Journal of
Marine Science and Engineering

MDPI

Article

Revisiting the MV Estonia Accident Using Numerical Simulations with a Statistical Approach

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Abstract

The loss of the MV Estonia has been investigated by various organizations since the accident in September 1994. The root cause of the accident has been assumed to be known and the consequent sinking process well established. However, in September 2020, a new video recording by an underwater ROV was published, showing a new, previously unknown, penetrating damage on the starboard side of the MV Estonia wreck lying on the seabed. Based on this new evidence, the Estonian Safety Investigation Bureau (ESIB) initiated a preliminary assessment of the new information on the MV Estonia accident. Whether the New Side Damage (NSD) on the starboard side was already present while the MV Estonia was afloat on the surface, or whether it resulted from the collision of the sinking vessel with the seabed somewhat later, is an important issue needing clarification: In the first case, the validity of the conclusions on the root cause of the accident presented in the previous studies could prove premature. One of the goals of the present investigation by the Hamburg Ship Model Basin (HSVA) is to shed light on this question: The results of the numerical simulations of the sinking process carried out for various damage configurations in seaway using not only single simulations, but also a statistical approach are presented.

Keywords: MV Estonia; sinking sequence; new side damage; HSVA Rolls; numerical seakeeping computation; statistical approach

1. Introduction

1.1. New Investigations on the Loss of MV Estonia

The loss of the MV Estonia has been investigated by various organizations in the course of years since the accident took place on 28 September 1994. The root cause of the accident has been assumed to be known and the consequent sinking process well established. However, in September 2020, a new video recording made by an underwater ROV was published by the Discovery Channel, showing a new, previously unknown, penetrating damage on the starboard side of the MV Estonia wreck lying on the seabed. Also, new video footage on the state of the doors in the center casing on the vehicle deck became available. Aside from this, the results of a new sonar survey conducted in November 2023 show debris from the vessel on the seabed in a much more detailed manner than previous studies [1]: This allows an improved reconstruction of the track of the MV Estonia during the ship heeling and sinking process. Finally, new reliable information on the collapse loads of the windows in the ship superstructure, needed in simulations of the ship sinking process, were established in 2024 [2].

Based on the new evidence, the Estonian Safety Investigation Bureau (ESIB) initiated a preliminary assessment of the new information on the MV Estonia accident in October 2020.

Check for updates

Academic Editor: Simone Mancini

Received: 7 January 2026
Revised: 26 February 2026
Accepted: 2 March 2026
Published: 6 March 2026

The objective of the ESIB assessment is to identify the cause of the penetrating deformations on the ship starboard side, to assess the validity of the conclusions presented in the final report of the JAIC [3], and to assess whether the safety investigation of the accident should be re-opened.

For this purpose, in 2024, the ESIB contracted the Hamburg Ship Model Basin HSVA, together with the Kiel University of Applied Science, to carry out numerical simulations and analysis of various sinking scenarios of MV Estonia [4]. One of the goals of the investigation by HSVA is to shed light on the question of whether the New Side Damage (NSD) on the starboard side was already present during the sinking process of the MV Estonia still being afloat on the surface, or whether it resulted later from the collision of the sinking MV Estonia with the seabed. This is an important issue needing clarification, as it has potential to fundamentally challenge the well-established view of the accident's sequence of events.

In the first HSVA study of the MV Estonia sinking sequence in 2006–2008 [5], the numerical simulations in irregular seas led to three alternative outcomes: (1) The ship capsizes in or shortly after the first turn. (2) The ship survives the complete turn and, in stern quartering seas, the flood water sloshes gradually out of the vehicle deck; as the ship pitches in waves it survives for an unlimited period. (3) The ship survives the complete turn, but heels gradually over in stern-quartering seas due to the progressive water ingress through several openings in the ship hull, eventually capsizing.

The computed roll motion behavior of the ship depends strongly on the random wave sequence used in the computations [5]. The simulations show altogether that it is well possible that the heeling and sinking process approximately took place as first suggested in the JAIC Final Report [3].

For the present investigation, the numerical code HSVA Rolls was first updated to a modern operating system and program compiler. The input data in the numerical model HSVA Rolls has been updated, when new information has become available. The most important updates are the new HSVA track based on the more detailed debris locations [1], the new window breaking loads [2], the updated information on the condition of the center casing doors, and, as a separate case, the information on the new side damage.

As the actual state of internal doors in the MV Estonia and the actual wave sequence the ship encountered are not accurately known, it was assumed that the upgraded modeling would benefit from a small fine-tuning of the center casing door conditions, on which the available information remains scarce. After this initial fine-tuning of the center casing door discharge coefficients, the majority of the simulations landed in the desired Category 3, showing behavior like that of the MV Estonia during the accident. Thereafter, all simulations were carried out with these very same input conditions.

With individual numerical simulations using a chosen wave sequence as input, it was shown in [5] that it is possible that the ship heeling and sinking process took place as approximately reconstructed based on all known facts of the MV Estonia accident. Any such simulation, however, gives no certainty that the sinking process must have happened as simulated. The core challenge of the present study is to establish beyond any reasonable doubt, whether the NSD was present when the ship was still afloat, or whether it came into being later, most likely when the ship hit the seabed. For this task, single simulated time-histories alone are not enough, but statistical likelihoods are needed. Therefore, the individual simulations presented in this paper are complemented with a statistical approach, providing likelihoods for different types of behavior of the damaged ship in random seas.

For the statistical approach, most of the damage cases studied were simulated using the very same 100 randomly generated wave sequences. The results give the likelihoods of different types of ship behavior. These computed likelihoods, together with the results from the individual simulation cases and all other known facts of the accident, give a fairly complete picture of the most likely sinking process. Some scenarios can also be closed out, as the majority of their simulation results in random seas show a very different ship behavior than the one reconstructed based on the survivors' testimonies and other known facts of the accident.

The statistical approach was complemented by comparisons between individual damage cases, computed always with an identical wave sequence. This wave sequence was selected to reproduce in the simulations of the basic case, a heeling and sinking behavior closely matching that based on the known facts of the MV Estonia accident. The different damage cases show clear differences in the ship heeling and sinking process. A comparison yields very good indications of what took place in the MV Estonia sinking process, or alternatively what would have taken place under other given input conditions.

