculating the ship's stability as well as verifying stack weight limitations. They are in close co-ordination with the loading terminal and planning office for any possible changes of the provisional plan during the loading operations. Such changes always occur, because it is technically impossible to allocate containers to their final stowage positions during the pre-stow planning. Therefore, terminals are to inform the planning office and the crew in case weight distribution of the container stowage is altered significantly. In order to ensure that the right parameters are used for the calculations, all plans are reviewed by the planning office and the vessel's crew. After loading, the departure plan is obtained from the terminal and loaded in digital format into the loading computer on board. The container data are automatically loaded into the computer through standard EDIFACT (.edi) files and no data is entered manually.

Despite the preparation for the voyage from Sines to Bremerhaven, the loading computer on board the MSC ZOE indicated red warning boxes in bays 10 (9/11), 18, 26, 30, 50, 62 and 70. During the safety investigation, it was not possible to determine which limits had been exceeded. In the lashing software of the loading computer the applicable service area can be selected by a tick box (eg *Asia-Europe*). Depending on the area of operation, parameters used for the calculations may differ. MSC provided a simulation with the lashing software based on the loading condition of the accident voyage. The simulation showed a clear difference when ticking the box *Unrestricted service* or *Asia-Europe* in the service area menu. However, the displayed values as seen during the on-site investigation could not be reproduced afterwards, because it was not feasible to retrieve all used settings. MSC states that changing a few tick boxes in the computer may change all the calculations and this could have happened on board the MSC ZOE, since many people had been working on the computer, before the investigators were shown the data in Bremerhaven.

Based on the information retrieved during the investigation in Bremerhaven and questions asked to MSC, MSC presumes that the software on the loading computer in the cargo office was probably not set for the right service area. The computer that was shown during the investigation may not have had the service area *Asia-Europe* selected for the calculations. However, the simulation with the service area *Asia-Europe* also showed red warning boxes, but in different areas.

The MSC ZOE had several loading computers with lashing software. At least there was one on the bridge and one in the cargo office. During the investigation in Bremerhaven, the loading computer in the cargo office was shown to the investigators. It could not be determined why the investigators were shown the computer in the cargo office and not the one on the bridge or whether the computers had the right service area selected for the current voyage. Therefore, it can't be determined if the MSC ZOE sailed with the correct settings in the lashing software on the loading computer.

MSC states that they always aim to avoid excessive forces, which are forces in excess of the set limits (100%). However, this may not always be achievable because of stowage restrictions, terminal changes to the plan etc. In such cases, they carry out a risk assessment to check whether some excess is justified. The reasons for justifying some local excess are laid down in the fact that the set maximum permissible value for the lashings are the Safe Working Loads. For instance, 120% would mean that the forces are still operating within the safety margin between the Safe Working Load (100%) and the load at which lashings are actually expected to fail (200%).

MSC suggests that data shown to the investigators was incorrect (accidental changes before shown to the investigator, wrong loading computer, incorrect settings). The investigators therefore conclude that the loading computer shown to the investigators indicate excess of tolerance limits without further specification and that it cannot be determined whether and if so how these excess of tolerance limits have been recognized and addressed. The simulation with the service area *Asia-Europe* also showed red warning boxes, but in different areas. The red warning boxes indicated in the loading computer or the simulation do not predict the loss scheme, but in the red crossed areas where containers were lost, imperfections in loading status may have contributed to the accident, as it may have made the bay and/or specific stack more vulnerable to excessive forces.

Both the loading computer of the MSC ZOE shown to the investigators and the post-accident simulation indicated red boxes based on the loading condition of the accident voyage. This indicates that one or more tolerance limits were exceeded. The red warning boxes, however, do not predict the loss scheme, but in the red crossed areas where containers were lost, imperfections in loading status may have contributed to the accident, as it may have made the bay and/or specific stack more vulnerable to excessive forces.

Use of the loading computer on the MSC ZOE

In paragraph 4.4, it was mentioned that the CSM of the MSC ZOE states that the stowage and securing system as described in the manual is designed under the conditions of GM<=2.08 m. It also notes that if the ship is operated with larger GM-values, the expected accelerations will increase accordingly. Therefore, if a GM-value greater than 2.08 m cannot be avoided, a reduction of stack masses or stack heights or a shifting of masses to lower tiers in the stack should be effected.

The lashing system of MSC ZOE as a standardized system is designed for any loading condition within the operational range of the vessel. However, the condition shown in the CSM, calculated for a maximum GM of 2.08m, is a sample condition. Manual recalculation of lashing conditions is not possible anymore as each actual loading condition is very individual. The use of lashing software is essential, all calculations and validations regarding safe working loads are thus done by the loading computer. The container securing arrangement part of the CSM may not be relevant for actual loading conditions, however it is, among other things, used as a basis for approval of the lashing computer system. Therefore it cannot be checked whether the containers are secured in accordance with the regulations of the Cargo Securing Manual (CSM) and the rules and guidelines regarding lashing have been complied with.

Yet, the details of the loading computer and lashing software modules are not fully transparent. The CSM does not elaborate on the procedure that is followed inside the lashing computer to calculate most probable accelerations levels for a given loading condition and GM value. That approach is approved by DNV GL SE since the extensive method of calculations can be found in the class rules.

The requirements of the CSM are not suitable for ultra large container ships, as the CSM does not match with the stability booklet concerning the loading conditions. In most of the loading conditions of the MSC ZOE, calculations and validations regarding safe working loads are done by the loading computer, because the GM exceeds the GM in the sample condition of the CSM.

The details of the procedures in the loading computer and the lashing software are not elaborated by the CSM. The calculation method of how accelerations and other external forces are translated into lashing forces is described in DNV GL SE rules. Details of the loading computer and lashing software modules are due to the complexity of the calculations not fully transparent. It is not clear which design accelerations are incorporated in the calculations in the software.

5 DEVELOPMENTS OF CONTAINER SHIPS

5.1 Container ship growth

The increase in world trade has largely contributed to the enormous growth in sea traffic. Due to this growth, the market has developed ever larger containerships. Their numbers and size have increased rapidly over the last 60 years; the first container ship with a capacity of 60 containers to the largest now called Ultra Large Container Ship (ULCS). This is the generic name for container ships with a nominal container capacity of 10,000 TEU and over. The MSC ZOE was with a capacity of 19,224 TEU a ULCS. The capacity of the individual ships doubled over the last 15 years (see figure 29).

The vessels grew in size like length and beam, but also in stack height. The growth of capacity resulted in container ships carrying more containers on deck. In 2018, 451 ULCS were sailing worldwide with an expected 129 more to be delivered in 2020.

Figure 29. Container ship growth (Source: Safety and Shipping Review 2019, Allianz)

Most containerships operating on the route the North Europe-Far East and vice versa are ULCS larger than 18,000 TEU. The size of a ULCS has some practical limits, only a few ports can handle them. The harbour limitation with regard to the berth length, air draft under the gantry crane or diameter needed for turning inside the harbour are limiting factors.

Structural design of ULCS

The structure of the containership is characterized by a large deck opening. This and the ever increasing length and width of the structural design of ULCS container ships result in an increased sensitivity to torsional and horizontal bending loads. Containerships are not rigid; they respond to the wave-induced periodic loads. Due to the waves, the motion of the ship and cargo, the dynamic forces are reacting on the hull in different forms and directions.

Longitudinal stress: Hogging and Sagging
Hogging occurs if the wave crest is considered at mid-ships. The buoyancy in this region will then be increased. With the wave trough positioned at the ends of the ship, the buoyancy here will be reduced and together with the loading condition the maximum bending moment will occur. The ship is in a hogging position.

Figure 30: Ship in hogging position. (Source: Ship Knowledge, K. van Dokkum)

Sagging is the opposite of hogging. The ship is supported at the ends by the crests of waves while the middle remains unsupported.

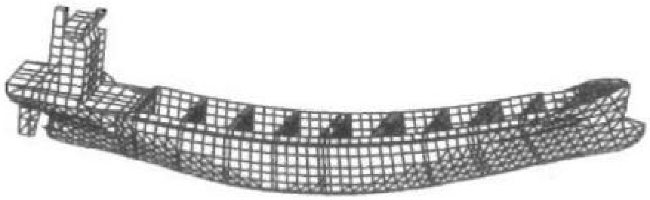


Figure 31: Ship in sagging position. (Source: Ship Knowledge, K. van Dokkum

Transverse stress: Racking
Racking occurs when a ship rolls in a seaway. It results in forces in the structure tending to distort it transversely and may cause deformation at the corners. The deck tends to move laterally relative to the bottom structure, and the shell on one side to move vertically relative to the other side

Torsional stress:
The torsional moment has two main components: static torsion or still water torsion (depending on the loading of cargo), and dynamic torsion or wave induced torsion. A ship heading obliquely to a wave will be subjected to righting moments of opposite direction at its ends, twisting the hull and putting it in 'torsion'. In ships with extremely wide and long deck openings, like large containerships, these torsional moments and stresses are significant. The magnitude and distribution of the torsional moments depend also on the direction of ship advances relative to the encountered waves.

Whipping stresses:
Whipping of a ship is the rapid flexing of the hull as a consequence of a wave impact on the hull. Impulsive forces that arise when severe pitching results in slamming (pounding) cause the ship to vibrate at its natural frequency. High stresses can result from this action.

The stresses and accelerations are imposed from the ship onto the container stack. They cause static and dynamic responses in the container stack. Cargo lashing and deck fittings have to accommodate these stresses and motions. Measurement done by several projects[32] indicate:

- The cross-deck structure may move by as much as 50 mm as the containers surge forward and aft as the ship makes its way through a head or stern quartering sea. The hull twists, distorting the hatch openings.
- Overall hull bending amplitudes as obtained from accelerometers from a 350 meter containership suggest bending deflections in the order of 1 to 2 meters and a hog-sag deflection of around 1.4 m.
- Shape distortion of the hull which stretches the container supports;
- Extra local accelerations imposed from the hull onto the cargo.
- Due to bending of the hull, cargo hatch motions around 2 cm may be expected
- The flexible response was found to add seriously to the actual accelerations loads.

The main conclusion with respect to bending deformations is that vertical bending deflections can be expected to increase the induced vertical accelerations by 40% to 50% compared to the rigid body accelerations alone.

The calculation of these forces is clearly a very complex matter.

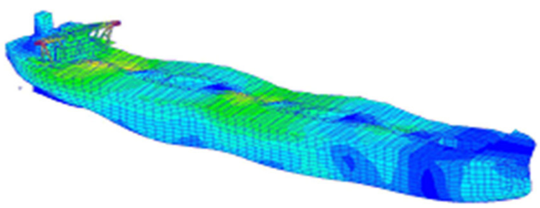


Figure 32: Simulation in hull vibration (Source: JMU)

In the last 15 years, the size of containerships has increased and the capacity of individual ships doubled. The structural design of an ultra large container ship has large deck openings which makes them sensitive to torsional and horizontal bending loads. The flexible response of the ship to dynamic forces cause accelerations in different locations and directions, with different strengths and are imposed from the hull onto the cargo. The calculations for these accelerations are complex.

[32] NNPC and Lashing@sea

5.2 Influence of GM

Ship stability is the extent to which a ship can restore itself after being unbalanced. Stability depends on the shape of the ship (ship design) and the loading (the operational condition).

A ship's ability to return to its original equilibrium position is determined by the moment between the ship's center of gravity (G) and the center of buoyancy (B), see figure 33:

- G is the center of gravity of the entire ship including cargo;
- B is the center of buoyancy, the center of gravity of the part of the ship that is submerged underwater;
- M is the metacentre, at the intersection of the line of the upward force and the centerline of the ship.

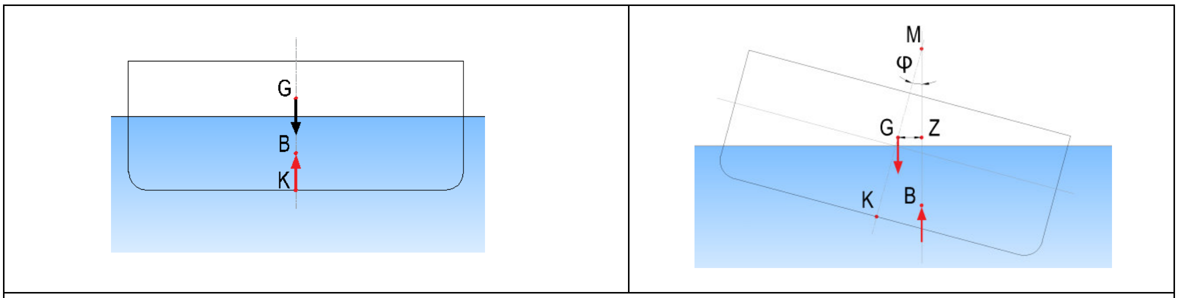


Figure 33: Centre of Gravity, centre of Buoyancy and Metacentre

In the equilibrium situation, the center of gravity (G) and the center of buoyancy (B) are on top of each other, so that the forces are aligned. When the ship is forced to heel over to one side, the shape of the submerged body changes, as does the position of the center of buoyancy (B). Gravity and the upward force are no longer in line and this creates a moment.

The metacenter height (the distance between G and M, also called GM) is a measure of the ship's ability to return to equilibrium. The larger metacentric height, the higher the stability of the vessel. A ship with a very large GM, excessive stabile, is called a stiff ship. The characteristics of a stiff ship would be a very short rolling period, which means the ship would after heeling return to upright very quickly, which leads to motions which are uncomfortable for the persons on board. If the GM is small, a so-called tender ship, she will swing further, but slower, making it more comfortable to sail on. The ship’s GMis a key factor influencing the forces and accelerations acting on containers and their securing system while the ship is at sea.

High stability condition of the MSC ZOE

The trim and stability booklet is a stability manual which has to be approved by the classification society, in this case DNV GL SE, and has to be used by the captain to be able to operate the ship safely. It contains among other things the

- Intact Stability: Vessel stability in normal situation
- Damage Stability: Vessel stability when a compartment floods[33]

[33] Due to breach of the hull

- Longitudinal Strength: The structural design of the vessel when it is floating in still water or in waves
- Container stowage information
- Calculation of draft[34] and trim[35]
- Visibility table
- Freeboard[36]
- Tank capacity

The stability information on board should cover foreseen operating conditions. The IMO standards require a minimum GM, however, not a maximum. At the time of the accident, the average draft of the MSC ZOE was 12.4 meters. With this draft, the minimum GM found in the table in the stability book has to be 3.5 meters.

The sample conditions in the CSM are based on a GM of <=2.08 m, the loading computer on board should be used for any different GM to make the corresponding calculations. The MSC ZOE sailed with a solid[37] GM of 10.23 m which was corrected for (partly) filled tanks, the so-called free surface correction. The corrected GM of 9.01 m was used in the loading computer. Thus the MSC ZOE sailed with a high stability.

The table from the stability booklet confirms that although a solid GM of 10.23 is considered a high value, this was not an unusual condition for the MSC ZOE (see figure 34).

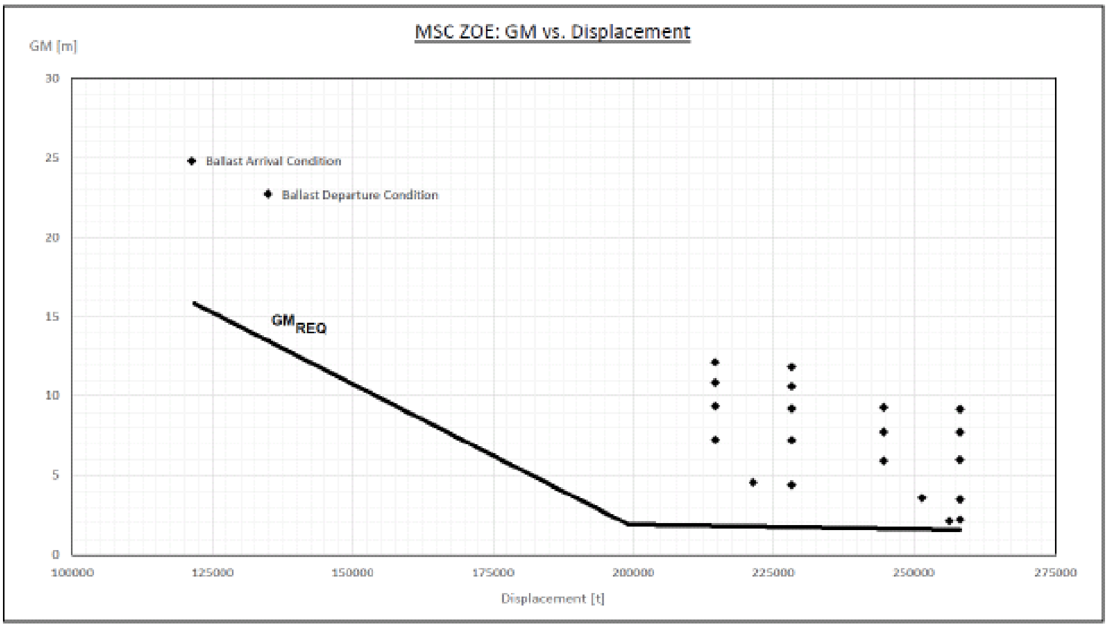


Figure 34. Summary of stability booklet loading conditions of MSC ZOE (Source: TUHH)[38]

[34] Draft of the ship's hull is the vertical distance between the waterline and the bottom of the hull (keel).
[35] Trim is the variation in draft forward and aft of the vessel.
[36] A vessel's freeboard is the distance from the waterline to the upper deck level.
[37] A Solid GM is calculated with a center of gravity which is not corrected for the free surface effect. The effect of the liquid inside the tanks in the vessel can result in a displacement of the center of gravity.and therfore give a different GM. The relevant GM for the accelerations is the Solid GM.
[38] The displacement of a ship is its weight based on the amount of water its hull displaces at varying loads.