Various opening conditions of the center casing doors, including the presence or absence of the opening through the NSD, were applied to the damaged vessel. The response of the vessel and that of the flood water were computed in numerous wave sequences reproducing one specific sea state. By analyzing the overall response trends, it was concluded that the likelihood of the NSD occurring while the MV Estonia was still afloat is very low. It could also be shown that the turning of the vessel to port with the open bow damage was not the optimal course of action during the accident.

1.2. Simulation of Progressive Flooding in Damaged Ships

Over the past four decades, numerical codes for time-domain simulation of the flooding and motion of damaged ships have been introduced and further developed. A very comprehensive recent review of the available methods and their development for modeling the flooding process and the behavior of damaged ships in irregular seas is given by Rodrigues [6].

Most of these available codes capable of simulating complete, extensive ship flooding are based on quasi-static or hydrostatic modeling. Although the numerical approaches differ, sufficiently validated numerical tools are generally considered to provide reliable indicators for assessing the sinking process. Thus, these codes are able to yield practical results and to determine, mostly correctly, whether a ship's condition is safe or not. Details of the flooding process and of the ship motion behavior show many more differences between the different codes applied and the corresponding model test results. Two recent benchmark tests, one for a Ropax ship [7] and one for a cruise ship [8], indicate the need for further research to accurately capture the flooding process of ships, in particular, for a damaged ship in waves.

The need to improve the quasi-static approach in modeling the flooding process has been known for a long time. Efforts to improve the accuracy of the codes have been carried out in various ways: Several authors have studied the values of the discharge coefficients in ship flooding. See, e.g., [9]. The value of the discharge coefficients based on 'vena contracta' has, however, been well-known for almost 400 years and the newer studies do not show significantly different values.

In a damaged ship, flooding can lead to air being trapped and compressed in closed compartments. This also has an effect on the flooding of the ship. Flooding models including air compression have been developed, for example, by Ruponen [10], already in 2007. In many forensic cases, it is, however, not known for sure, whether a certain compartment remained airtight or whether it was ventilated during the flooding accident process.

The basically quasi-static solution methods can be improved with the introduction of dynamic aspects in modeling. The improvements needed for cruise ships and Ropax ships with a large open vehicle deck differ: In a cruise ship, the dynamics of the progressive flow in complicated ship geometries are important, but in a Ropax ship, it is critical to model the dynamic motion of the flood water on the moving vehicle deck as accurately as possible.

In many numerical simulation codes for ship survivability, the water inflow and outflow through a damage opening on a ship side or bottom are modeled with the Bernoulli equation (BE) and the discharge coefficient. The BE describes a steady flow in an inertial frame of reference. This equation takes neither the flood water inertia in the opening into account nor does it regard the effect of the prevailing flow direction or speed in the opening. Besides this, the damaged ship floating in waves is not rigorously an inertial frame of reference. Thus, there are quite a few approximations involved in the common use of the BE for this purpose. Lee [11] used the dynamic orifice equation (DOE) as an alternative. This model takes the inertia of the water mass in the orifice into account, which is a clear improvement over the Bernoulli equation.

Valanto [12] studied the flow through a damaged opening in a ship in calm water and in waves. The traditional Bernoulli equation (BE) for steady flow and the dynamic orifice equation (DOE) introduced by Lee [11] were used. In general, simulations using DOE provided better results than the commonly applied simple BE method, although there were still notable differences between simulation results and those from the dedicated model tests. Further, problems caused by the use of the BE in connection with the rapid shallow-water outflow from Ropax ship deck openings are described in [12], and an improved boundary condition for the use, together with the shallow-water-equations is suggested.

Van't Veer et al. [13] presented the development of a unified internal flow model (UIF) for the prediction of fluid behavior in a network of 3D floodable cells, such as internal ship compartment subdivisions. The UIF model is incorporated in a generic time-domain ship motion simulation environment. The flow model uses cell-averaged fluid momentum to account for dynamic inertia effects in compartments. The newly developed UIF model is stated to overcome the shortcomings seen in the steady Bernoulli-based simulations. Its application can lead to a more accurate prediction of the flood water progression, particularly in large passenger ships [13].

Modeling the flooding and sinking process of a modern cruise ship or a Ropax is altogether a very complicated task. Also for this reason, in practice, the available simulation codes are still based on relatively simple modeling techniques. Besides the improvements in these classical methods, new ship flooding simulation methods are emerging. Perhaps one of the most promising of these is the method of Smooth Particle Hydrodynamics (SPH), see, e.g., [14–17]. SPH is a meshless numerical approach that has attracted significant attention in the last two decades. A good review is given by Le Touze and Colagrossi [18].

Thanks to its Lagrangian formulation, this meshless method shows very high potential in modeling fast and complicated free-surface flows with moving boundaries. This comes, however, with a large modeling effort and high computational cost. A more reasonable approach could be to use the SPH method for modeling the flooding in the damaged ship, where this is relevant, and combine this method with a more classical ship motion program, see, e.g., [19].

The present paper shows an application with a more classical modeling, with hundreds of ship flooding and motion simulations with a validated simulation code in irregular seas. For such an application, the use of more sophisticated methods, like SPH, is still hardly affordable, if possible at all. Regardless of this, important development work on SPH is going on, and wider use of such meshless particle methods for modeling the flooding process and motion behavior of complicated large ships is still expected to come.

2. The MV Estonia Accident

2.1. Main Particulars of the MV Estonia

The main particulars of the intact and damaged MV Estonia are listed in Table 1 following [5].

Table 1. Main particulars of the vessel with and without visor.

Description	Notation	Unit	With Visor	Without Visor
Length over all	L_{OA}	m	157.30	152.65
Length between perpendiculars	L_{PP}	m	137.40	137.40
Breadth over all	B_{OA}	m	24.20	24.20
Draught at midship	T_M	m	5.39	5.36
Draught at AP	T_A	m	5.61	5.67
Draught at FP	T_F	m	5.17	5.05
Metacentric height (fluid)	GM	m	1.19	1.26
Vertical center of gravity	KG	m	10.62	10.62
Height of metacenter above keel	KM	m	11.81	11.88
Displacement	∇	m^3	11,931	11,872
Heel to starboard on 27–28 September 1994	φ	deg	1.0	2.0

2.2. Course of Events of the MV Estonia Accident

The passenger ferry Estonia sank on 28 September 1994, during a voyage from Tallinn in Estonia to Stockholm in Sweden. Of the 989 people on board, only 137 survived the accident. The timeline of the MV Estonia accident as summarized below is mostly based on the survivors' testimonies. More details regarding the survivors' statements and descriptions in time can be found in the HSVA report (2008) [5]. Note that all time references are given in Estonian time, that is, in ship's time.

On 27 September 1994:
At ∼19:15: Departure from Tallinn.

On 28 September 1994:
At 00:30: Waypoint reached. New course 287°. Fin stabilizers were taken into use.
At 00:30–01:02: Visor damaged and ramp loosened by heavy wave loads.
At 00:45: Crash behind the ramp heard by a Seaman. Water on the vehicle deck.
At 00:46: Narrow water jet at the side of the closed ramp.
At 00:56–00:57: Two to three heavy blows heard from the bow and a scraping sound.
At 00:58–01:01: The bow ramp last seen in closed position.
At 00:59–01:01: Watertight doors close.
At 01:02: The large sudden heel.
At 01:02–01:05: The ship starts to turn to port.
At 01:04–01:08: (ECR time 01:20) Bridge: Stabilize the ship.
At 01:06–01:12: (ECR clock shows 01:18–01:24) Main engines stop.
At 01:06–01:12: The crew members C7 and C33 leave the ECR.
At 01:10–01:20: Alarm sounded in Estonian.
At 01:12–01:21: Auxiliary engines stop.
At 01:22: MV Estonia sent a Mayday call, reported blackout and 20–30° list.
At 01:15–01:25: Crew members C7 and C33 reach open deck. Heel angle below 30–35°.
At 01:30: Last message transmitted from bridge.
At 01:31: The ship list ca. 90°.
At 01:35: The clock on the bridge stopped. Probably due to submersion.
At 01:35–01:40: List 125–140°.
At 01:40–01:48: The MV Estonia on one single spot.
At 01:48–01:52: The MV Estonia sinks stern first, bulbous bow submerges last.

2.3. Previous Accident Investigations

The Joint Accident Investigation Commission (JAIC) of Estonia, Finland and Sweden was established on 29 September 1994, on the day following the accident, to investigate it. The final report of the JAIC was published three years later in December 1997.

The JAIC report [3] gives a picture of the accident, which understandably is not complete and appears partly controversial. In addition, the MV Estonia did not capsize, what would have been expected by many experts for a RoPax-ship to do in such an accident, but heeled relatively slowly to the starboard side and sank. The discussion on the MV Estonia accident did not calm down even after many years and perhaps as a consequence the Swedish Governmental Agency for Innovation Systems VINNOVA carried out a public procurement in 2005 for a new investigation. This resulted in the commissioning of two consortia, namely the SSPA-consortium [20] and the HSVA-consortium [5], to investigate the MV Estonia foundering anew. These two consortia carried out their investigations during 2006–2008 independently, but both came in general to rather similar views of the accident process than the JAIC, thus also confirming the overall JAIC accident scenario. Through these studies, light was shed on many remaining open questions in the JAIC report related to the MV Estonia foundering.

2.4. On-Site ROV-Survey on the MV Estonia Wreck

In September 2020, a new video recording made by an ROV was published, showing a new, previously unknown, penetrating damage on the starboard side of the MV Estonia wreck lying on the seabed. For the numerical assessment of the vessel's contact with the seabed, a simplified cargo shift assessment was performed [21]. This model consists of four stages with increasing heel and trim. Figure 1 corresponds to Stage 4, with the estimated ROV track from the 2023 survey marked in orange.

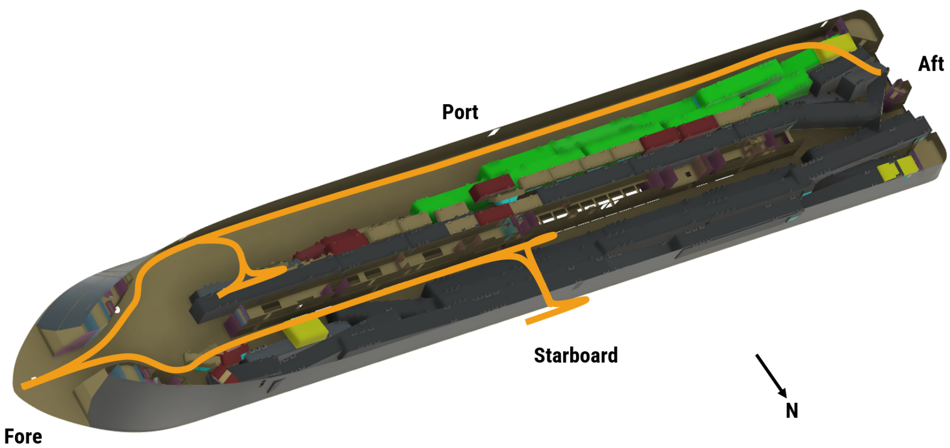

Figure 1. Reconstructed cargo shift status in the vehicle deck space of a grounded ship from ROV observations [22].

In reality, the ROV had a field of view of only a few meters, which made it difficult to obtain a full and three-dimensional view of the vehicle deck space. As presented in Figure 1, ROV observations on the port side, along the inner hull showed that all cargo, including trucks, trailers, and cars, had shifted towards the center casing. Consequently, the ROV had only a limited access to the casing, and apart from the two foremost doors in the bow section, the opening conditions of the remaining doors could not be identified.

As the ship heeled to starboard during the accident, all cargo on the starboard side shifted toward the outer wall, allowing the ROV to take video along the center casing (see Figure 1). The ROV confirmed the opening conditions of six forward center casing doors, but information on the remaining aft doors is still missing. Figure 2 shows ROV observations of the center casing door conditions on both sides of the MV Estonia wreck.

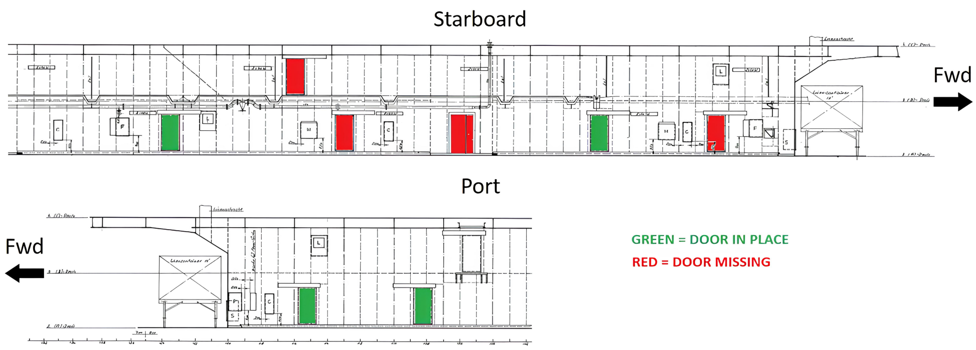

Figure 2. Opening conditions of the doors at the forward center casing on the vehicle deck: doors on the starboard (**top figure**) and port side (**bottom figure**).