Influence of GM on the roll motion

The roll motion of a ship can be influenced by waves exciting the ship. When considering the roll motion of a ship, two parameters are important for the period at which the ship will oscillate after it has been excited by a wave:

- the wave period;
- the natural period of motion of the ship.

As with all mechanical systems, a resonance situation will occur if the excitation period approaches the natural period of the ship. Figure 35 depicts an example wave spectrum and roll response function of a ship. The roll reaction of the ship will increase when the peak of ship's roll response function is closer to the peak wave period encountered.

A ship's GM has an effect on this roll response function. MARIN states in its report (Appendix D) that present-day ULCSs show relatively high stability in roll because of their large beam and a fairly low position of the centre of gravity due to the stowage plans applied. As a result, these type of ships are more likely to show a higher roll response to wave periods present in the North Sea north of the Wadden Islands.

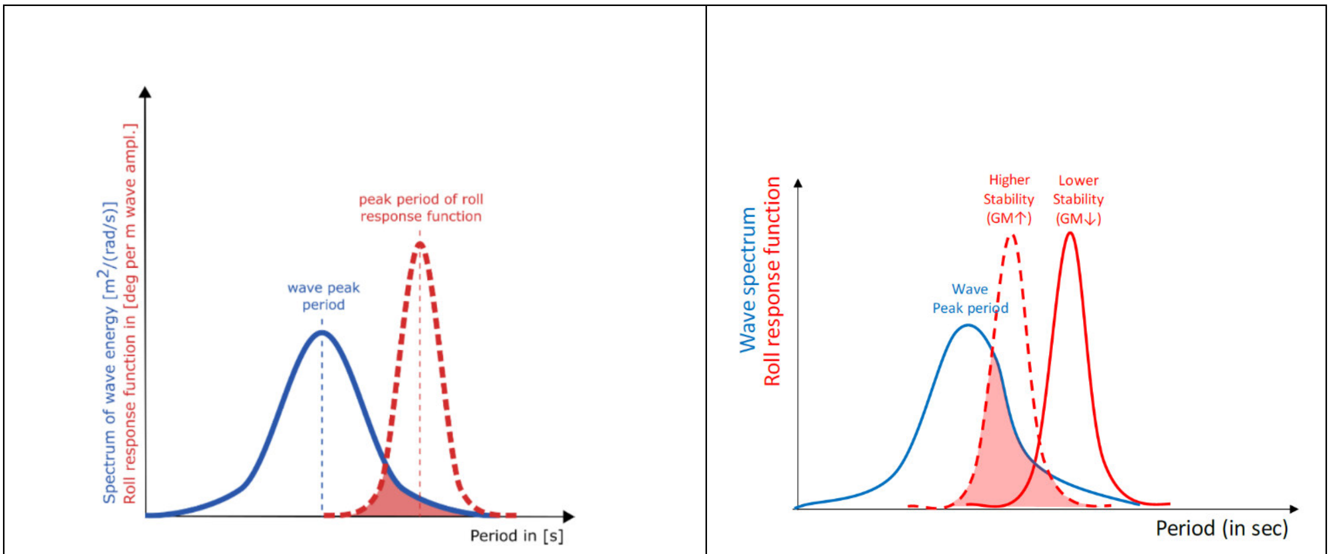


Figure 35: The shaded area below the wave spectrum (blue) and response function (dash-red) determines the roll reaction of the ship on the wave spectrum [Source MARIN]

As a result of the higher roll response, strong ship movements lead to large accelerations on the containers and lashing systems on the deck of the ship. The lashing systems present on ULCS container ships are the same as on all other types of container ships however, the lashing system (configuration) should take the larger accelerations into account.

The roll motion of a ship is influenced by roll damping. The following factors are relevant for roll damping: forward speed, ship hull form, bilge keels and anti-rolling tanks. The report of the TUHH (Appendix E) demonstrates the effect of ship speed on the roll angle and depicts the results of the numerical calculations performed for different ship speeds. An increase in ship's speed, increases the damping forces, which results in a decrease of the accelerations.

The BSU has also asked the TUHH to study the effect of bilge keel sizes on the roll damping and resulting lateral accelerations. The result are also presented in Appendix E. It suggests that larger bilge keels may reduce accelerations. The TUHH concludes that larger container ships as the MSC ZOE may have insufficient roll damping in situations with large stability. These findings on sensibility for speed and size of bilge keels further add to the problem of roll motions of high stability ships in wave periods to be experienced in the sailing routes north of the Wadden islands.

Some points mentioned here have been known for a longer period and had already been dealt with within the scope of the accident investigations, e.g. by the BSU in the cases of the CHICAGO EXPRESS in 2008 and the CCNI GUAYAS in the following year[39]. However, corresponding safety recommendations were not implemented.

Research and development in safety

Previous research projects have looked into lashing loads on containerships. The Lashing@sea project started in 2006 and took three years to investigate how to innovate while maintaining and/or improving safety standards. It was a joint industry project and addressed safety and efficiency for container ships, RoRo ships and Heavy lift transport ships. Observations from Lashing@sea project regarding container ships were:

- A number of unexplained incidents with cargo losses indicated that "new" phenomena may have reduced safety levels.
- Container transport was growing dramatically from 4000 to 15000 TEU and from 4/5 layers to 7/8 layers. The rules for stowing containers have remained the same.
- Dynamics from the flexibility of the ship and interaction between adjacent rows are identifiable factors that can endanger the loaded containers. The project found that accelerations on a ship can be amplified by 50% because of the ship's hull flexing compared to rigid body response .
- Container stack dynamics: On properly secured rows the effect of one or two rows that are destabilised by adding weight and loosening lashing, was dramatic; loads increasing up to 200%.
- Reliability of loaded situation may deviate, which means that critical limits can be exceeded.
- Feedback from interviews with crew found that some 50% said it was difficult to judge the force of developing wave and cargo loads on very large container vessels from the bridge. This makes it impossible to evaluate while sailing whether loads remain in safe limits and when preventive action to avoid damage is needed.

[39] See BSU-reports 510/08 and 391/09, both published on www.bsu-bund.de

Inspired by these results (among others) proposed measures to prevent loss of containers were submitted by Australia, The Netherlands and Demark at the IMO in 2011 (MSC 89/22/11).

The following outputs were envisaged:

- amendments to SOLAS regulations VI/2 and VI/5.5, strengthening the requirement that shippers verify that the gross mass of units is in accordance with the gross mass declared on the shipping documents and that containers shall not be loaded to more than the maximum gross weight indicated on the Safety Approval Plate (to be developed by the DSC Sub-Committee);
- guidelines on the appropriate stowage and vertical weight distribution in the container stacks (to be developed by the DSC Sub-Committee);
- a unified interpretation on cargo securing, which takes into account environmental conditions such as wind, sea state and accelerations (to be developed by IACS on request of the Committee, for consideration by the DE Sub-Committee); and
- a feedback instrument and guidelines for the crew on dealing with extreme GM conditions (to be developed by the SLF Sub-Committee in cooperation with the STW Sub-Committee, if and where applicable).

This has led to the following safety developments:

- SOLAS requirement (2016); Containers have to have a verified weight before loading onto a ship for export. (MSC.1/Circ.1475)
- Amendments ISO standard 3874 (2017); Freight containers-Handling and securing
- Amendments CTU Code(2014); Code of Practice for Packing of Cargo Transport Units (MSC.1/Circ.1497)
- Amendments CSS Code(2014); Cargo Stowage and Securing Code (MSC.1/Circ.1352/Rev.1)
- Amendments CSM (2014) Cargo Securing Manual Revised guidelines for the preparation of the Cargo Securing Manual, (MSC.1/Circ.1353/Rev.1)
- Revised guidance to the master for avoiding dangerous situations in adverse weather and sea conditions (MSC.1/Circ.1228)

And in November of 2009, the World Shipping Council (WSC) and the International Chamber of Shipping (ICS) published “Safe Transport of Containers by Sea: Guidelines on Best Practices”.

Observations from the Lashing@sea project still open:

- Reliability loaded situation may deviate, which means that critical limits can be exceeded.
- Design limits may be exceeded: The crew is expected to prevent extreme accelerations from parametric oscillation, dynamic loss of stability, resonant oscillation and impulsive loads by slamming or pounding. These mechanisms are therefore not included in the design principles. Due to the size of the ships, the crew has less and less feeling for the ship. There are less control options due to limited ballast options and extreme GM.

- Acceleration by deforming of the hull. The modern container ships are so large and flexible that their own vibrations come close to the wave periods they encounter. As a result, the hull can vibrate above the normal design load.
- Adjacent stack of containers are calculated separately from each other. In practice, these stacks lean against each other and in heavier weather they go back and forth and collide. Model tests have demonstrated that multiple stacks can resonate and collapse when the ship's natural vibrations have the same frequency as the natural frequency of the stacks of containers.

The MSC ZOE sailed with a corrected GM of 9.01 m, thus the MSC ZOE sailed with a high stability which is not unusual for ULCS-type vessels. Therefore the MSC ZOE was more likely to show a higher roll response to wave periods which can occur also in the North Sea north of the Wadden Islands. As a result of the higher roll response, strong ship movements lead to large accelerations on the containers and lashing systems on the deck of the ship.

Large bilge keels reduce accelerations. The TUHH concludes that container ships as the MSC ZOE may have insufficient roll damping in situations with high stability. These findings on sensibility for speed and size of bilge keels further add to the problem of roll motions of high stability ships in wave periods as the MSC ZOE encountered in the sailing routes north of the Wadden Islands.

The lashing systems present on ULCS container ships are the same as on all other types of container ships. They do not take into account the higher accelerations that can occur due to the higher roll response.

Not all results of the Lashing@sea project which indicate serious risks pertaining to exceeding limits, resonance of the ship with waves and resonance of the stacks with the ships have led to regulatory changes or different practices.

6 SEA CONDITIONS AND SHIP MOTIONS

The MSC ZOE lost 342 containers in the shipping route north of the Wadden Islands. Previous chapters described the sequence of events and the loading conditions of the ship. Understanding the environmental conditions the MSC ZOE encountered and the ship's motions are essential in understanding the events.

The conditions the MSC ZOE encountered have been further investigated. This chapter first sets out the environmental conditions during the night of 1 – 2 January 2019. Then, using these conditions, the behaviour of a large containership and the risks of container loss have been analysed. The research performed has revealed new insights in the conditions, ship's motions and hydrodynamic phenomena that may be encountered in this part of the North Sea. The main outcomes are presented in this chapter. The full research reports are included in Appendices C, D and E.

6.1 Environmental conditions

This paragraph first provides information on the weather and sea conditions in the area at the time of the accident, followed by the weather information that was available to the crew on the bridge in the form of forecasts messages communicated through NAVTEX.

6.1.1 Weather

The German National Meteorological Service (*Deutscher Wetterdienst*, DWD) performed a general assessment of the weather in the southern part of the German Bight at the time of the accident (Appendix B). DWD has measurements and observations from various surrounding stations at its disposal as well as ship reports and it uses different weather and sea-state models for the assessment.

The weather on the night of 1-2 January 2019 was affected by a hurricane-force depression of 985 hPa over the Gulf of Finland, which slowly tracked south-east, see the weather chart in figure 36. This was countered by an extensive high of 1045 hPa over Great Britain, which spread to Morocco with a wedge of 1030 hPa. This triggered the development of a brisk north-westerly air flow over the North Sea.

The DWD performed a wind analysis for the accident area in the southern part of the German Bight at respectively 22.00 hours LT (21.00 UTC) on January 1 and 01.00 hours LT (00.00 UTC) on January 2 (see also charts in Appendix B). According to this analysis, the wind approached from roughly 340° (north-northwest) and reached 35 knots (18.0 m/s, 8 Bft) on average and up to 40 knots (20.6 m/s, 8 Bft) around 01.00 hours LT.[40] At the same

[40] Wind force 8 Beaufort corresponds to windspeeds between 34-40 knots and 17.2-20.7 m/s.

time, gusts with wind forces of two over the mean wind (gusts of up to 10 Bft) almost certainly occurred due to the unstable atmospheric stratification.

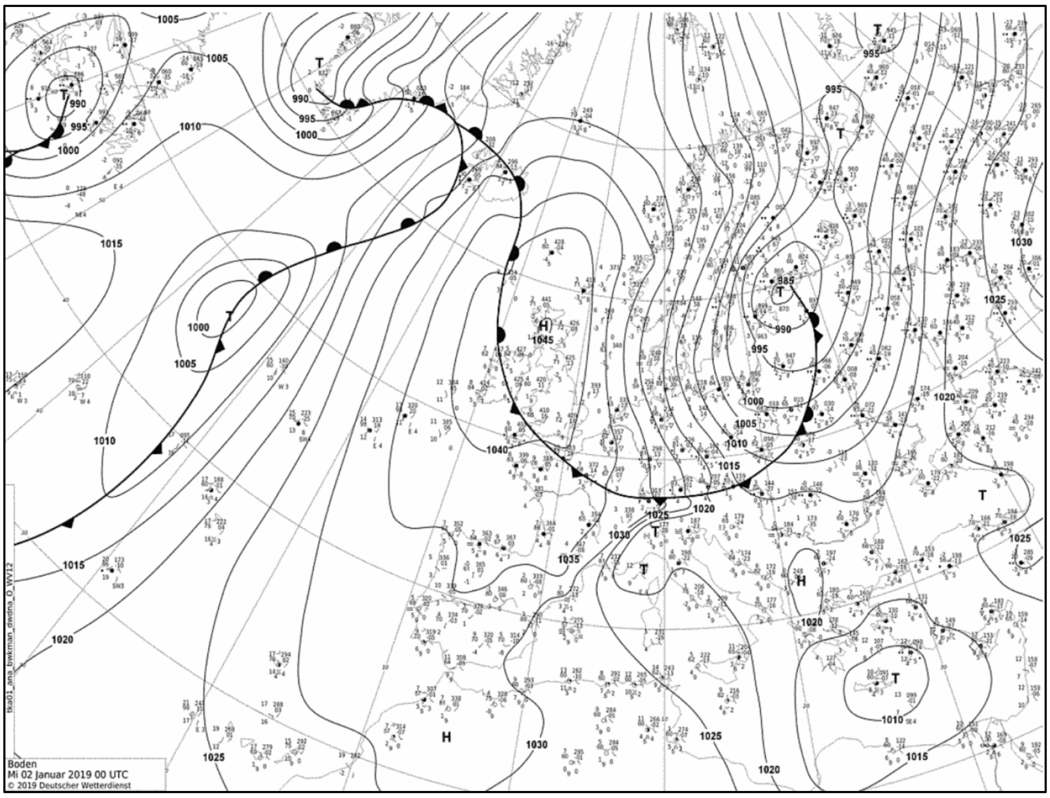


Figure 36: Weather chart: Ground pressure and frontal analysis of the DWD at 0000 UTC on 2 January 2019 (Source: DWD)

The research institute Deltares conducted a study on metocean (meteorological and ocean) conditions on the North Sea on 1-2 January 2019 along the track of the MSC ZOE. The full study can be found in Appendix C. Deltares used numerical models to determine the metocean conditions along the track of the ship and validated their model results with real measurement data of metocean parameters coming from local buoys and platforms. The ship's track (location and timing) was projected on Deltares' model outputs of the environmental parameters. This allowed to establish the conditions the MSC ZOE encountered north of the Wadden Islands along its route.

Modelled wind speed and wind direction along the route of the MSC ZOE are depicted in figure 37. On January 1, the wind direction changed gradually from west to north-northwest. The wind speed increased during the day. At the time of the peak of the storm (around 01.00 hours LT on January 2), the MSC ZOE passed north of Schiermonnikoog.

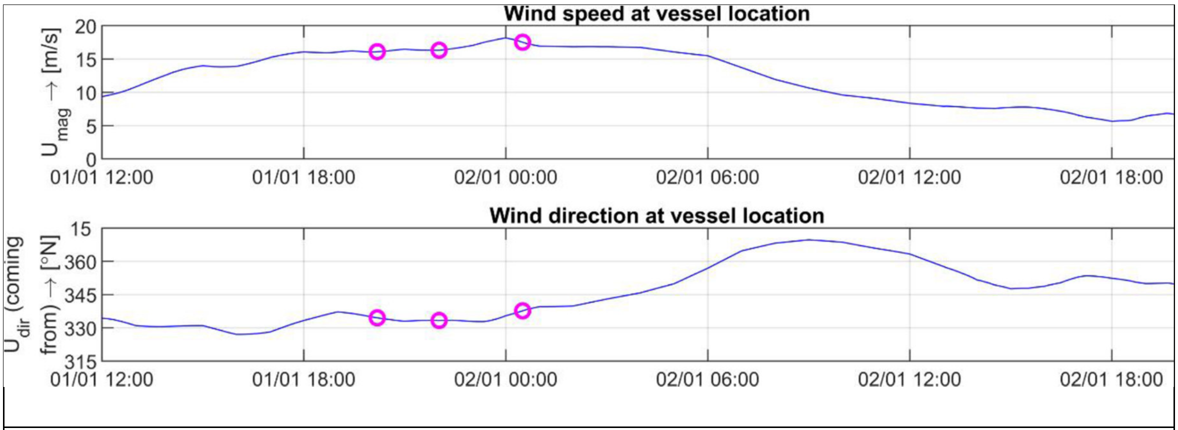


Figure 37: Modelled wind speed and wind direction along the route of MSC ZOE.
Note: time is indicated in UTC (local time = UTC + 1). The circles indicate specific times that were used as input for the basin tests conducted by MARIN.

This data indicates that the hourly averaged wind approached the ship from almost exactly abeam. The wind speeds the MSC ZOE encountered were between 16-18 m/s (up to 8 Bft) with gusts of wind force two over the mean (gusts of up to 10 Bft).

Deltares has performed a statistical analysis on how often these values in the North Sea are exceeded. This analysis shows that these conditions are met and exceeded on average one to two times in a year. Therefore these heavy conditions can be considered neither extreme nor exceptional. [41]

The wind speeds encountered by the MSC ZOE in the TSS Terschelling – German Bight were between 16-18 m/s (up to 8 Bft) with gusts of wind force two over the mean. The peak of the storm occurred around 01.00 hours LT on January 2. The wind approached the ship from abeam. The encountered heavy conditions are neither extreme nor exceptional for this part of the North Sea.

6.1.2 Sea conditions

During the passage in easterly direction through the TSS Terschelling – German Bight, the MSC ZOE encountered heavy wind conditions from north-northwesterly direction. This wind direction on the North Sea enables waves to build-up, as there is a long fetch length available.

A wave can be characterized by wave height (vertical distance from wave crest to trough), wave length (distance between two wave crests), wave period (time between two wave crests) and the direction of propagation. A deep water wave may be described as of sinusoidal shape, see figure 38.

[41] Some underestimations in wind speed were found around the peak of the storm (2 January, 00:00h). This does however not affect the conclusions regarding the exceptionality of the conditions.

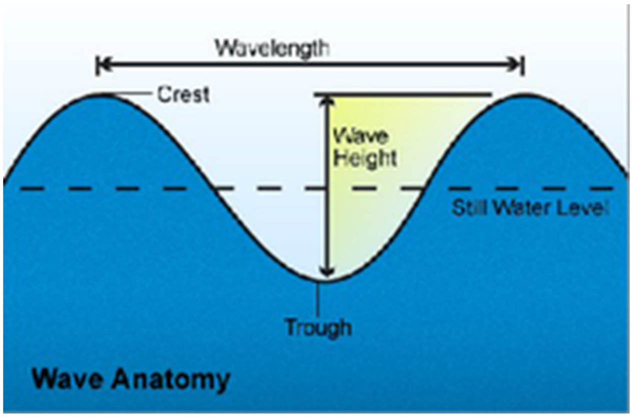


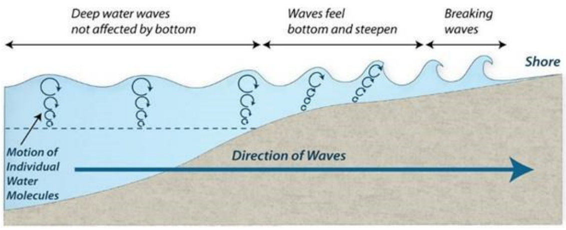
Figure 38: Schematic representation of waves and the wave height and wavelength

A wave field consists of many wave components with different heights and wave periods. The following parameters are used to describe a wave field:

- The significant wave height H_s is a measure to describe the average of the highest one-third of the waves occurring in a wave field. This is considered to be a measure for height of a wave condition in a wave field.
- The maximum wave height H_{max} is the largest individual wave height in 1,000 waves.
- Peak wave period T_p is the wave period at which the highest energy density is present in the wave spectrum describing the distribution of wave energy over the different wave frequencies (wave periods).
- Wave propagation: long-crested and short-crested waves. Different than long-crested waves, short-crested waves in a wave field have more directional spreading. Short-crested waves are more representative of the situation at sea. Long-crested[42] waves are usually considered by the maritime industry as they yield predictions generally thought to be more conservative and their numerical modelling is less complicated[43].

In shallow water, the waves experience the influence of the sea bottom. When a wave approaches the shallower depths in the vicinity of the coastline, non-linear shallow-water effects will influence the shape of the waves. This causes a steepening of the crest and a reduction (and stretching) of the troughs, see figure 39.[44] Breaking or white-capping is more likely to occur for steep waves in shallow water than for less steep waves in deep water. In these shallow water conditions, steep waves occur that can break forward with high velocity at the crest.

[42] The conclusions in this report are based on tests in realistic short crested waves.
[43] MARIN, Behaviour of an Ultra Large Container Ship in shallow water, 2020.
[44] Deltares, North Sea conditions on 1 and 2 January 2019, 2020.



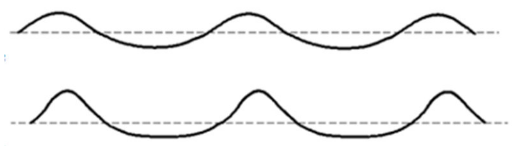


Figure 39: Waves approaching coast (left); and the shallow water effect (right): the sine-like waveform in the open sea (top) changes into shallow water in a wave pattern with high, steep ridges and flat, wide wave valleys (bottom). (Source: Deltares)

The DWD made an assessment of the general sea conditions in the southern part of the German Bight. Overall in the North Sea, the significant wave height (H_s) was about 5.5 meters overall with a wave period (T_p) of 13 seconds, see figures in Appendix B. The maximum wave height (H_{max}) statistically expected was about 10 m.

DWD also assessed that the current initially stood at 1 knots from east to west (270°) in the period considered and veered to 250° by 03.00 hours LT (02.00 UTC) on January 2. It later dropped to 0.7-0.8 kn. Accordingly, DWD concluded that the current had hardly any effect on wave behaviour but rather was almost perpendicular to the swell.

Deltares modelled the wave conditions encountered by the MSC ZOE when it was sailing in the TSS Terschelling – German Bight based on, among other sources, information of three wave buoy and five offshore platforms, see figure 40. The wave height that the MSC ZOE encountered developed with the increasing wind speed. On January 1 at around 15.00 hours LT, at the time that the ship was sailing along the Dutch west coast, the significant wave height (Hs) was 2.5 meters. Five hours later, at 20.00 hours, the significant wave height (Hs) was around 5.2 meters. The ship experienced the largest waves with a significant wave height of 6.5 meters at approximately 01.00 hours on January 2, after passing the island of Schiermonnikoog. The peak wave period (Tp) experienced during the moments of container loss (between 20:00 hours and 01:30 hours LT) were between 11.8 and 12.5 seconds.

The maximum wave height during this time reached up to 11 meters. Deltares considers it probable that along the route the vessel encountered these higher individual waves. Whether or not the vessel indeed experienced this maximum wave height cannot be confirmed, because such individual higher waves can have occurred anywhere in the wave field.

Deltares also concludes that the local wave conditions were influenced by the shallower depths. Particularly the highest and longest waves will have shown steepened and heightened crests and flattened troughs. Non-linear wave behaviour such as white-capping due to the steepened crests did occur along the sailing route, resulting in more complex wave conditions compared to deep water linear waves.

Also the water levels and the corresponding water depths experienced by the MSC ZOE were determined along the sailing track. The results show that during the critical part of the transit, between 20.00 hours LT January 1 and 00.30 hours on January 2, the water level was dropping (ebb tidal phase). The lowest tidal water level occurred around 00.30 hours on January. Overall it can be stated that the water level was MSL[45]+0m to MSL+1m. Because of the positive offset caused by the wind-induced surge present during the storm, the low water level did not go below MSL.

The presence of a wind-induced storm surge, offsetting the total tidal cycle upwards, resulted in water levels not dropping below mean sea level around the moment of low tide. The timing of the water levels, combined with the sea bed levels along the route, resulted in the vessel experiencing relatively small water depths at two locations along the sailed track (around 20-22 m). Water depths experienced could have been even smaller, if the lowest tidal water levels would have occurred while the vessel was at the shallowest location.

Deltares has performed a statistical analysis on how often these values in the North Sea are exceeded. The wave conditions as a result of the storm are exceeded on average one to two times in a year. These conditions can considered to be neither very extreme nor exceptional. [46]

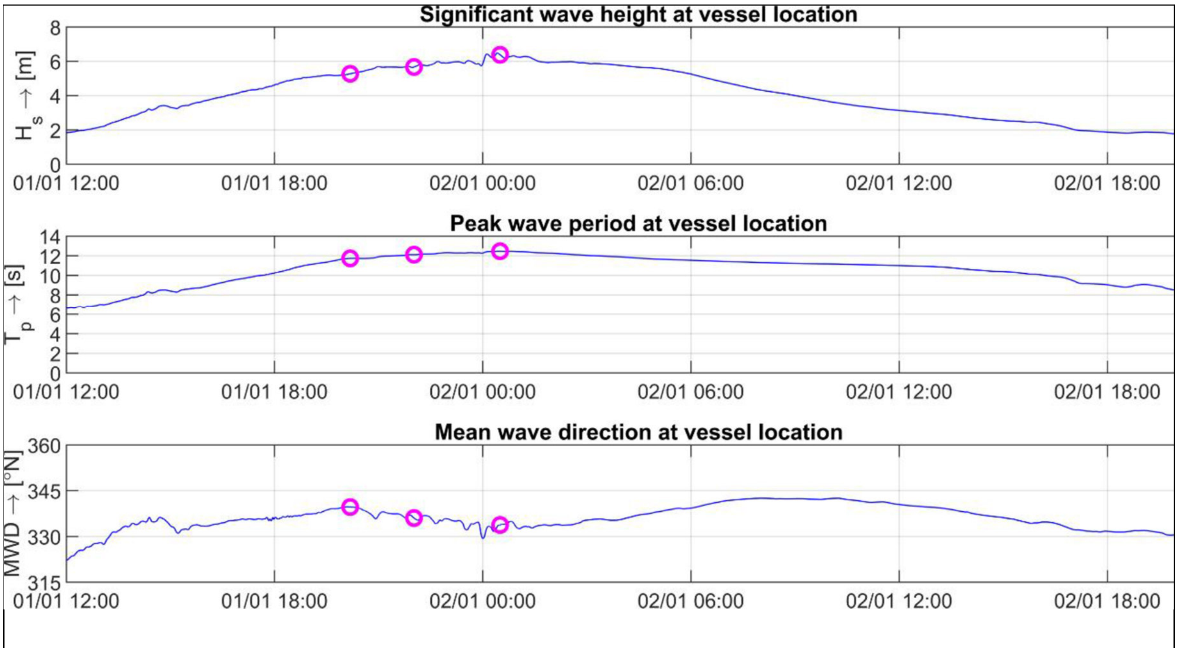


Figure 40: Wave conditions along the route of the MSC ZOE.
Note: time is indicated in UTC (local time = UTC + 1). The circles indicate specific times that were used as input for the basin tests conducted by MARIN.

[45] Mean Sea Level
[46] Some underestimations in wind speed were found around the peak of the storm (2 January 2019, 00:00h). This does however not affect the conclusions regarding the exceptionality of the conditions.

The waves approached the MSC ZOE from abeam. This wind direction allows the waves to build up as there is a long fetch length available on the North Sea. Significant wave height increased from 5 m to 6.5 m at the peak of the storm. The maximum wave height during this time reached up to around 11 meters. The peak wave period encountered was approximately 11.8 - 12.5 seconds. The wave conditions are neither very extreme nor exceptional for this part of the North Sea.

The vessel experiencing relatively small water depths at least at two locations along the sailed track (around 20-22 m).

6.1.3 Weather forecast information available to the crew

Internationally, responsibility for meteorological services and meteorological warnings for ships are laid down in chapter 5 of SOLAS, safety of navigation, published by the International Maritime Organization (IMO). States are required to warn vessels of hard winds, storms and tropical storms, and must broadcast weather forecasts usable by shipping via radio communication services on at least two occasions every day.

Weather forecasts and safety warnings, including weather warnings, are announced to shipping by means of radio communication and NAVTEX reports. In this way, international shipping is kept informed of expectations and warnings. The different States, such as Germany, the Netherlands and the United Kingdom, issue reports and warnings for the North Sea area, resulting in a certain degree of overlap. It is the responsibility of the crew to take note of all safety warnings that apply to the route to be followed by the vessel.

On board the MSC ZOE, the printed NAVTEX reports available to the crew for 1 and 2 January 2019 were documented by the investigators. For the German Bight area north of the Wadden Islands, these were mainly reports from the Netherlands and Germany. A list of the reports is presented in table 6 below.

The forecasts available on the ship were in line with the weather and sea conditions encountered by the MSC ZOE as assessed by both DWD and Deltares. It has to be noted that information on wave periods is not included in the NAVTEX messages.

Received (UTC)	Transmitted	Message
07:01	NAVTEX-Hamburg	German Bight: Northwest about 7, for a time increasing * l*ttle, shifting north. Near hurricane force gusts. Shower, sea 7 metre.
07:44	NL Coastguard	German Bight Fisher Northwest 10
09:08	NL Coastguard	German Bight Fisher Northwest 10

11:00	NAVTEX-Hamburg	For German Bight: Gales Northwest 8 to 9 bft
13:50	NAVTEX-Hamburg	Deutsche Bucht: St*rm Nordwest bis Nord 8 bis * bft.
14:35	NL Coastguard	Forecast Dutch EEZ: German Bight Northwest 10 Forecast valid Tuesday 15:00 till Wednesday 03:00 UTC: German Bight, Northwest 8-9, veering north to northwest and decreasing mainly 8. Risk shower. Good. In precipitation possibly moderate. Waveheight 5.5-7.5 decreasing 5.0-6.5 meter.
15:02	NAVTEX-Hamburg	Weather forecast for German Bight until 02.01.2019 12 UTC: German Bight Northwest 7 to 8, for a time increasing a little, in some areas 9. Shifting North. Near hurricane force Shower Squalls, sea 7 metre.
16:52	NL Coastguard	German Bight Forties Viking Northwest 9
17:53	NAVTEX-Hamburg	DEUTSCHE BUC*T: NW 8-9, N-DREHEND, ABNEHMEND UM 5, ANFANGS ORKANARTIGE SCHAUERBOEEN, SEE 7m
19:00	NAVTEX-Hamburg	FOR GER*AN BIGHT: GALES*NORTHWEST TO NORTH 8 TO 9 *?!5.
19:01	NAVTEX-Hamburg	?? not legible
?	NL Coastguard	GERMAN BIGHT FISHER NORTH TO NORTHWEST 9
21:50	NAVTEX-Hamburg	DEUTSCHE BUCHT: STURM NORDWEST BIS NORD 8 BIS 9 BFT.
22:01	NAVTEX-Hamburg	DEUTSCHE BUCHT: STURM NORDWEST BIS NORD 7 BIS 8 BFT.
23:01	NAVTEX-Hamburg	FOR GERMAN BIGHT: GALES NORTHWEST TO NORTH 7 TO 8 BF*.
23:03	NAVTEX-Hamburg	WEATHERFORECAST FOR GERMAN BIGHT UNTIL 02.01.201* *8 UTC: NO*THWEST TO NORTH*7 TO 8, DEC*EASING ABOUT 5, FIRST SEVERE GALE FORCE GUSTS, SEA FIRST 6 METRE.

Table 6: Passages from NAVTEX reports 1 January 2019 for German Bight, transmitted by the Netherlands and Germany, as documented on board the MSC ZOE.

NAVTEX reports forecasting the wind speed and wave heights were available on the ship. The forecasts were in line with the actual weather encountered. The NAVTEX reports did not indicate information on the wave period in the area.

6.2 Ship's motions

Wind and waves are external forces acting on a ship. A ship moves in response to these forces. The effect on the ship depends on the direction and characteristics (such as magnitude and encounter frequency) of the external forces, the shape of the hull and the stability of the ship. A ship moves along six degrees of freedom, see figure 41:

- Heave, in vertical direction,
- Sway, in lateral direction,
- Surge, in longitudinal direction,
- Roll, motion around longitudinal axis,
- Pitch, motion around lateral axis,
- Yaw, motion around vertical axis.