Figure 3 highlights the location of the two newly identified side damages on the starboard side, marked in red near the waterline. One dent or small damage, located between building frames 76 and 80, would open into the engine workshop: However, no crew member reported any collision or water ingress there [4], so this damage is not modeled in the present study.

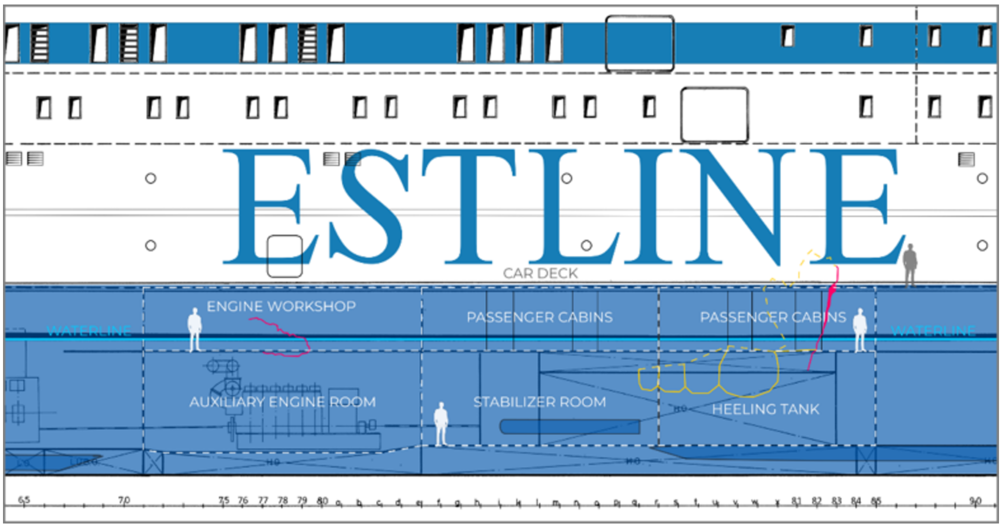

Figure 3. Location of the starboard side damages as viewed by ROV and marked (in red) on the vessel GA plan. The forward damage (NSD on the right) is included in the simulations, the protruding aftward damage (on the left) is not [23].

Another new side damage (denoted as NSD in the present study) extends across building frames 82 to 83 and, in the vertical direction, connects to three different internal compartments: The vehicle deck, the compartment for cabins, and the starboard side heeling tank. The corresponding damage opening areas, respectively, are 0.54 m^2, 0.60 m^2, and 0.099 m^2. Detailed descriptions of the openings and leaks modeled on the damaged vessel in this study can be found in [4].

2.5. The Present Investigation

For the present investigation, the numerical code HSVA Rolls was updated to a modern operating system and program compiler. Otherwise, the numerical HSVA Rolls model of the MV Estonia is to a very great extent based on the earlier modeling carried out by the HSVA in 2006–2008 [5].

The input data in the numerical model HSVA Rolls has been updated, when new information has become available. Most important updates are the new HSVA track based on the more detailed debris locations [1], the new window breaking loads, the updated information on the condition of the center casing doors, and as a separate case the information on the new side damage.

3. New Inputs from Recent Surveys and Investigations

This section summarizes updates from subsequent ESIB investigations in 2020–2024, highlighting new findings in the following areas:

- Track of the vessel during the course of the accident based on debris locations on the seabed (sonar and ROV-surveys);
- Collapse loads of the MV Estonia superstructure windows (numerical and experimental investigation);
- Cargo shift on the vehicle deck (ROV-survey);
- Opening conditions of the center casing doors (ROV-survey);
- Newly founded side damages on the starboard side (ROV-survey).

These items are important modeling details, which have relevant effects on the capsize process of the advancing damaged vessel. They are taken into account in the present study in the simulation of the ship capsize and sinking process. The details of the conditions at the time of the accident for each parameter are described below. The final input conditions are first determined based on plausible assumptions and some of them are later also fine-tuned with a statistical approach. Thereafter, they are applied in all following numerical simulations.

3.1. Old and New Track of MV Estonia

In the previous studies, first by the JAIC (1997) [3] and somewhat later by the SSPA and HSVA Consortia (2008) [5,20], several probable tracks of the MV Estonia during the accident were proposed. A high-resolution seabed imaging sonar survey of the MV Estonia wreck location was carried out in November 2023. The cloud of possible man-made objects (about 300) from this survey matches quite well with the earlier proposed tracks. In addition, more than 35 cigar-shaped elongated objects were detected. The distribution of those meets very well with the curvature of the earlier proposed HSVA track [22]. In July 2024, several objects were checked with the ROV camera, and all of these elongated objects were found to be wooden logs [22].

The obtained distribution of debris and possible tracks is shown in Figure 4. The JAIC track is green, the HSVA track (2008) [5] yellow. Blue targets are elongated objects that are connected with a dashed blue curve. When this curve is shifted south to go through the visor location (green dot), one can see the comparison with the HSVA track of 2008. The difference is that with the blue curve, the western extent of the curve lies roughly 300 m to the west. In addition, a part of the ramp railing (green cross) was found 485 m west of the visor location. The shipwreck is marked by a blue square. Possible life raft containers are marked with orange [22].

Based on the coordinates of the various objects on the seabed, as listed in [1], the blue track suggested in Figure 4 was reconstructed by HSVA based on the following considerations: The elongated objects, obviously wooden logs, were moved against the direction of the prevailing current of 0.5 kn in the direction of ENE (east-northeast = 67.5°), see [3,5], to account for their likely drifting before setting at their final resting place on the seabed. The best match to the ship's track through the position of the fallen bow visor in the direction of 287° was achieved by moving them 180 m against the direction of the mentioned surface current. With these values, the objects would have reached their final lateral position, either in deep water or on the seabed, in ca. 11–12 min. It is further assumed that some of the elongated objects possibly could stay afloat and move longer distances on the surface, but most of them would not move against the surface current.