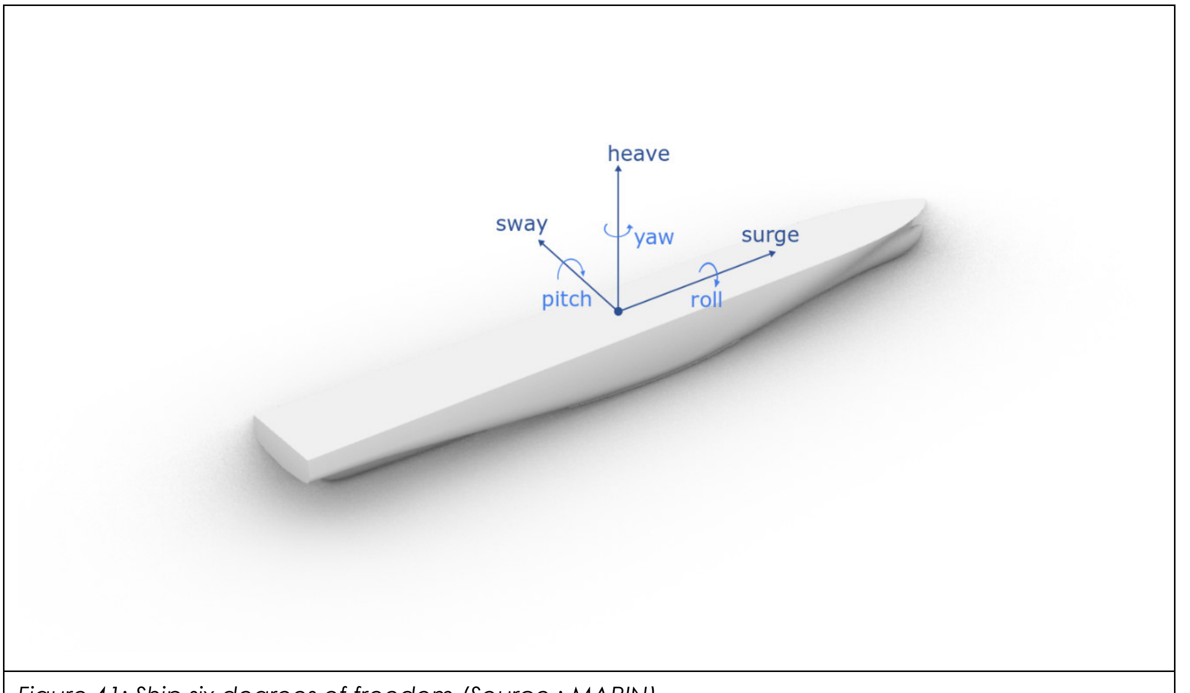


Figure 41: Ship six degrees of freedom (Source : MARIN)

Ship motions induce accelerations and resulting forces in longitudinal, transversal and vertical directions that are experienced by the crew, ship and cargo. For the conditions present during the MSC ZOE accident, wind and waves approaching the ship from abeam, three degrees of freedom are dominant: roll, heave and sway. For a ship that moves due to the waves (see figure 42), the wave force translates into inertial forces (mass), damping forces and restoring forces (stability).

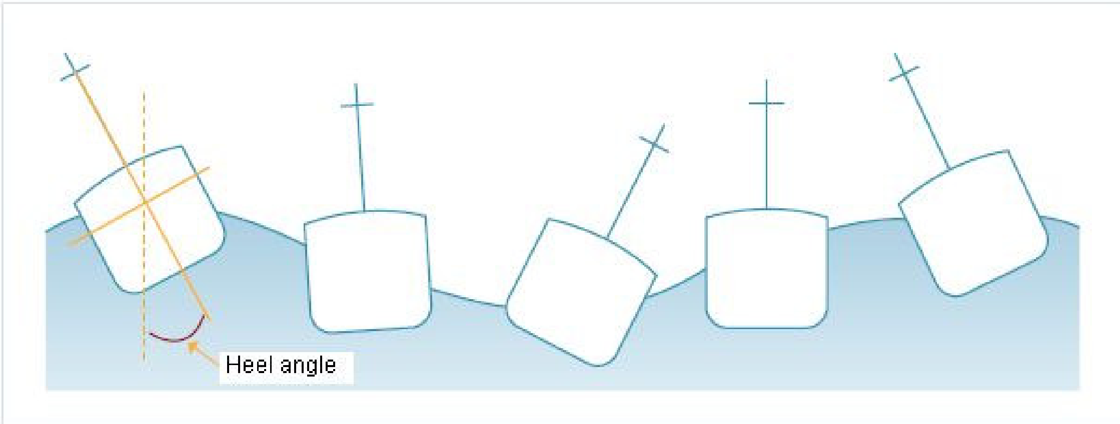


Figure 42. Schematic representation of a ship's swinging motion in transverse waves

Containerships as the MSC ZOE have containers stored on deck. Ship's motions therefore result in accelerations and forces acting on the cargo and the securing devices such as twistlocks, lashing rods and lashing bridges. These forces can result in overload of containers and/or the securing devices with a possible loss of containers overboard.

The previous paragraph presented the environmental conditions the MSC ZOE encountered on January 1 and 2. The ship was sailing in heavy but neither exceptional nor extreme weather conditions: wind force 8 Bft and a significant wave height of 5 up to 6.5 meters and a maximum wave height of around 11 meters, with both wind and waves coming from a north-northwesterly direction. The orientation of the TSS Terschelling – German Bight was such that both wind and waves approached the ship from abeam. The ship was sailing in shallow water, which influenced the shape of the waves.

When the MSC ZOE entered the TSS Terschelling – German Bight, the wind and waves approached the ship from abeam. This resulted in the ship rolling continuously.

A further analysis of the VDR audio recording was done by the investigators. On the recordings of the microphones on the bridge, at certain intervals a peak in amplitude was noticed, caused by shifting equipment moving back and forth. The assumption was made that movement of the equipment was due to the rolling of the ship to such a degree that objects on the bridge would start to shift. Automated analysis was used to determine the roll period and periods where the rolling was most intense (audible to the human ear).

The mean, median and mode all indicate that a full roll period of the ship was approximately 14.7 seconds. Furthermore, based on the audio analysis, figure 43 was created. More intense rolling periods, where the peaks are audible to the human ear, are indicated in red.

When looking more closely at the GPS data, a swaying motion in the track of the ship was observed when it was sailing in the TSS Terschelling – German Bight. The time of a full sway corresponds with the time found through the audio analysis (approximately 14.7

seconds). This swaying motion is not present earlier on when the ship's course was approximately 26 degrees, before entering the TSS Terschelling – German Bight.

Figure 43: Periods where the rolling motion was intense enough to be detectable by the human ear through shifting objects on the bridge are indicated in red. (Source: Google Earth)

6.3 Simulations and model tests

The data from the VDR and the statements made by the crew indicated that the ship was rolling continuously. Understanding the ship's motions is essential in reconstructing the events. Both BSU and DSB consulted domain experts regarding ship's behaviour in sea conditions. Seakeeping calculations and model tests in a basin were conducted, as the VDR of the MSC ZOE did not register data regarding the actual roll motions and accelerations the ship encountered.[47]

For the conditions present during the accident, wind and waves approaching the ship from abeam, three degrees of freedom are dominant: roll, heave and sway. The following aspects therefore have been further investigated by the experts: roll motions, accelerations and under keel clearance. Considering the beam sea scenario the MSC ZOE experienced, parametric rolling[48] can be excluded for the MSC ZOE, as this scenario occurs in head or following seas.

[47] There are VDR systems that register such motions but these are not mandatory.
[48] Parametric roll is a phenomenon occurring in head or following seas, which is characterized by rapidly developed, large ship rolling.

The BSU commissioned the Hamburg University of Technology (TUHH, *Technische Universität Hamburg*) to perform a simulation of the ship's motions and resulting accelerations. The TUHH performed seakeeping calculations by using the code E4ROLLS. A ship model was created according to the dimensions and characteristics of the MSC ZOE. Simulations were performed using a solid GM=10,23m, vessel speed of 10 kn, wave period of 13 seconds and Hs = 5 m.

In addition, the DSB set up a partnership with the research institute MARIN (Maritime Research Institute Netherlands) to conduct model tests in a basin, see figure 44. The aim was to investigate the influence of environmental conditions and the properties of Ultra Large Container Ships (UCLS) in general in view of the risk for the ship to lose containers. As the available prediction methods do not accurately predict the behaviour of ships in shallow water and wave conditions as experienced at the time of the accident, these basin tests were considered essential. For the tests, a wooden scale model of a containership in size and shape comparable to the MSC ZOE was manufactured according to international standards[49]. The superstructure and container stowing were reproduced on the model based on the stowing plan of the MSC Zoe prior to the accident.

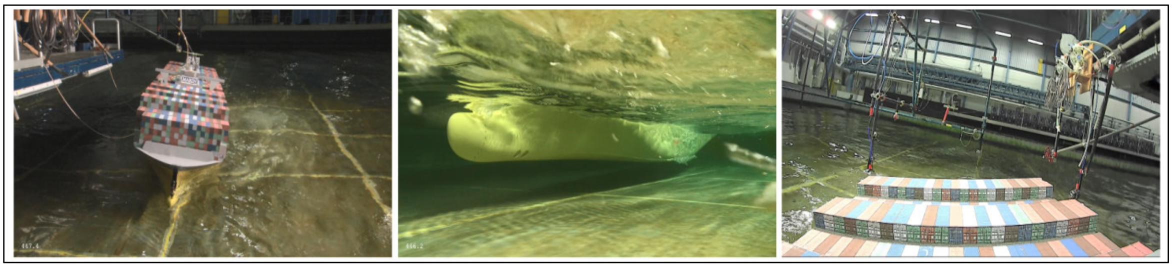


Figure 44: Scale model in MARIN test basin with video above water, underwater and from the bridge (Source: MARIN)

The results of the Deltares study presented in paragraph 6.1 were used by MARIN as input for the study. Different scenarios were tested in a basin with variations in GM[50] (9.08 and 6.0 m), vessel speed (0 knots and 10 knots[51]), water depth (21.3m, 26.6m, 37.5m, 635m) and different combinations of significant wave height H_s (5.2m, 6.5m, 7.5m) and wave period (11.8s, 12.4s, 14.5s). Deltares concluded that their models slightly had underestimated the wind speed conditions. This also influenced the wave conditions. As a solution to the resulting underestimation in wave condition, Deltares recommended MARIN to cover this as part of the tests by considering a set of wave conditions that also included slightly elevated values of H_s (significant wave height) and T_p (peak wave period). The scenarios of the different water depths represent the conditions on the sailing route of the MSC ZOE (21.3 m and 26.6 m), conditions in the TSS German Bight Western Approach[52] (37.5 m) and in deep water (635 m).

[49] International Towing Tank Conference (ITTC).
[50] Corrected GM
[51] Actual speed of the MSC ZOE at the time was between 8 and 10 knots.
[52] The TSS German Bight Western Approach is the TSS north of the TSS Terschelling-German Bight, see also chapter 7 on Routeing.

The reports of the expert consultations can be found in the appendices C, D, and E. A summary of the main results is outlined in the paragraphs below.

6.4 Roll motions

In beam sea scenarios, the waves exert a direct excitation force on the ship introducing a roll motion. The roll response of the ship depends on the natural roll period of the ship, the excitation forces of the waves and the roll damping of the ship[53].

6.4.1 Maximum roll angles

The TUHH performed numerical simulations to calculate the roll motions for the MSC ZOE at the time of the accident results of the simulation show the vessel permanently rolling with roll amplitudes between 5 and 10°, see figure 45. It also shows that at one time, a roll angle of around 16° occurs. According to TUHH, this roll angle may be the result of a group of larger waves hitting the ship.

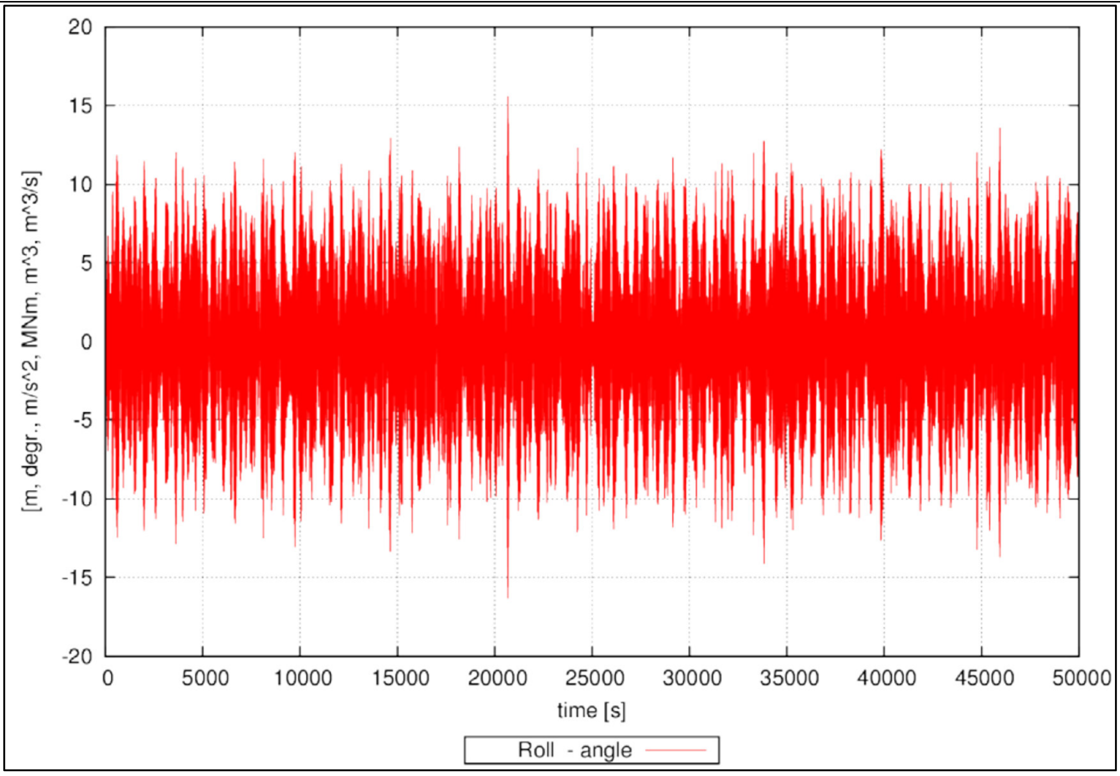


Figure 45: Computed time series of the roll angle of MSC ZOE. Accident condition, speed 10 kn, encounter angle 93°, 50000 s simulation time (Source: TUHH)

Calculations by the TUHH of the effect of the beam wind on the roll motion indicate that the effect is limited. As the stability of the ship is very high, the wind force will not lead to a significant increase of the roll angle. The calculation including the wind heeling moment showed an increase of the maximum roll from 16.3° to 16.9°.

[53] MARIN, Behaviour of ULCS in shallow water, 2020.

Similar results for UCLS in general were obtained from the basin tests performed by MARIN. The basin tests were conducted with variations in the significant wave height H_s and wave period T_p. The measured extreme roll amplitudes increase with an increase in H_s and T_p, see figure 46. For a significant wave height of 6.5m and a water depth of 26.6m, the largest roll amplitude measured was around 16°.

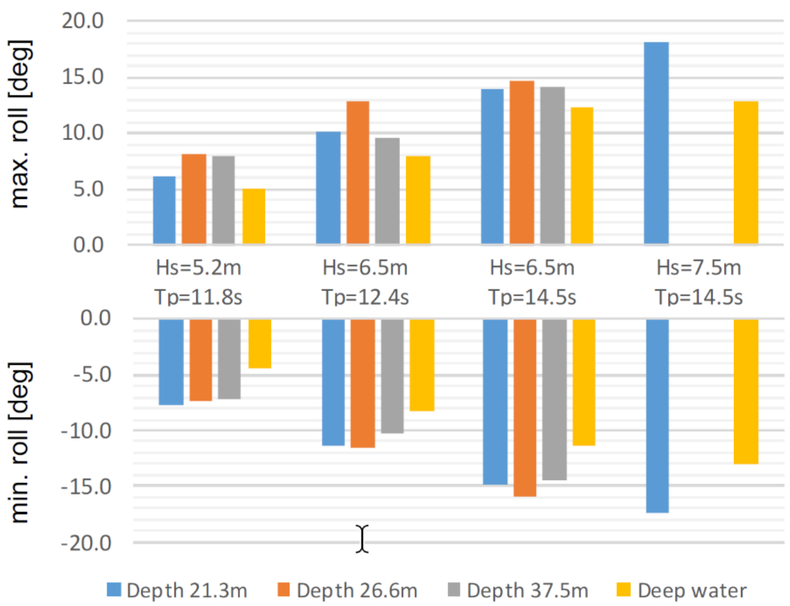


Figure 46: Extreme amplitudes of roll Vs = 0 kn, short-crested waves (Source MARIN)
Note: tests in waves of height 7.5m were only performed for depths 21.3m and deep water.

The effect of speed and wave direction

The TUHH calculated the limiting (minimum) significant wave height for a roll amplitude of 15° in waves with a peak period of 13s on different courses, see figure 47. The results show that for the MSC ZOE the beam sea scenario was unfavourable for roll motion under the conditions encountered. The ship is assumed to be in the center of the polar plot. The radial rings represent the ship speed; the sectors indicate the encounter angle of the waves. It can be concluded that a 15° roll amplitude is reached in beam seas in all speeds already for significant wave heights of about 5 m. For all other courses, much larger wave heights are required to reach the 15° roll amplitude. As an example, two moments along the sailing route of the MSC ZOE are presented in the figure (situation 1 and 2 in figure 47). It further shows that also in bow quartering seas, comparable roll angles are possible for wave encounter angles slightly above 30° and slow speed (example situation 3 in figure 47).