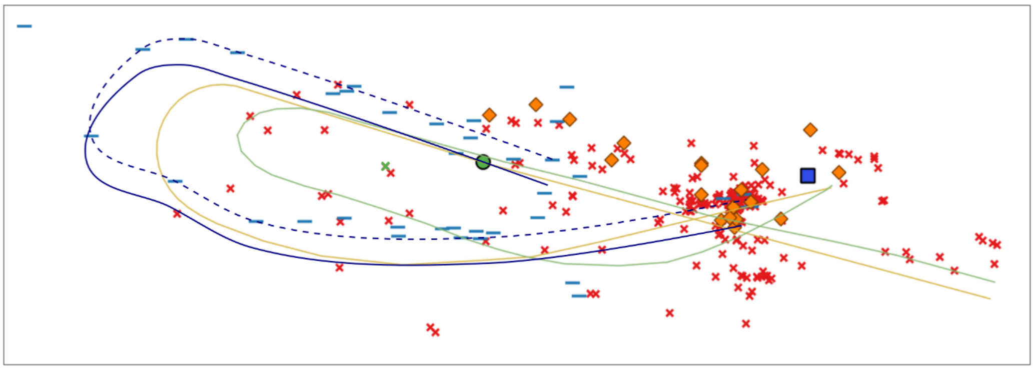

Figure 4. Possible tracks of the MV Estonia during the capsizing and sinking process [22].

The bow visor, the shipwreck itself and two additional solitary objects were assumed to have sunk rapidly enough to not have been significantly moved by the current. Thus, their positions on the seabed were used directly in plotting the new HSVA track. The solitary objects were assumed to have dropped to the starboard side of the vessel, as the ship heeled to that side. The position of the railing of the ramp on the seabed does not fit into anything else. It is likely that during the accident, the bow visor tore the railing from the ramp. These objects are marked with black in Figure 5.

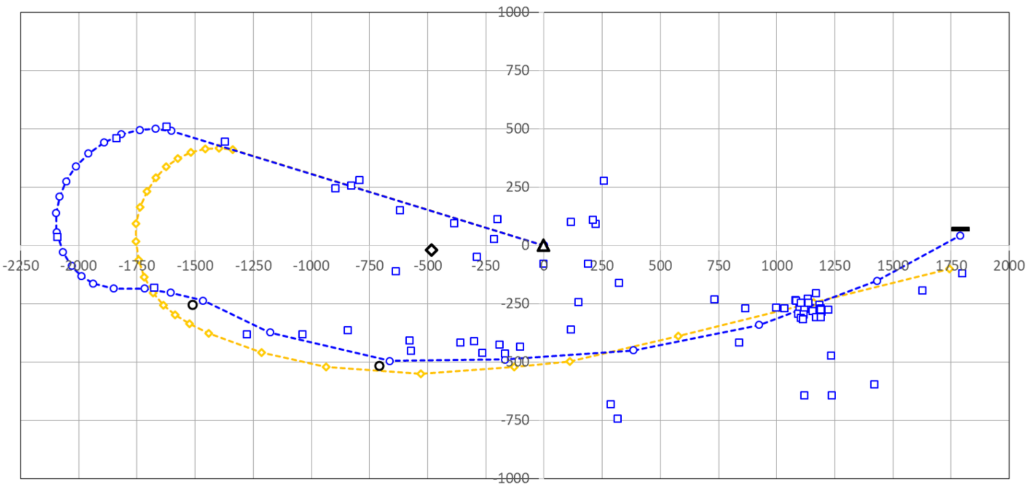

Figure 5. The yellow curve shows one of the old HSVA tracks, and the blue curve, the newly constructed HSVA track, both under the influence of current and wind. The blue markers show the elongated objects moved 180 m against the current. The black diamond marks the railing, the triangle the visor and the bar the shipwreck.

Figure 6 shows the track of the ship through water, showing the actual heading, without the effect of current and wind. The ship speeds along the HSVA tracks, old and new, are based on the loss of kinetic energy of the ship through its resistance in calm water as the ship advances. This speed reduction was computed by HSVA already in 2008. The effect of the accumulation of flood water in the ship is coarsely taken into account in this speed calculation. Further, it is known that with its initial speed and driven by the surface current and wind the vessel completed its track in ca. 40–45 min, that is, in the time gap between the loss of the visor and the final sinking of the vessel. With these restrictions the leeway in defining the speed reduction of the vessel is rather small, which should provide a fairly good accuracy.

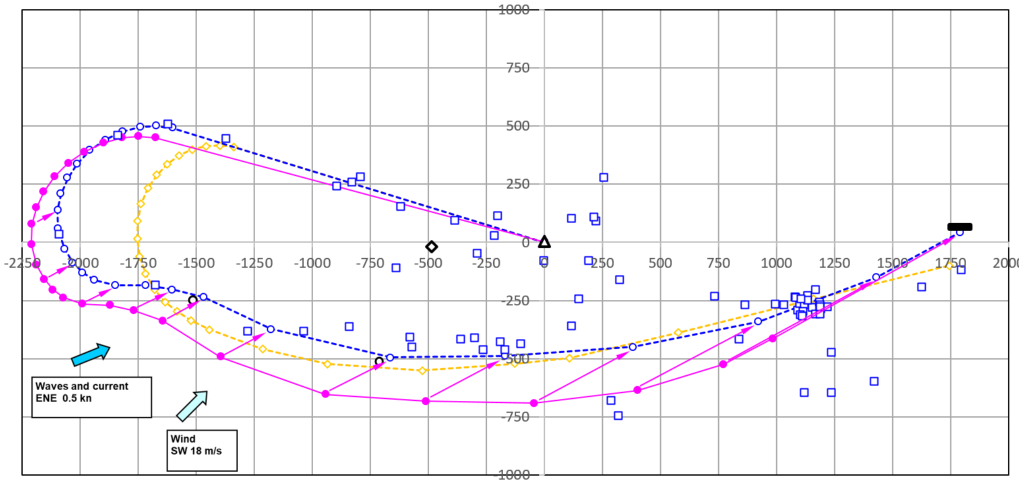

Figure 6. The yellow curve shows one of the old HSVA tracks, the blue curve the newly constructed HSVA track. The pink curve shows the actual (new) track of the ship through water without the effect of current and wind.

The new HSVA track is based on more debris locations than the old HSVA track. It is 6003 m long. The corresponding time between the visor drop and the final position of the wreck is 42 min for the new track.

3.2. Collapse Loads of the Superstructure Windows

In the previous HSVA investigation in 2008 [5], the breaking of the superstructure windows was modeled based on the best information on the window strength available at that time. The windows installed on MV Estonia were categorized into two sizes: large and small. The following breaking load criteria in water column height for large and small windows were used in 2008:

- Small window: 8.2 m;
- Large window: 3.3 m.

This, however, led in the numerical simulations to unreasonably rapid increase of the heeling angle towards the end of the time-histories. In order to improve the results the discharge coefficients of the window groups were reduced, until the computed time-histories of the heeling angle were similar to the heeling angle curves constructed based to the survivor's testimonies. This resulted in unreasonably small discharge coefficient values close to zero for the windows. It was known already in 2008 that the window breaking modeling was problematic, but the reason was not known. With new window strength data becoming available in 2024 [2], this problem has in the present investigation to a great extent been removed.

According to the experimental results on the collapse loads of the MV Estonia windows conducted in 2024 [2], the water column heights corresponding to the collapse loads for the two window sizes are found to be as follows:

- Small window: 17.7 m to 26.1 m (mean water column height: 23.1 m);
- Large window: 6.5 m to 8.1 m (mean water column height: 7.5 m).

The current project applies an average value for each size. The discharge coefficient C_d for both types is chosen to be 0.15, assuming the realistic situation of a partial collapse of the windows when the maximum water column height is reached. It is assumed that the windows do not fail simultaneously. Once one window fails, water enters through it, reducing the external pressure load acting on the adjacent intact windows.

In the simulation, the window is considered to collapse, when the total height of the time-varying wave elevation, including the static water depth due to ship sinkage and heel, exceeds the limit water column height at the center of each window. This is based on the assumption that the instantaneous dynamic wave pressure on a window, e.g., due to a slamming impact, which momentarily exceeds the window-breaking criteria, is unlikely to cause permanent damage to the window.

The update in the window collapse loads has a limited effect on the time–history of the heeling angle, very late during the capsize and sinking process, only near the end of the time–history curve, where both the ship sinkage and heeling angle are large. Thus, during most of the time of the heeling and capsize process, the windows remain intact.

3.3. Cargo Shift on the Vehicle Deck

Based on the results of a field survey carried out by ESIB, the transverse shift of all cargo weighing approximately 1100 tons, including unlashed cars, trucks, and trailers lashed on the vehicle deck, is determined to be 1.5 m and is taken into account in the calculation of the heeling moment on the vessel.

This is an increase of 1.1 m compared to the 0.4 m applied by HSVA in 2008 [5]. The cargo moves gradually from the original position up to 1.5 m towards starboard during the initial turning of the vessel. On the new HSVA track, this takes place between 240 s (heading 287°) to approximately 420 s (heading 147°) after the start of the simulation. During this period, the heeling moment due to the cargo shift is modeled with a sinusoidal ramp. After 420 s, the cargo shift of 1.5 m remains constant and the corresponding heeling moment is applied in the computation at each time step.

The heeling arm and thus also the heeling moment resulting from cargo shift depend also on the heeling angle [4]. As the HSVA Rolls does not inherently account for the cargo movement and the associated heeling moment with it, the time-dependent external moment is intentionally applied from the onset of the turning maneuver to reproduce this effect.

Note that all simulation results presented in the following sections are obtained with the updated window collapse criteria and cargo shift.

3.4. Modeling the Leaking Doors Between Center Casing and the Vehicle Deck

Previous studies show that the estimated inflow rate and the volume of accumulated water on the vehicle deck can significantly vary depending on the encountered wave sequence and on the ship speed and course. The distribution of the flood water on the vehicle deck depends also on the opening conditions of the center casing doors to the vehicle deck. These determine to what extent the flood water remains on the vehicle deck and how much flows into the lower compartments. This has a direct effect on the stability of the damaged ship.

As presented in Figure 7, two of the seven doors on the port side and two of the eleven doors on the starboard side were found to be in place in the ROV survey carried out by ESIB in 2023. The opening conditions of the other doors remain unknown due to the limited view of the ROV to the center casing often blocked by displaced vehicles:

- Port side (PS): 2 fire doors out of 7 are in place;
- Starboard side (STB): 2 doors out of 11 are in place.

An additional issue is that the observed state of the doors in the wreck does not definitively indicate their condition at the time of the accident. Since all doors are non-watertight and industrial experience suggests that fastening devices may fail if the heeling angle exceeds 35–40°, it is likely that the integrity of some center casing doors was compromised. Nevertheless, their condition at the time of the incident remains unknown.

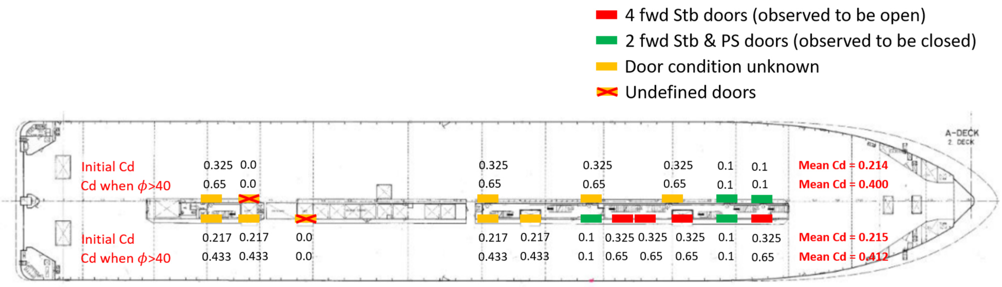

Figure 7. Modeled condition of the center casing doors.

3.4.1. Port Side Center Casing Doors

In the first HSVA investigation in 2008, the numerical simulations show how the flood water from the damaged bow flows onto the vehicle deck to both sides of the center casing, even if the ship is inclined to starboard. On the port side of the vehicle deck, water flows to starboard to the lowest area on the deck at the port side wall of the center casing. On the starboard side of the vehicle deck, the water flows down towards the starboard ship side, away from the center casing.