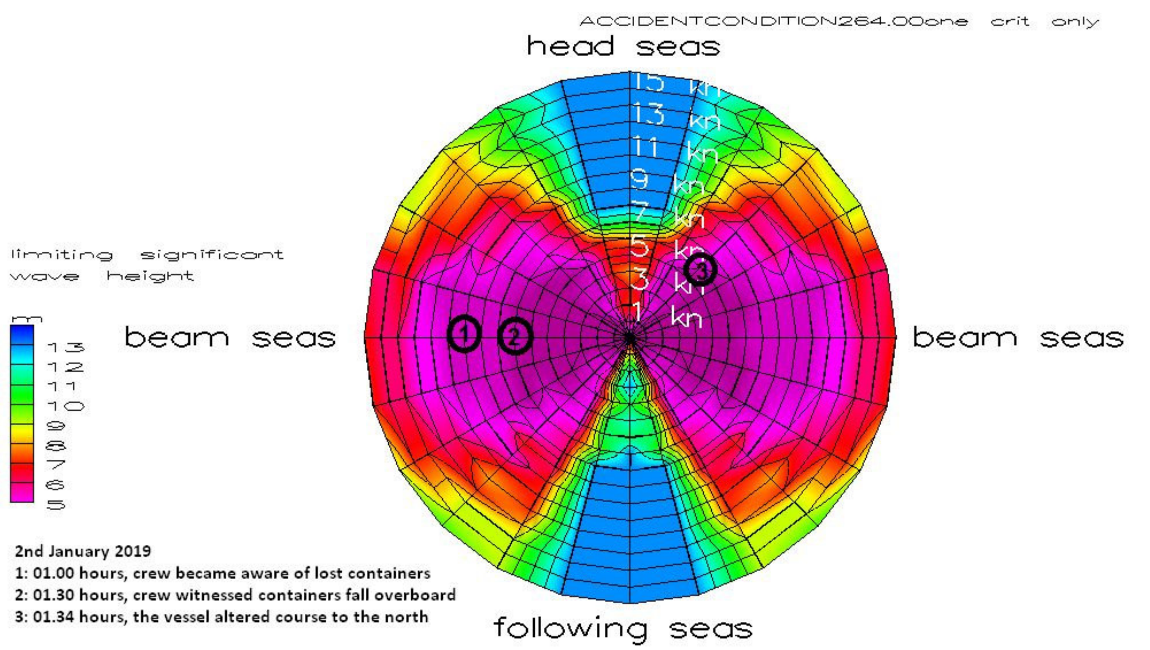


Figure 47: Computed Polar Diagram for MSC ZOE, Accident Condition, wave period 13 s, roll angle 15°, 50,000 s simulation time (Source: TUHH)

6.4.2 Reading of the inclinometer

On board the MSC ZOE, a mechanical inclinometer was installed to provide information to the crew about the actual heel angle of the ship. The inclinometer consists of a pendulum that freely moves and two drag-pointers that indicate the maximum deflection of the pendulum. The drag points can be reset.

The inclinometer of the MSC ZOE indicated a deflection of 30° after the accident, see figure 48. The crew interpreted this deflection as the actual heel angle of the ship and referenced that in their statements following the accident.

Figure 48: Photo of the inclinometer at the bridge of the MSC ZOE after the container loss

Earlier investigations of mechanical inclinometers have already highlighted that the design of the inclinometer is generally insufficient for drawing conclusions as to the dynamic roll angle a ship experienced[54]. It was concluded that if the ship rolls dynamically, the inclinometer actually measures the accelerations due to the mass of the pendulum. Also MARIN research[55] confirms that the mechanical inclinometer on the bridge is a device that is sensitive to accelerations and that under severe motions it will provide a reading of the combined gravity angle due to the transverse and vertical accelerations.

For the purpose of the safety investigation, the inclinometer reading was therefore not considered as presenting a reliable value of the maximum heel angle of the MSC ZOE during the accident voyage[56].

The mechanical inclinometer is not a good instrument to determine the real roll angles a ship experienced, as the instrument is sensitive to accelerations. The safety investigators disregard the reading of the inclinometer of the MSC ZOE.

6.5 Ship behaviour in relation to container loss

As a result of the simulations and tests conducted, four hydrodynamic phenomena were observed that are considered to have played a role in the loss of containers by the MSC ZOE:

[54] BSU, Fatal accident on board the CMV Chicago Express during Typhoon "HAGUPIT" on 24 September 2008 off the coast of Hong Kong
[55] MARIN, Behaviour of an Ultra Large Container Ship in shallo water, 2020.
[56] TUHH: The ship would have touched the seabed if the heeling angle was larger than 19.2 degree.

1. Extreme ship motions and accelerations;
2. Contact or near contact with the sea bottom;
3. Lifting forces and impulsive loading on containers due to green water;
4. Slamming induced impulsive loading on the ship's hull.

These phenomena will be further explained in the paragraphs below.

6.5.1 Extreme ship motions and accelerations

Ship motions induce accelerations in longitudinal, transverse and vertical directions. These accelerations result into forces acting on the crew, ship and cargo. For a ship that is experiencing roll motions, both transversal and vertical accelerations are dominant.

The MSC ZOE had stacks of containers on deck up to the 8th tier. As a result of the ship's roll motion, accelerations and resulting forces acted on the containers on deck. The containers on deck were secured through twistlocks and lashing rods. The ship's motion led to tensile and compression forces in containers and the lashing equipment. Too high accelerations or forces may result in failures of containers and /or the lashing systems, which can lead to containers or its content falling overboard.

TUHH calculated the transversal accelerations for the MSC ZOE's highest containers (tier 8) in bay 58. Results indicate that during the accident condition, a maximum transversal acceleration of -4.6 m/s^2[57] was reached when the maximum roll angle of 16.9° occurred. Typically, container lashing equipment is designed for a lateral acceleration of approximately 0.5g[58], which is 4.9 m/s^2. The computed maximum acceleration is close to this value, see figure 49.

[57] Sign convention: negative acceleration is from ship to starboard side, positive from ship to port side.
[58] See paragraph 4.4.

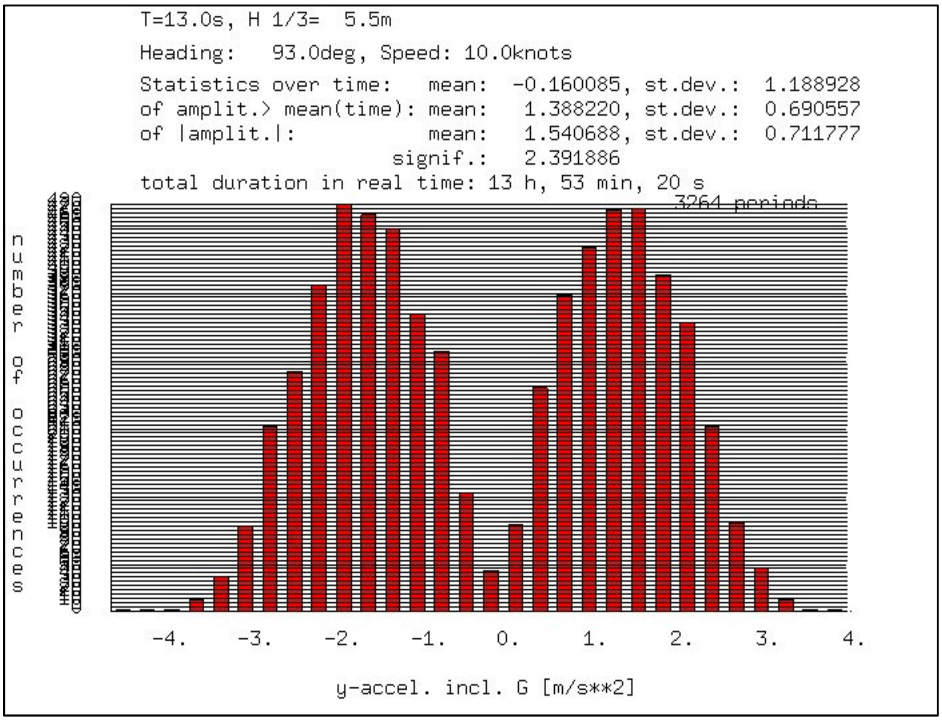


Figure 49: Computed scatter diagram of the transversal acceleration at (130,0,53). MSC ZOE. Accident condition, speed 10 knots, encounter angle 93° including beam wind of 10 Bft. Simulation time 50,000 s. *(Source: TUHH)*

The TUHH repeated the calculation with a significant wave height of 6 m. The maximum roll amplitude is now -18.4°, resulting in a maximum transversal acceleration of -4.8 m/s^2. Assuming a wave height of 6.5 m leads to a maximum roll angle of -19.6° and acceleration of -5.2 m/s^2.

MARIN also measured accelerations during the basin tests. The accelerations were measured at four different locations on the scale model (table 7):

UPS2	Lowest container on deck, against the windward side and approx. amidships
WH	Amid the wheelhouse (on centerline)
UPS2-UP	High on container stack above deck, against the windward side and approximately amidships
CL-UP	High on container stack above deck, on centre line and approximately amidships

Table 7: Different locations of measured accelerations during the basin test. (Source: MARIN)

Considering the water depth the MSC ZOE encountered, the MARIN results for water depths of 21.3m and 26.6m are depicted below. The highest transverse accelerations in wave heights up to 6.5 m (Tp=14.5 s, water depth 26.6 m) reached 4.0 m/s^2 at the lowest tier of containers on deck, 4.8 m/s² at the top of tier 7 and exceeded 5 m/s² at the wheelhouse, see figure 50. Overall it can be stated that the transversal accelerations increase with the height on deck due to the effect of roll. Accelerations are also found to be larger at a water depth of 26.6m, following the trend of roll (higher maximum roll angle in water depth of 26.6 m compared to 21.3 m).

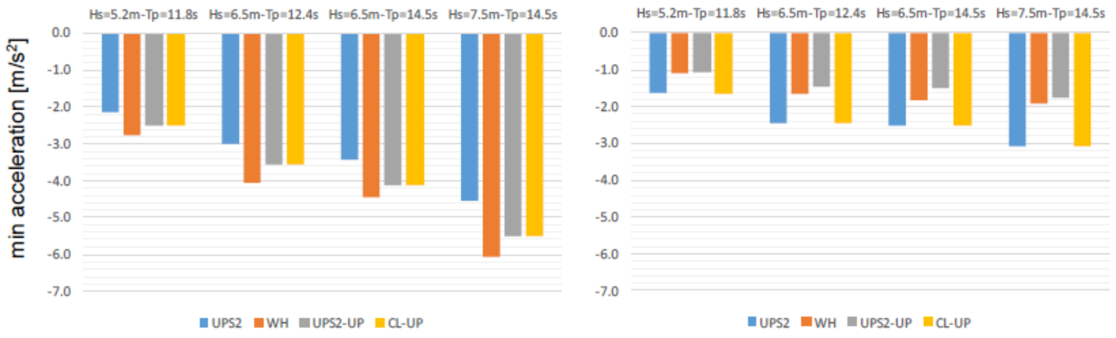


Figure 4-15: Most negative transverse and vertical acceleration at four reference points
Water depth 21.3 m, Vs = 0 kn, short-crested waves

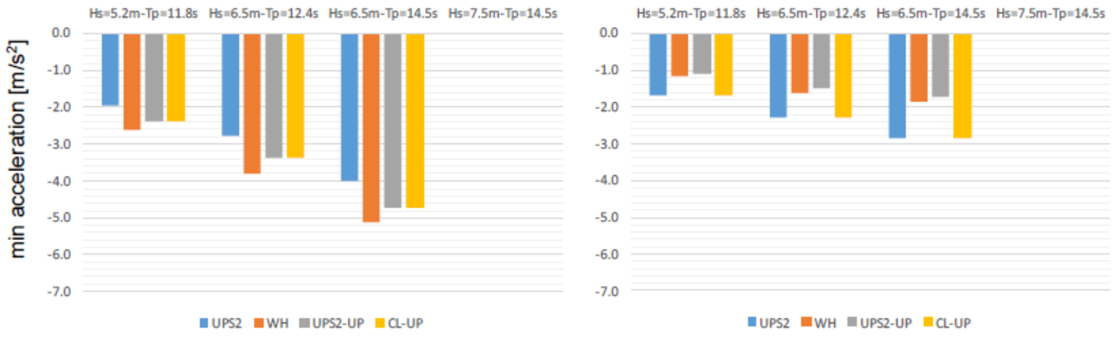


Figure 4-16: Most negative transverse and vertical acceleration at four reference points
Water depth 26.6 m, Vs = 0 kn, short-crested waves

Figure 50: Most negative transverse and vertical accelerations at four reference points. (Source: MARIN)

Note: tests in waves of height 7.5m were not performed for depth of 26.6m.

Based on the calculations by the TUHH and the model test by MARIN, the highest transverse accelerations in wave heights up to 6.5 m, representative of the conditions the MSC ZOE encountered, reached 4.0 m/s² at the lowest tier of containers on deck and 4.6 to 4.8 m/s² at the top of tier 7, which is close to the design lateral acceleration for the system of containers and/or lashing equipment of approximately 4.9 m/s².

6.5.2 Contact or near contact with the sea bottom

The southern shipping route north of the Wadden Islands has a few specific and known shallows, which means that in specific circumstances such as low water and high waves (and the resulting vertical and rolling movement of the ship) the under keel clearance can become very small. Whether a large container ship will come close to or touch the ground on the southern shipping route depends on the environmental conditions such as water depth and wave conditions (wave height and period). The characteristics of the ship such as main dimensions (draft, length and width) and stability also have an important role.

During the tests in the basin, contact or near contact of the model ship with the floor of basin was observed (see figure 51). The frequency of this varied with the wave and ship conditions. During the tests with short-crested waves contact with the basin floor was observed at a water depth of 21.3 m and a wave height of 6.5 meters and above and a peak period of 14.5 meters. The analysis by MARIN of the ship's motions shows that the model can touch the basin bottom when a large vertical heave motion is combined with a large roll motion at the same time in the passage of a group of relatively high waves. The ship also makes a transverse sway motion at that time.

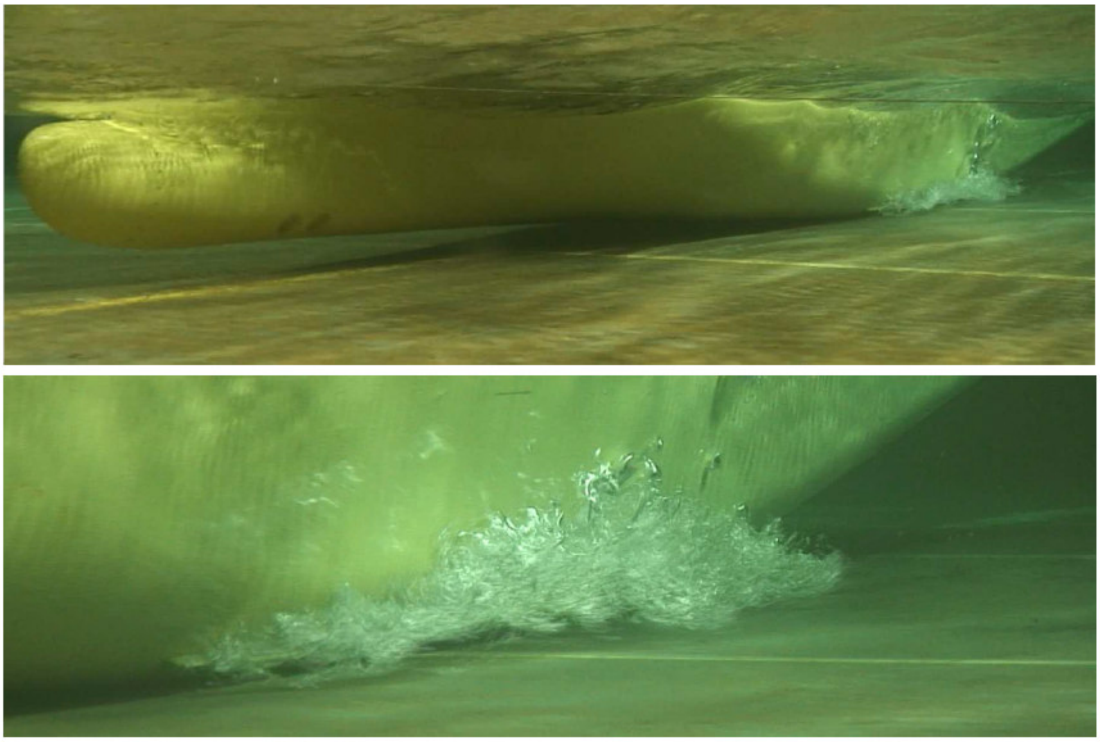


Figure 5-1: Contact with the bottom observed at t = 6460 s during test 101009012: Hs = 6.5 m, Tp = 14.5 s

Figure 51: Underwater images of the model ship at the moment of bottom contact (water depth 21,3 meter, Hs=6.5m, Tp=14.5s, Vs=0kn). (Source: MARIN)

Risk of bottom contact

Whether a large container ship such as the MSC ZOE touches the seabed depends on many factors. For example, the loading condition and thus the stability of the ship have a strong influence on the vertical movements of a ship. The difference is mainly in the rolling movement. For example, MARIN conducted tests that showed that a model ship with lower stability has a lower chance of ground contact.

In addition, the environmental conditions are not constant during several hours of shallow water passage. As Deltares has shown, the water depth under the ship varies due to the bottom profile and the tide and the wave conditions vary with the course of the storm. In any case, the tests show that there is a real chance that the model ship will touch the bottom in the conditions with transverse waves with a significant wave height of 6.5 meters and a peak period of 14.5 seconds.

Effects of bottom contact
In chapter 2.4 it was mentioned that, following the accident, divers carried out an underwater inspection of all the bottom and bilge areas of the MSC ZOE (the transition from the ship's bottom to the side). The survey statement of the classification society DNV-GL stated that the divers found no damage caused by grounding.

A contact of the ship with the bottom does not necessarily lead to structural damage. Nevertheless, it will be the cause of vibrations and deformations that will be propagated to the whole structure due to the flexural response of the ship.

The tests with the model ship show that vibrations pass through the ship when bottom contact occurs. However, the measured accelerations on the model ship cannot be translated into actual accelerations, due to the difference in stiffness and the flexibility of the actual hull (bending, torsion, vibration). In addition, the test model hit a flat concrete bottom where the impulsive load will be different than with a sandy bottom such as in the North Sea. Further research is needed to gain more insight into the effects of soil contact.

Basin tests showed that when a group of relatively high waves passed, the ship model experienced large vertical heave motions with a large roll motion at the same time, resulting in near contact or in some cases contact with the floor of the basin. A contact of the ship with the bottom does not necessarily lead to structural damage. Nevertheless, it will be the cause of vibrations and deformations that will be propagated to the whole structure due to the flexural response of the ship.

Along its route in the TSS Terschelling – German Bight, the MSC ZOE has encountered extremely small clearance between the lowest point of the hull and the seabed along its route. A diver's survey carried out as part of the class society's inspection did not reveal any detectable damage to ship's bottom and bilge areas caused by grounding. However, contact of the hull with the sea bottom cannot be ruled out, as soft contact with the sea bottom will not necessarily cause detectable damage to the ship.

6.5.3 Green water

The water of waves that flows over the deck or against the cargo on the deck is called "green water". Shallow, beam waves reflect strongly against the side of the ship, particularly when steep crests with high horizontal velocity are (close to) breaking. These waves cannot penetrate the ship and can hardly propagate underneath in the restricted clearance, therefore they run upwards against the ship side (see figure 51). The green water effect is extra strong at high steep wave peaks, especially when the waves break forward at high speed. This is a characteristic of shallow water, such as on the southern shipping route.

For a container ship, green water has the effect of exerting direct force from the wave on a container. The upwardly directed water can reach above the deck of the ship and can hit the bottom of the lowest containers above the gangway. This can lead to several problems: the bottom containers can be damaged themselves, or containers can be lifted causing damage to the lashings. If one container is damaged or has broken lashings, a whole stack of containers can fall over. The green water can also cause a lateral force on higher-lying containers, so that the container pushes against the container in the next row. This can lead to (part of) a row of containers falling over like a domino.

Figure 52: Images of the ship model and green water effects (source MARIN).

During the basin tests, green water effects were visually observed (using video recordings) for the tested shallow water conditions. Considering the cumulative number of events as observed during the three test conditions, green water was mostly concentrated on six container bays around the wheelhouse (bays 26 to 46). As shown in figure 53, this is in this area where most of the containers on the MSC ZOE were damaged or lost. Although no green water load measurements have been taken in the present tests, this suggests that green water can play a role in the loss of containers in the tested conditions.

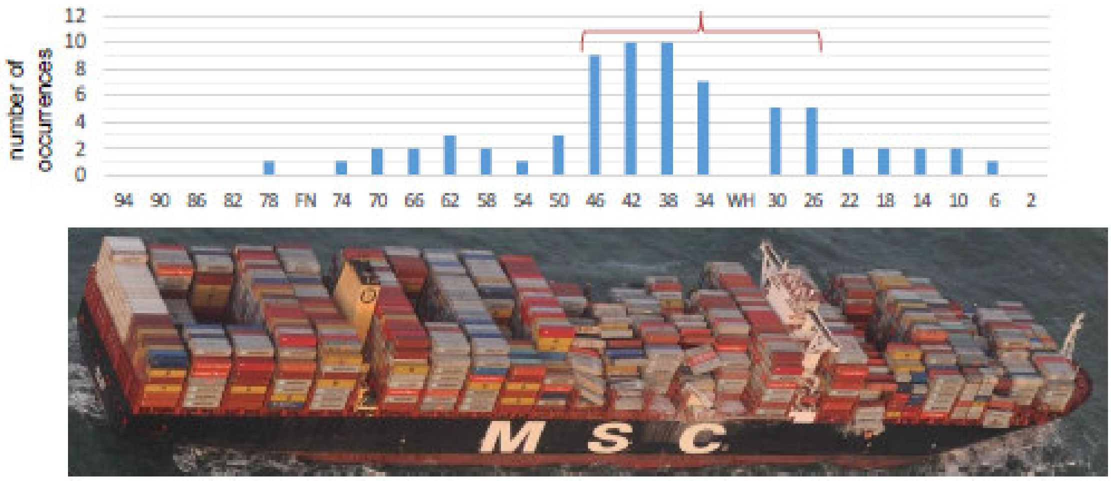


Figure 4-40: Spatial distribution of green water events as observed during three tests at zero speed, compared with the damaged container stacks of the MSC Zoe (view from starboard side)

Figure 4-41: Loss of containers on the wave (port) side of the MSC Zoe, in the area where during the model tests the largest number of green water events was observed (view for port side).

Figure 53: Comparison of the green water events from the basin tests with the loss of containers of the MSC ZOE. (Source: MARIN, pictures: Netherlands Coastguard)

The occurrence of green water was observed during the basin tests. Although no green water load measurements were taken during the basin tests, occurrences of the phenomenon were counted visually, using the video recordings. The comparison with the situation on board the MSC ZOE after the accident, suggest green water might have played a role in the loss of the containers.

6.5.4 Slamming leading to impulsive loads

In the wave conditions of the shallow southern shipping route, steep waves occur that occasionally break. Interaction of these waves with their high horizontal water speeds with a moving ship creates wave impacts against the side of the ship. Visual observation during the MARIN tests indicates that large wave impacts occur against the skin of the ship along the entire length of the ship (see figure 54), including at the flared bow and stern. The short (breaking) waves resulted in wave-induced slamming against the side of the ship, particularly in wave heights of 6.5 m and above. These can result in vibrations in the hull and can affect the dynamic behaviour of the containers and their lashings. They can fail as result.

The phenomenon of wave impacts is of the order of magnitude twice as much as green water. The ship model vibrated due to the wave impact. . These vibrations create forces on the frame of the containers and the lashing systems and there is a chance that the lashing systems will break and that containers will fall overboard.

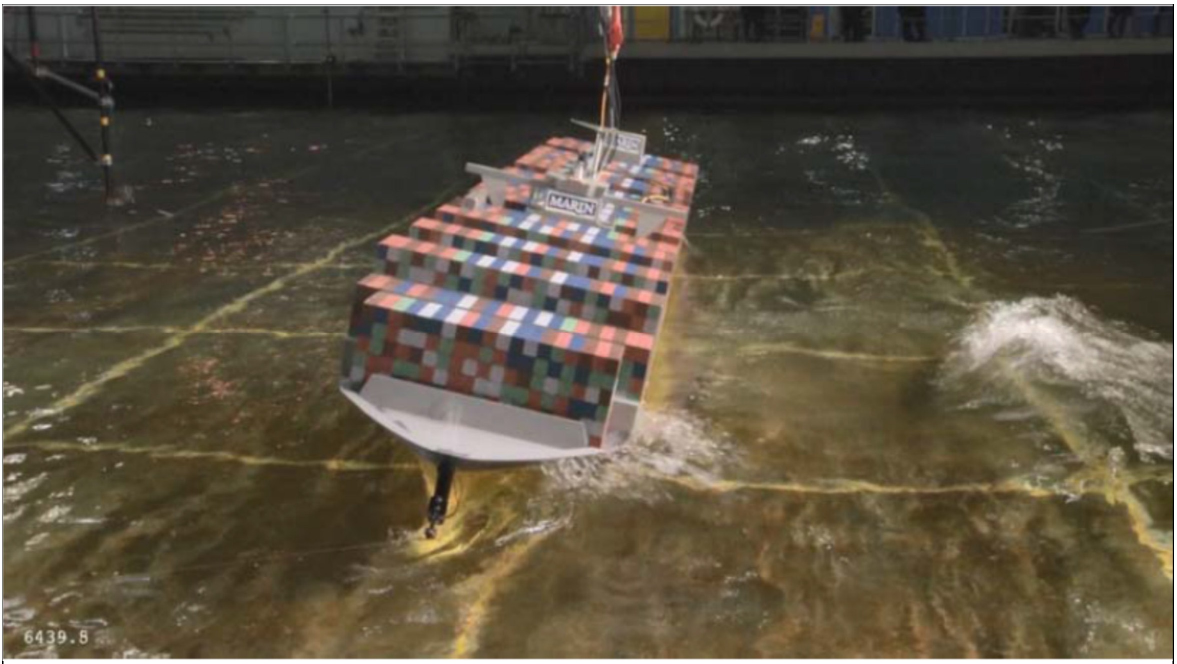


Figure 54: Images of modelship at the moment of slamming (source MARIN)

Slamming was observed in the test for the conditions that were encountered by the MSC ZOE. Impulsive wave loads can result in vibrations in the hull and consequently can create forces in containers and the lashing system.

Following the performed simulations and tests, it is concluded that the MSC ZOE encountered during its passage in the TSS Terschelling – German Bight different hydrodynamic phenomena: extreme motions and accelerations, contact or close contact to the seabed, green water and slamming. These phenomena can occur individually or in combination and lead to large accelerations and forces on containers and the securing equipment.

It is considered that the MSC ZOE whilst sailing in the TSS Terschelling – German Bight experienced these phenomena and that these played a role in the six losses of containers. The six moments of container loss can be seen as independent events that may have a different (combination of) cause(s). It is not clear which phenomenon, or combination of the four phenomena, led to the container loss at each of the moments.

7.1 Ships routeing

The North Sea is one of the busiest seas in the world. Ships' routeing measures have been implemented in this area to assist in safe navigation of the ships. The IMO is the international body responsible for establishing ships' routeing measures. The selection and development of routeing systems are primarily the responsibilities of the governments (interested coastal States). The routing established by IMO is included in the IMO publication "Ships' Routeing". Certain routing may be made mandatory for all ships, certain categories of ships or ships that carry a certain load. The condition for these additional measures is that the routing is adopted and implemented in accordance with the guidelines and criteria drawn up by IMO.

The MSC ZOE was sailing in the TSS Terschelling – German Bight when the loss of containers occurred. A TSS is a routeing measure aimed at the separation of opposing streams of traffic by the establishment of traffic lanes. The TSS Terschelling–German Bight is a routeing measure adopted by the IMO, see figure 55.

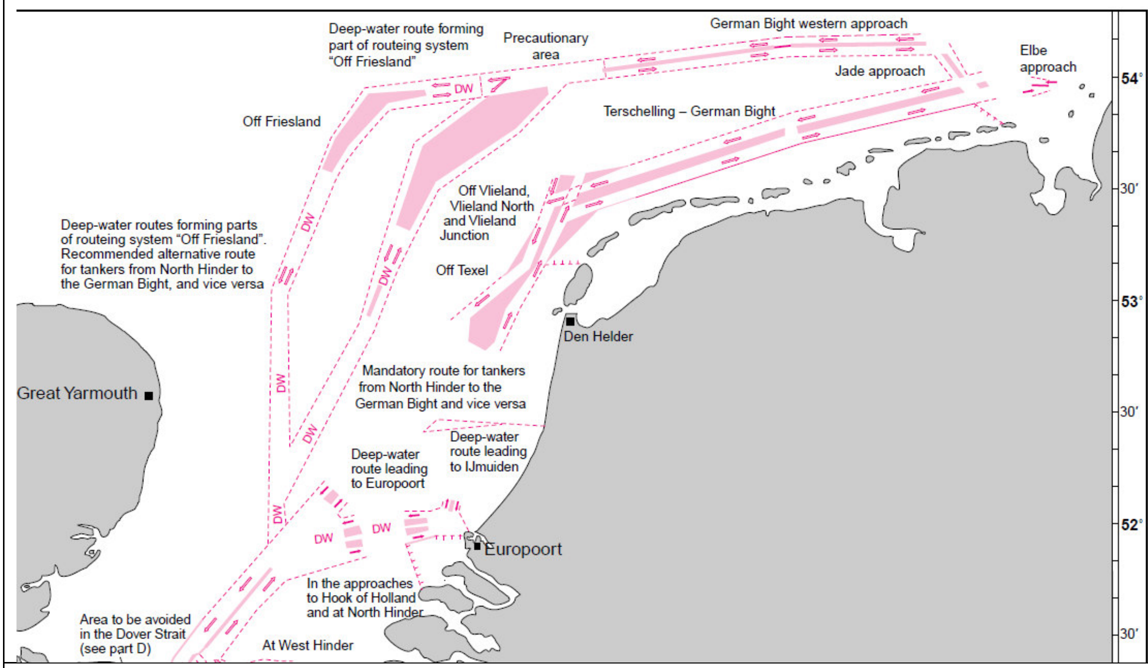


Figure 55: Adopted IMO ships routeing systems in the North Sea along the Dutch coast. (Source: IMO Ships' routeing).

The Wadden Sea in Denmark, Germany and The Netherlands has been designated by the IMO under MARPOL 73/78 as Particularly Sensitive Sea Area (PSSA). This status allows to implement additional protective measures for shipping[59]. As a result a mandatory route has been established for some classes of tankers and vessels carrying noxious liquid substances when sailing from North Hinder to the German Bight and vice versa. These vessels are not allowed to make use of the TSS Terschelling-German Bight, but shall make use of the more northerly route TSS East Friesland and TSS German Bight Western Approach.

Currently, no additional protective measures have been implemented for containerships in view of the risks of container loss.

The TSS Terschelling – German Bight is an international shipping route in the vicinity of the Particular Sensitive Sea Area the Wadden Sea. The status of PSSA allows to implement additional protective measures for shipping. There is an obligation for tankers and vessels carrying noxious liquid substances to follow the deep water route, which is laying north of the TSS Terschelling-German Bight. Containerships do not fall under this obligation.

7.2 Passage planning

The passage planning required for a voyage is made in accordance with the applicable regulations and guidelines as stated in IMO SOLAS[60] Chapter V, Regulation 14 and Resolution A.893(21). This includes regulations for safe navigation (current nautical charts, navigation equipment, qualified and trained crew, logbook). In addition, prior to departure, the captain shall ensure that the intended voyage is planned using the appropriate nautical charts and publications for the area concerned, and subject to guidelines and recommendations established by the IMO. When making a passage planning, the route must be chosen such that:

- Any routing systems for ships are taken into account;
- It is ensured that there is sufficient sea space throughout the voyage for the safe passage of the ship;
- Anticipation of known navigation hazards and bad weather conditions; and
- The current measures for the protection of the marine environment are taken into account and activities that could affect the environment are prevented as much as possible.

The IMO Maritime Safety Committee (MSC) has established Circular 1228, a guideline for the captain to avoid dangerous situations in bad weather and heavy sea conditions. It is recommended that the captain follows the described procedures when navigating in bad weather conditions and thus avoid dangerous situations. Specific attention is paid to certain combinations of wavelength and wave height that lead to dangerous situations for ships.

[59] In 2005, revised IMO guidelines for the identification and designation of a PSSA were adopted (IMO Resolution A.982(24)). These require that at the time of designation of a PSSA, an associated protective measure must have been approved or adopted by IMO.
[60] International Convention for the Safety of Life at Sea

Without prejudice to this, the captain must also take reasonable measures in less severe circumstances if this seems necessary. Good seamanship of the captain means that in all situations the specific characteristics and condition of the ship, cargo and crew are taken into account to maintain a safe voyage.

The routing and deployment of container ships are extensively planned by the shipping company. Usually they work with fixed sailing schedules that are adjusted depending on delays during a trip. Considerations are constantly made in which commercial and operational interests play a role. For example, it may be necessary to adjust loading plans in ports, to increase or decrease sailing speed, or to reschedule a ship's voyage due to a delay. The arrival and departure times in a port are often accurately determined due to the availability of a berth at the quay or because of the tide. The time spent in a the port is depending on the number of containers being unloaded and loaded. This requires careful planning. An important cost factor is the fuel consumption of the ship, mainly influenced by the length of a route and the sailing speed.