Survivors coming up from Deck 1 below reported water in the center casing stairs at the level of the vehicle deck and in the bow compartments on Deck 1, supporting the assumption that some of the center casing doors between the staircases in the center casing and the vehicle deck were either open or broken, or they were leaking considerably. It was, however, not known which doors may have been ajar, damaged or leaking. Therefore, all six port side doors in the center casing were modeled one-third ajar, having a discharge coefficient C_d of 0.2, which is one-third of the usual value (0.6). This numerical modeling explained the observations by the survivors fairly well. For this reason, it is further used in a somewhat modified form in the present investigation.

Since the 2023 ROV investigation, it is known that the two foremost doors on the port side of the center casing are still closed on the MV Estonia wreck on the seabed. Therefore, they are assumed to be closed throughout the capsize process, but leaking with discharge coefficient C_d of 0.1. Instead of the original assumption that one third of the remaining four doors on the port side of the center casing are open in the beginning [5], it is assumed that half of these four doors are open in the beginning, which leads to an overall discharge coefficient C_d of 0.65/2, that is, 0.325 for these doors. In addition, it is assumed that these doors open completely, once the heeling angle reaches 40°. See Figure 7 for illustration.

These opening conditions can explain the testimonies of survivors coming up from Deck 1, who reported that there was water in the center casing stairs between the vehicle deck level and the forward compartments on Deck 1, giving direct evidence that some doors were already open or damaged in the early stages of the accident, leading to considerable water ingress.

3.4.2. Starboard Side Center Casing Doors

In the first HSVA investigation in 2008, no center casing doors on the starboard side of the vehicle deck were modeled. This was not considered necessary, while on the starboard side of the vehicle deck, the flood water tends to flow away from the center casing towards the ship's starboard side shell plating. In addition, at that time, there was no information available on the state of these doors. This latter issue has now changed with the results of the ROV investigation on the wreck in 2023. For this reason, the starboard side center casing doors are modeled in the present investigation.

The video footage of the starboard side doors shows that only two of the six foremost doors are in place and closed. The other four doors are missing. These doors are modeled in a very similar manner to the port side doors of the center casing: The two closed doors are assumed to be leaking with discharge coefficient C_d of 0.1. Of the remaining four doors, half are assumed to be open in the beginning, which leads to an overall discharge coefficient C_d of 0.65/2, that is, 0.325 for these doors. In addition, it is assumed that these doors open completely once the heeling angle reaches 40°.

Behind the area surveyed by the ROV, there are five doors on the starboard side of the center casing, whose conditions are unknown. Like on the port side, the starboard side (double) doors of the elevator used only by the crew are assumed to be closed (denoted with a cross in Figure 7). Of the four remaining doors, one third are assumed to be open in the beginning, thus leading to discharge coefficient C_d of 0.65/3, that is, 0.217. In addition, it is assumed that these doors become two thirds open once the heeling angle reaches 40°.

3.4.3. Modeling the Center Casing Doors

The lack of information on the state of the center casing doors during the accident introduces an undesired uncertainty into the simulated results: It is possible to use completely feasible sets of center casing door conditions and, for each set, to find an individual wave sequence, which together yield a simulated time–history of the heeling angle closely matching the one based on the known facts on the accident.

However, further guidance on suitable center casing door conditions can be obtained through a large number of numerical simulations using typical wave sequences for the irregular seas in the HSVA Rolls: Assuming that the MV Estonia did not encounter a very rare or unusual wave sequence, but rather a fairly typical one, a large number of simulations (e.g., 100 realizations) can be carried out using completely randomly generated wave sequences, applying reasonably assumed center casing door conditions. The center casing door conditions are then slightly modified until the majority of the results reproduce behavior similar to that of the MV Estonia during the accident. With this process, the natural randomness of the waves on the sea surface is used to narrow down the most likely set of center casing door conditions. Although the accurate condition of many individual doors during the accident remains unknown, the overall modeling of them appears very plausible.

3.5. Time of Occurrence of the New Side Damage (NSD)

Video footage from the recent underwater survey shows a breach on the starboard side of the MV Estonia wreck on the seabed, which penetrates into the inner compartments. In order to include this New Side Damage (NSD) in the numerical model, it is necessary to reasonably infer the time of occurrence of the damage. Theoretically, it cannot be closed out that the NSD could have occurred while the vessel was afloat in the early phase of the accident.

The known facts on the accident support the scenario that once the visor was detached due to external forces, it fell down and struck the bulbous bow of the ship [3]. The visor did not sink immediately, but floated at the water surface or submerged slowly. It is at least theoretically possible that it came into a further collision between the advancing vessel and the detached visor still being at or near the water surface. The NSD could be a result of such a collision at the ship side.

For the purpose of defining a plausible opening time for the NSD, it is assumed that the advancing MV Estonia collided with its own bow visor, which was still floating after having just been lost. The NSD is assumed to be a result of this collision, which damaged the ship hull at the starboard side about 67 m behind the original position of the visor at the ship bow. The MV Estonia advancing at 14.4 kn needed 9 s to cover this distance between the visor drop-off point and the point of impact on the ship side. Thus, in the numerical simulations, the new side damage is modeled to open 9 s after the drop of the visor and opening of the bow ramp, which is also the starting point of the simulation.

This scenario aligns with survivors' testimonies describing the observation of a water jet on the vehicle deck at the side of the bow ramp, hearing two to three heavy bangs, and then perceiving a scraping sound from the lower part of the vehicle deck and the aft section of the vessel. There is, however, no evidence that the NSD was present during the accident, when the ship was still afloat. If it was, the presented scenario appears the most plausible explanation of what caused the NSD and when it came into being.

4. Methodology

4.1. HSVA Rolls

The simulation of the ship motions in the seaway, together with the time-dependent flow in and out of the damaged compartments and on the vehicle deck, is carried out with the program Rolls. The version used in the HSVA is referred to as the HSVA Rolls. The ship is considered as a six-degrees-of-freedom system traveling at a given mean heading angle relative to the dominant direction of a stationary seaway. The dynamic motion of the flood water on the vehicle deck is solved with shallow-water-equations. More detailed descriptions, including the governing equations applied, can be found in [24]. The newest benchmark test results on the HSVA Rolls among other numerical codes are presented in [7,25].