Passage plan of the MSC ZOE

A passage plan must be drawn by the ship's crew for each voyage. The basis for this is the schedule drawn up by the shipping company. The Third officer on board the MSC ZOE was responsible for preparing the passage plan. He has to adjust the plan to current weather conditions and navigational warnings. He has to identify potential problems or hazards along the route to ensure the vessel's safe passage. The final plan is adopted by the Master. The route from Asia to Europe and vice versa is for MSC a regular service, this route was sailed more often. The most common choice, when sailing from the south to Bremerhaven is the TSS Terschelling – German Bight as it is the shortest route for these kind of ships.

To identify potential problems or hazards along the route, the crew shall use current charts and booklets (IMO: Guidelines For Voyage Planning). Information about passage through the North Sea can be found in the North Sea (East) Pilot (NP 55) in the British Admiralty Sailing Directions series. It covers the eastern part of North Sea from Scheveningen, the Netherlands to Skagen, Denmark. Chapter 4.7 reads: *"Northerly storms can cause very rough, short and steep seas in the coastal route of Texel and the German bend. In these circumstances, the Off Friesland TSS alternative can offer better seas and more room for manoeuvre."*

The TSS Terschelling - German Bight has a few shallower areas that are indicated on the navigational charts, see figure 55 below. In order to calculate the remaining Under Keel Clearance (UKC) for the ship, the static draught, water depth, tide, squat and heel angle are to be taken into account. The passage plan of the MSC ZOE for the journey from Sines to Bremerhaven indicates that the ship had a static draught of 12.6 m forward, 12.6 m amid and 12.7 m aft. The passage plan also indicates that at least 4 meter UKC should be kept at all times. A general remark is made on the plan that speed and heel angle may cause an increase of draught.

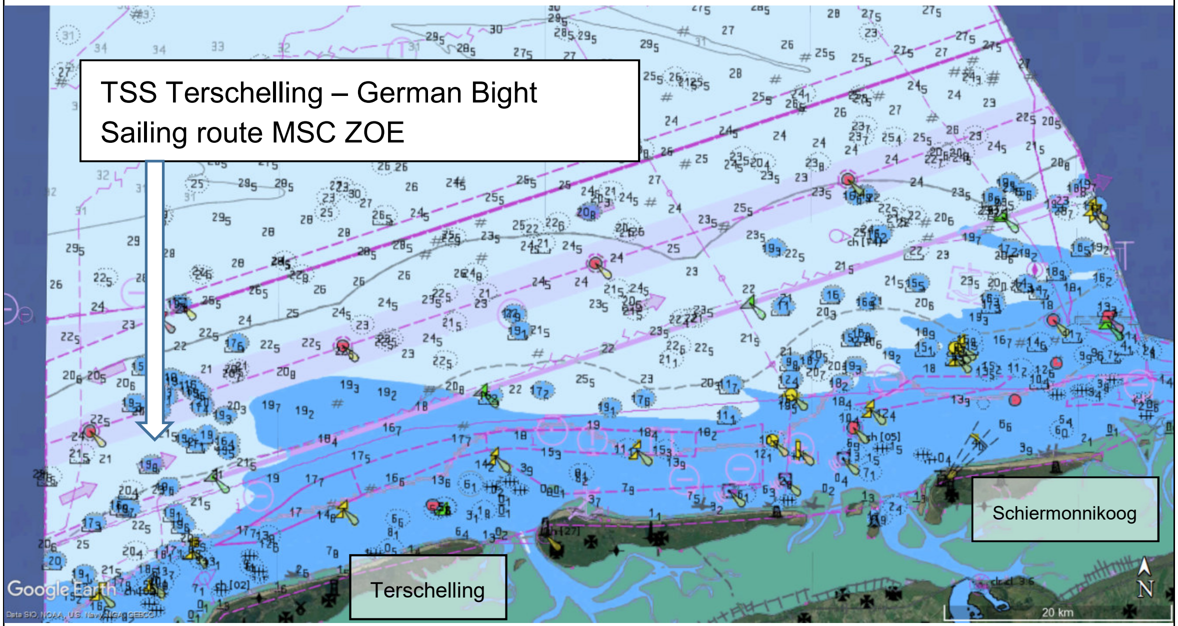


Figure 56. Navigational Chart, depth in meters, approximately the level of lowest astronomical tide (LAT). (Source: iChart).

The chart datum[61] is the water level that depths displayed on a nautical chart are measured from. In the above chart, the shown depths are Lowest Astronomical Tide (LAT) which is defined as the lowest tide level which can be predicted to occur under average meteorological conditions and under any combination of astronomical conditions. Water levels below the LAT can also occur due to weather conditions such as high air pressure or strong winds.

The master selected to sail through the TSS Terschelling–German Bight. This is the shortest route to Bremerhaven. A ship such as the MSC ZOE is obliged to sail in a TSS. There are no restrictions for containerships on this specific route.

Available information on hazardous conditions in the TSS Terschelling- German Bight in the Nautical pilot 55 was considered not applicable for the passage of the MSC ZOE.

[61] Chart Datum is a commonly applied vertical reference level for shipping applications, such as nautical charts. It differs from region to region and is set at the lowest water level that typically occurs in an area, indicating that a vessel can expect at least that water depth – or higher – to be present.

8 CONCLUSIONS

This report presents the results of the investigation into the loss of 342 containers by MSC ZOE whilst sailing on the North Sea in the TSS Terschelling – German Bight. The containers and content severely polluted the Wadden Sea region in The Netherlands and Germany.

The weather and wave conditions along the route of the MSC ZOE during 1 and 2 January 2019 were studied, as well as the effects of these conditions on the ship‘s motions and lashing system. In addition, the shallow water effects that occur along the route have been examined in relation to the large size of the ship and Ultra Large Container Ships in general. The research performed as part of this investigation has revealed new insights in the conditions, ship's motions and hydrodynamic phenomena that may be encountered in this part of the North Sea.

During the passage in easterly direction through the TSS Terschelling – German Bight the MSC ZOE encountered heavy wind conditions from north-northwesterly direction. The waves approached the MSC ZOE from abeam. The prevailing wind direction allowed the waves to build up as there is a long fetch length available on the North Sea. The significant wave height increased from 5 m to 6.5 m at the peak of the storm, around 01:00 local time on January 2, with a chance of individual waves of around 11 m height. The conditions resulted in the ship rolling continuously. The weather forecasts were in line with the actual weather encountered and the encountered heavy conditions are not considered extreme or exceptional for this part of the North Sea.

The following conclusions are drawn from this investigation.

Container loss
The investigation has revealed that during the passage through the TSS Terschelling – German Bight, MSC ZOE experienced four different hydrodynamic phenomena, either individual or in combination, that played a role in the loss of containers.

- Extreme motions and accelerations;
- Contact or near contact with the sea bottom;
- Green water;
- Slamming.

The main cause of the loss of containers by MSC ZOE was the high stability at which the ship was sailing in a beam sea scenario in shallow water conditions where it encountered combination of the four hydrodynamic phenomena. The encountered transversal accelerations were at the design limits, leading to failure of the container structure and/ or the lashing equipment and subsequent container loss.

The MSC ZOE was, with a corrected GM of 9.01 m, sailing in a high stability condition. As a result, the MSC ZOE was more likely to show a higher roll response to the wave periods present in the North Sea north of the Wadden Islands, resulting in strong ship movements.

There were at least six moments at which the MSC ZOE lost containers. The first losses of containers were not noticed by the crew. Only the last event, around 01:30 local time on January 2, was witnessed by the crew.

The six moments of container loss can be seen as independent events that may have a different (combination of) cause(s). It is not clear which phenomenon, or combination of the four phenomena, led to the container loss at each of the moments/locations.

High stability
The actual GM of the MSC ZOE was typical for vessels of that size in operation. The high stability of large and wide Ultra Large Container Ships leads to shorter natural roll periods than smaller ships with lower stability. This brings the natural roll period closer to the wave periods that were present above the Wadden Islands during the accident, resulting in larger resonant roll motions in the beam seas. The shorter periods also result in higher accelerations. Large bilge keels are a way to reduce accelerations. Container ships like the MSC ZOE have insufficient roll damping in situations with large stability.

High stability is a safety risk that has not been recognised and formalised in the IMO Intact Stability Code and documents as the Stability Booklet. Current limits are only set for a minimum GM. The effects of high GM are underestimated.

Under Keel Clearance
Basin tests showed that when a group of relatively high waves passed, the ship model experienced large vertical heave motions with a large roll motion at the same time, resulting in near contact or in some cases contact with the bottom of the basin.

Along its route in the TSS Terschelling – German Bight, the MSC ZOE has encountered extremely small clearance between the lowest point of the hull and the seabed. The investigation showed that contact with the sea bottom cannot be ruled out. A diver’s survey carried out as part of the classification society’s inspection did not reveal any damage to ship’s bottom and bilge areas caused by grounding. However, soft contact with the sandy sea bottom will not necessarily cause detectable damage to the ship. Nevertheless, it will be the cause of vibrations and deformations that will be propagated to the whole structure due to the flexural response of the ship.

Insight in accelerations
After the accident, the mechanical inclinometer indicated a deflection of about 30°. The crew interpreted this deflection as the actual heel angle of the ship and referenced in their statements following the accident to a 30° heel angle. The investigation determined that the maximum roll angle of the ship was in the order of 16°. The mechanical inclinometer is not a good instrument to determine the real roll angles a ship experienced, as the instrument is sensitive to accelerations.

For the crew to act, it is essential to have insight in the actual forces and accelerations acting on the ship, containers and lashing system. The crew of the MSC ZOE had no indication on the bridge of occurring roll angles, forces and accelerations. The design of the mechanical inclinometers is generally insufficient for drawing conclusions as to the dynamic roll angle a ship experiences.

Lashing and loading
The loading computer software on board the MSC ZOE shown to the investigators indicated warnings for several bays, indicating an exceedance of a tolerance limit. The exceedance of the tolerance limits where, however, not further specified. MSC suggests that data shown to the investigators was incorrect (accidental changes before shown to the investigator, wrong loading computer, incorrect settings), however, neither other loading condition data nor risk assessments have been shared. The investigators therefore conclude that the loading computer shown to the investigators indicate excess of tolerance limits without further specification and that it cannot be determined whether and if so how these excess of tolerance limits have been recognized and addressed. The warnings in the loading computer do not predict the loss scheme, but in bays where containers were lost and also warnings were indicated, imperfections in loading status may have contributed to the accident, as it may have made the bay and/or specific stack more vulnerable to excessive forces.

Apart from the red warning boxes, no structural deviations of international regulations pertaining to lashing material and the lashing itself have been observed. Regardless of the state of the lashing equipment, sailing with high stability in a beam sea scenario on the North Sea in shallow water led to large transversal accelerations and resulting forces in lashing equipment close to the design limits, even at moderate roll angles.

The lashing equipment and container structures present on Ultra Large Container Ships are the similar on all other types of container ships. The Code of Safe Practice for Cargo Stowage and Securing (CSS code[62]) cannot be used to calculate design accelerations for vessels like the MSC ZOE. The design limits for lashing systems on an Ultra Large Container Ship are determined by complicated software calculations and are not transparent. Therefore, it cannot be checked whether the containers are loaded and secured in accordance with the regulations of the Cargo Securing Manual (CSM) and if the rules and guidelines regarding lashing have been complied with.

Routeing
According to all legal requirements the MSC ZOE was allowed to sail under the condition it sailed. The TSS Terschelling – German Bight is in the vicinity of the Wadden Sea, which is designated as a Particularly Sensitive Sea Area and a UNESCO World Heritage. The accident with MSC ZOE led to severe pollution of the area. The status of PSSA allows to implement additional protective measures for shipping under IMO. There are currently no specific requirements or restrictions for (large) container ships for the routes.

[62] IMO Res. A.714(17) (MSC/Circ.1026)

The pollution of the Wadden Sea by lost containers is an undesirable event. Interested coastal states such as The Netherlands and Germany, have the possibility to propose to IMO additional associative protective measures for shipping to protect the PSSA.

Increase in scale beyond regulatory ranges
The MSC ZOE is an ultra large container ship built in 2014 with a length of almost 400 m, beam of 59 m and a theoretical capacity of 19,224 TEU. In general, the capacity of individual container ships doubled over the last 15 years. The growth resulted in container ships carrying more containers on deck. The length and operational GM of ultra large container vessels like the MSC ZOE exceed the valid ranges of most international technical regulations and standards for calculation of accelerations. It is noted that in those cases a loading computer with lashing software is required, but the details of the procedures in the loading computer and the lashing software are not elaborated by the CSS-code, but through rules of classification societies. Details of the loading computer and lashing software modules, however, are due to the complexity of the calculations not fully transparent. It is therefore not clear which design accelerations are incorporated in the calculations in the software. Therefore, it’s not always clear for the crew which maximum accelerations the system of containers and lashing equipment needs to withstand.

The fact that the first losses of containers was not noticed by the crew is an undesirable event. If the crew had noticed the first loss, the necessary mitigating actions could have been taken and further container losses possibly avoided.

The size of the container ships continue to increase, as well as the share of the large ships in the fleet. This investigation revealed that the concept of the lashing of containers on deck of these large and wide ships needs to be reviewed and international technical and operational standards to be amended or developed where necessary.

9 ACTIONS TAKEN

Following the accident with the MSC ZOE, several actions were taken during the time of the investigation, by:

Dutch Safety Board
The Dutch Safety Board started an additional investigation that focused on the route-specific risks of the loss of containers for large container ships sailing on the shipping routes above the Wadden Islands. The focus has been placed on the circumstances that could potentially lead to unsafe situations involving large container ships on the shipping lanes above the Wadden Islands. In this process, the circumstances at the time of the accident involving the MSC ZOE were taken as the starting point, since this has emerged as a proven high-risk situation for large container ships.

On 31 October the Dutch Safety Board issued an interim warning to the Dutch Ministry of Infrastructure and Water Management to announce the risk of bottom contact on the southern shipping lane.

> "The investigation revealed the contours of a risk which the Dutch Safety Board considers sufficiently serious to bring to the attention of users of the Terschelling-German Bight traffic separation scheme North of the Dutch Wadden Islands.
>
> Along this route, specific wind and wave conditions and tidal situations can lead to considerable heave and roll motions that threaten the vessel's under keel clearance. For vessels with dimensions comparable to those of the MSC ZOE, this may lead to a risk of contact or near-contact with the seabed.
>
> The Dutch Safety Board therefore recommends you make this risk known within your organization, and you communicate this risk to users of the Terschelling-German Bight traffic separation scheme."

This investigation by the Dutch Safety Board focuses on route-specific risks of the loss of containers on the shipping lanes in the North Sea to the north of the Wadden Islands for ultra large container ships such as the MSC ZOE. Due to the focus on the shipping routes, the research does not focus on the technical design criteria and certification of container ships, containers and fastening mechanisms / lashing materials. Because of the focus on ultra large container ships such as the MSC ZOE, this investigation will provide useful but not a precise insight into the risk of the loss of containers from other types of (container) vessels.

The findings relevant for the investigation into the course of events surrounding the accident with the MSC ZOE were contributed to the international investigation, in accordance with international agreements. The full report, including the recommendations, is available on www.onderzoeksraad.nl

Deutscher Bundesrat zum Transport von Gefahrgut auf Großcontainerschiffen
After the loss of containers from the container ship MSC ZOE on 2 January 2019, the upper house of German parliament broached the issue of the aspects of the container identification and – tracking.

The upper house asked the Federal Government “, …, subject to the pending investigation report of the Bundesstelle für Seeunfalluntersuchung (BSU – file number: 03/19.) As regards the cause of the accident, the mandatory use of appropriate Traffic Separation Schemes – also for large container vessels in the North Sea – should be examined in international context.

According to the recommendation given by the upper house of German parliament, resolution 68/19, the Federal Ministry of Transport and Digital Infrastructure, examined the suitability of the Traffic Separation Scheme Terschelling – German Bight in collaboration with the Dutch Ministry of Transport with respect to the navigability for ships.

According to the report, binding shifting of large container ships with a small draught to the Vessel Traffic Separation Scheme German Bight – Western Approach under the terms of international law is currently not deemed necessary. There are already technical solutions put into effect to track container cargo, which are offered the shippers by logistic companies or bound by contract if their containers are used. The Federal Government sees no regulatory need for action at present.

The whole text can be found on:
https://www.bundesrat.de/SharedDocs/beratungsvorgaenge/2020/0101-0200/0185-20.html

Dutch Ministry of Infrastructure and Water Management
After the incident with the MSC Zoe the Ministry of Infrastructure and Water Management has started several investigations into the loss of containers above the Wadden Islands, some of which are still running. It concerns amongst others an investigation by MARIN to the behaviour of different types of containerships in adverse weather above the Wadden Islands, as well as an investigation by TNO, the Netherlands Organisation for applied scientific research, to the possibility of tracking of containers.

Immediately following the issuing of the warning, the Dutch Minister of Infrastructure and Water Management called upon the Dutch Coastguard to announce the warning in the form of a note on the electronic sea charts and to broadcast to shipping the specific wind and wave conditions and tide situation. Based upon the warning from the Dutch Safety Board in

October 2019, the Netherlands Coastguard issues warnings to ULCS's bound for the TSS Terschelling - German Bight in adverse weather, to take the alternative route of the TSS German Bight - Western Approach, i.e. the northerly route above the Wadden Islands.

10 RECOMMENDATIONS

1. The Merchant Marine General Directorate, Panama, the Dutch Safety Board, Netherlands, and the Bundesstelle für Seeunfalluntersuchung, Germany make the following recommendation to **their responsible administrations** in their capacity as representative of the flag states in the various committees of the IMO:

   1.1. Revise the existing technical and legal regulations for container ships regarding the design limits of cargo securing equipment, approved loading and stability conditions and the consideration of shallow water effects and speed on ship motions and resulting accelerations and forces. In doing so, especially the following provisions and aspects are to be taken into account:

   - IS-Code (Off-design stability conditions for very large containerships and Second Generation Intact Stability started in May 2020)
   - Code of Safe Practice for Cargo Stowage and Securing for very large containerships
   - Container safety convention (CSC) and ISO 1496-1 Freight containers - Specification and testing respectively
   - IMO Circular MSC.1/Circ. 1228 dated 11 January 2007, Revised guidance to the master for avoiding dangerous situations in adverse weather and sea conditions whether it works at all sea conditions.
   - Stability booklet, include that all loading conditions should be checked on high accelerations/forces.
   - Cargo securing manual, include design limits of the cargo securing equipment in accordance to the design accelerations.

   In doing so, the aforementioned authorities should act in such a way that results attained by existing international working groups are incorporated.

   1.2. Generate an obligation on all container ships

   1.2.1. to install electronic inclinometers or similar (inertia) systems to measure and display this information in real-time to the captain/crew, and

   1.2.2. to install sensors on critical locations on the ship in order to measure accelerations and to provide this information in real-time to the captain/crew in order to allow them to monitor these;

   1.2.3. and for ships with mandatory equipped VDR to record actual roll angle, roll period and accelerations for the purpose of safety investigations.

1.3. Evaluate and assess possible technical solutions that can assist the captain/crew in the detection of the loss of containers and propose international standards for implementation of such solutions.

2. The Merchant Marine General Directorate, Panama, the Dutch Safety Board, the Netherlands, and the Bundesstelle für Seeunfalluntersuchung, Germany make the following recommendation to **the responsible administrations of The Netherlands and Germany**, in their capacity as responsible authorities for the conservation and protection of the Wadden Sea to, in cooperation with the Trilateral Wadden Sea Cooperation:

   Ascertain whether the existing tracks of the German Bight Traffic Separation Schemes north of the Wadden Sea have to be adapted, or measures have to be taken particularly for large containerships to maximize the safety of the voyage on the sailing routes. In doing so, the following aspects and hydrodynamic phenomena have to be taken into account:

   - Extreme ship motions and accelerations;
   - Ships speed;
   - Green water effects;
   - Slamming;
   - Possibility of contact with the seabed;
   - Status of the Wadden Sea as Particularly Sensitive Sea Area (PSSA).

   If determined that adaptation is necessary or measures have to be taken, the responsible administrations in their capacity as representative of the flag states in the various committees of the IMO, should propose an amendment and/or measures for the above mentioned existing tracks.

3. The Merchant Marine General Directorate, Panama, the Dutch Safety Board, Netherlands, and the Bundesstelle für Seeunfalluntersuchung, Germany make the following recommendation to **the shipowning company MSC**:

   - In the construction and operation of ships, reduce high acceleration forces, which can cause damage to crew, passengers and cargo, by installing eg. bilge keels or anti-roll tanks or stabilizers or setting operational stability limits eg by limiting the operational GM.

   - Raise awareness and develop guidelines to the Masters and Navigational Officers on sailing with a high stability and the hydrodynamic phenomena that may be encountered in the sailing routes north of the Wadden Sea.

4. The Merchant Marine General Directorate, Panama, the Dutch Safety Board, Netherlands, and the Bundesstelle für Seeunfalluntersuchung, Germany make the following recommendation to **the World Shipping Council** and **the International Chamber of Shipping**:

    - Communicate actively the lessons from this safety investigation;
    - Propagate industry standards and principles that will increase the safety of container transport;
    - Start an initiative for innovation in ship design, to work towards hull and/or lashing system designs that are better suited for the conditions as described in this report.

APPENDIX A SHIP'S PARTICULARS

SHIP'S PARTICULARS

Vessel data	MSC ZOE
Call sign:	3FQA
IMO number:	9703318
Flag state:	Panama
Home port:	Panama
Type of ship:	Ultra Large Containership
Classification society:	DNV-GL
Year of construction:	2015
Shipyard:	Daewoo Shipbuilding & Marine Engineering Co. Ltd. / 4279
Length overall (LOA):	395.40 m
Length between perpendiculars (LPP):	379.40 m
Breadth:	59.00 m
Actual draft:	14.50 m
Gross Tonnage:	192237
Container capacity	19224 TEU
Engines:	MAN-B&W 11S 90ME-C10.2 TII
Propulsion:	1 propeller, 5-blads fixed pitch
Maximum propulsion capacity:	62500 kW
Maximum velocity:	22.8 kn
Vessel's certificates:	All valid

CREW COMPOSITION

Grade/Capacity	Number
Master	1
Chief Officer	1
Second Officer	1
Third Officer	1
Chief Engineer	1
2nd Engineer	1
4th Engineer	1
Stagiaire machinekamer	1
Electro technical officer	1
Bosun	1
AB	4

OS	2
Fitter	1
Oiler	2
Cook	1
Steward	1
Catering	1
Total	22

LIST OF STATUTORY CERTIFICATES OF THE MSC ZOE

Certificate	Issued Body	Date of Issuance (dd.mm.yyyy)	Date of Expiry (dd.mm.yyyy)
Registry	PMA	02.09.2015	01.09.2020
Class	DNV-GL	25.04.2018	23.06.2020
Safety Construction	DNV-GL	25.04.2018	23.06.2020
Safety Equipment	DNV-GL	25.04.2018	23.06.2020
Safety Radio	DNV-GL	25.04.2018	23.06.2020
Load Line	DNV-GL	25.04.2018	23.06.2020
Tonnage	PMA	03.06.2015	Permanent
Int. Oil Poll. Prevention	DNV-GL	25.04.2018	23.06.2020
Int. Air Poll. Prevention	DNV-GL	13.03.2018	23.06.2020
Int. Energy Efficiency Cert.	DNV-GL	25.04.2018	-
Int. Seawage Poll. Prev	DNV-GL	25.04.2018	23.06.2020
Int. Ship Security	PMA	04.01.2016	02.12.2020
ISM	DNV-GL	10.12.2015	02.12.2020
Document of Compliance (ISM)	RINA	18.09.2014	02.09.2019
Minimum Safe Manning	PMA	01.02.2017	-
Marit. Labour Certificate	DNV-GL	10.12.2015	07.12.2020
Radio Station Licence	PMA	31.08.2015	30.08.2020
Int. Ballast Water Man. Cert.	PMA	24.06.2015	23.06.2020
Panama Annual Tax	PMA	10121503A	31.12.2018
Last PSC Report	PSC Singapore	14.08.2018	None
PSC (ref Casualty)	PSC Germany	03.01.2019	7 Deficiencies
Annual Flag Inspection	PMA	15.08.2018	No Deficiencies
CLC for Bunker	PMA	20.02.2018	20.02.2019
CLC for Wreck	PMA	20.02.2018	20.02.2019

Vessel is insured for damages against third parties with “West Of England “according certificate Nr. 394935 issued on 02.02.2018 and is covered for H+M with “Auscomar Srl”.

APPENDIX B CHARTS DEUTSCHER WETTER DIENST

The wind analysis charts in figures 57 and 58 show the wind forces thus obtained in the accident area at respectively 21.00 UTC and 00.00 UTC, with the feathers representing the mean wind and the numerical value the gusts in Bft. The green line shows the course of the MSC ZOE in the period considered.

With the feathers representing the mean wind and the numerical value the gusts in Bft. The green line shows the course of the MSC ZOE in the period considered.

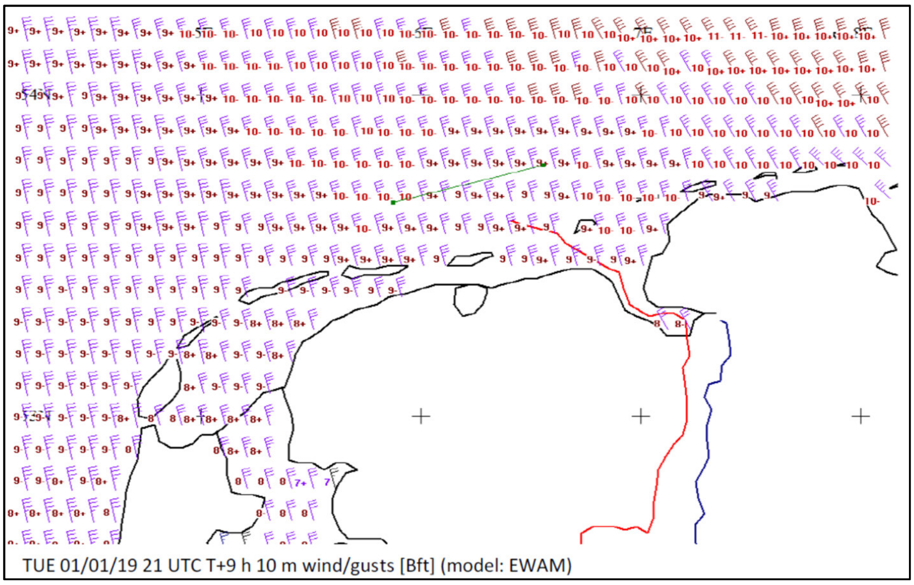


Figure 57: Wind analysis at 21.00 UTC on 1 January 2019 (Source DWD)
(one long feather of an arrow equals 2 Bft and a short feather 1 Bft)

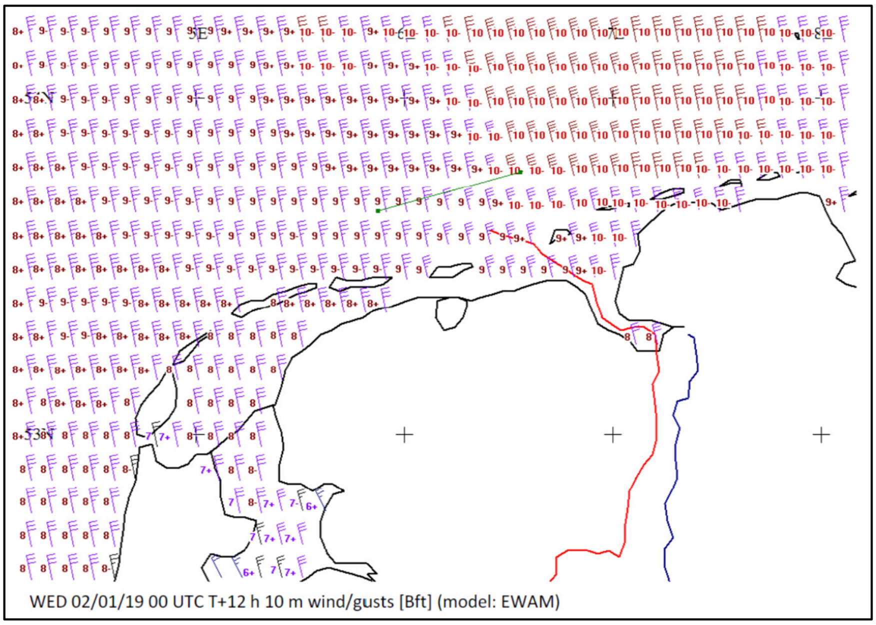


Figure 58: Wind analysis at 00.00 UTC on 1 January 2019 (Source DWD)
(one long feather of an arrow equals 2 Bft and a short feather 1 Bft)

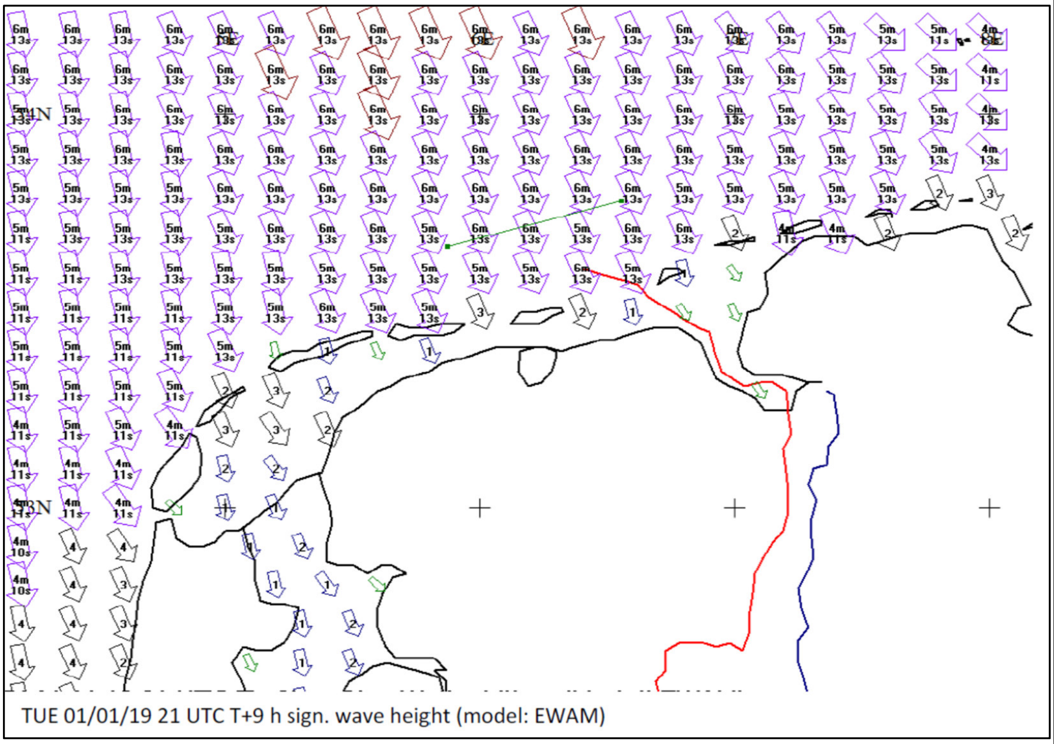


Figure 59: Wave analysis at 21.00 UTC on 1 January 2019 (Source DWD)

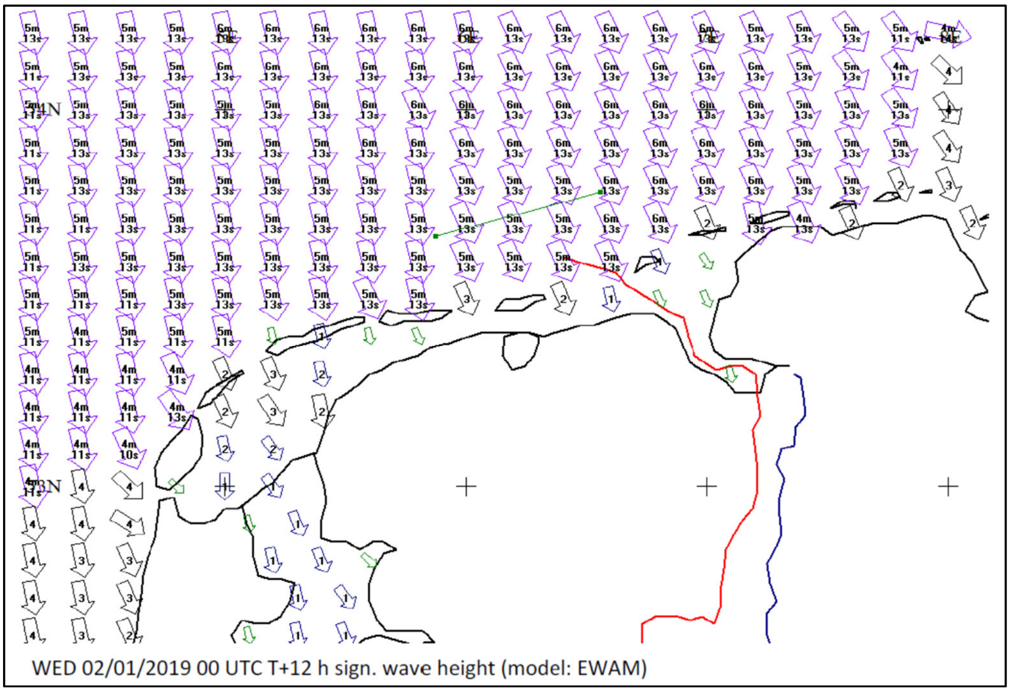


Figure 60: Wave analysis at 00.00 UTC on 1 January 2019 (Source DWD)

APPENDIX C TECHNICAL REPORT DELTARES

The report of Deltares is available on www.bsu-bund.de and www.onderzoeksraad.nl.

APPENDIX D TECHNICAL REPORT MARIN

The report MARIN is available on www.bsu-bund.de and www.onderzoeksraad.nl.

APPENDIX E TECHNICAL REPORT TUHH

The report of TUHH is available on www.bsu-bund.de and www.onderzoeksraad.nl.