4.2. Statistical Approach

Following HSVA (2008) [5], this study defines the sea state at the accident site as a single condition (see Table **??**) and conducts the numerical simulations accordingly.

Table 2. Definition of the sea state at the accident site at the time of the accident.

Significant Wave Height H_s (m)	Peak Period T_p (s)	Seaway-Spectrum
4.2	8.3	JONSWAP

Although there may have been slight variations in the sea state over the duration of the accident, it is assumed that the range of these variations was not large. Their influence on the simulated behavior of the vessel is likely to be rather small.

A much larger uncertainty is caused by the problem that the actual wave sequence encountered by the damaged MV Estonia during the accident is not known. During the accident, the vessel first advanced straight ahead about 4 min. After 7–8 min it had already turned about 180°. During this latter time period, the ship had encountered less than 60 random waves. When the number of the encountered waves is so low and their encountering angle and the ship condition significantly change during the encounter time, different wave sequences used in the simulations are bound to lead to significant differences in the simulated ship behavior.

Beside the actual wave sequence encountered by the MV Estonia during the accident, there is a second important uncertainty in the modeling of the sinking scenario of the MV Estonia: The state of the center casing doors during the accident is known only in part. These openings let some flood water from the vehicle deck to flow down into lower compartments, which has an effect on the overall development of the ship heeling.

The modeled state of center casing doors is based on the survivors' testimonies, on the video footage taken during the ROV-survey, and simple mechanical considerations on the door behavior possibly under loading in a heeling ship. These conditions provide constraints to the discharge coefficients used in modeling the flow through the center casing door openings, but not accurate information on the correct values of discharge coefficients to be used in the numerical simulations.

Based on all old and new available information, the center casing doors were modeled using the most plausible discharge coefficients, which also describe the initial leaking and later breaking of such doors with increasing ship heeling angle. Altogether the modified numerical model and the updated input data represent the most updated information on the accident, as correctly as possible.

At the start of this investigation, a few individual test runs were carried out: With little effort, a suitable wave sequence could be identified, which together with the selected (and uncertain) center casing door conditions, yields in the numerical model a heeling behavior for the ship closely matching the one reconstructed based on all known facts on the MV Estonia accident. Such a simulation demonstrates that the sinking process could have occurred as modeled, but it neither provides any estimate of its likelihood nor rules out alternative sinking scenarios. This result is clearly not entirely conclusive. In order to improve the situation, the following statistical approach was applied:

For each chosen set of center casing discharge coefficients, one hundred simulations were carried out using different random wave sequences within the envelope of the selected sea state. The discharge coefficients were then slightly adjusted until the majority of the simulated results reproduced ship behavior very similar to that of the MV Estonia during the accident. Using these final, slightly modified center casing door conditions, a numerical model of the MV Estonia was established, which produces the expected behavior for the majority of cases across the 100 completely random wave sequences. All results presented in the following Sections 5–8 were computed with 100 fixed different wave sequences for the sea state (H_s 4.2 m, T_p 8.3 s, JONSWAP spectrum) with 100 fixed different wave phase sets.

The process of determining the most probable opening conditions through a statistical approach is described in detail in the following Sections. Not only the computed likelihoods of these individual damage cases, but also all other known facts of the accident give a fairly complete picture of the most likely sinking process. Some scenarios can also be closed out, as the majority of their simulation results in random seas show a very different ship behavior than the one reconstructed based on the survivor's testimonies and other known facts of the accident.

Not only the overall trend of roll development over time, but also the capsize timing is a key focus. To determine which opening condition reproduces a large number of sinking processes with timings comparable to the actual accident, the following probability of exceedance (POE) is applied:

$$\mathrm{POE}(T) = P(C = 1, t > T) = P(C = 1) \cdot P(t > T \mid C = 1) \quad \text{, where} \tag{1}$$

$$P(C = 1) = P_{\text{capsize}} = \frac{n_{\text{capsize}}}{N_{\text{sim}}} \quad , \tag{2}$$

$$P(t > T \mid C = 1) = \mathrm{POE}_{t|C=1}(T) \quad . \tag{3}$$

The unconditional exceedance probability of capsize timing, $\mathrm{POE}(T)$, corresponds to the product of the probability of capsize across $N_{\text{sim}} = 100$ wave scenarios (P_{capsize}) and the conditional POE that the capsize time exceeds the threshold time T, given capsize ($C = 1$).

Based on this, the probability of capsize occurring within the actual accident time range ($T_1 < t < T_2$) is estimated as follows:

$$\begin{aligned} \Delta\mathrm{POE}_{[T_1,T_2]} &= \mathrm{POE}(T_1) - \mathrm{POE}(T_2) \\ &= P(C=1,\, T_1 < t < T_2) \\ &= P(C=1) \cdot \Delta\mathrm{POE}_{\mathrm{cond},[T_1,T_2]} \quad \text{, where} \end{aligned} \tag{4}$$

$$\Delta\mathrm{POE}_{\mathrm{cond},[T_1,T_2]} = \mathrm{POE}_{t|C=1}(T_1) - \mathrm{POE}_{t|C=1}(T_2) \quad . \tag{5}$$

It is further noted that a sensitivity analysis on the capsize probability P_{capsize} was performed for the number of realizations N_{sim} = 50, 100, 150, and 200. The results show convergence with an approximately 1% variation for $N_{sim} \geq 100$, confirming that N_{sim} = 100 realizations can be considered to provide practically converged statistical estimates for the purpose of the present study.

For each damage case, the unconditional empirical exceedance probability POE(T), based on the ensemble of all individual capsize events, together with its Jeffreys 95% confidence interval (CI), is provided to quantify sampling uncertainty, which becomes pronounced in the tail due to the rarity of extreme events. A three-parameter Weibull fitting curve is also applied to describe the overall envelope trend of the dominant capsize events, rather than being used as a strict probabilistic model for all events, including rare tail outliers (i.e., extremely late capsize events). In other words, when such rare events occur, they are excluded from the fit so that the fitted curve represents the main trend.

Based on the results, a single case that most closely matches the actual accident in terms of both timing and the magnitude of the roll response over time is selected as a representative case. The statistical approach is complemented with representative individual simulations in Section 9, conducted both with and without the presence of the NSD. These individual cases, always computed using the same wave sequence, are compared to identify differences. The comparisons provide clear indications of the dynamics of the MV Estonia sinking process and of how the ship would have behaved under alternative input conditions.

5. Damaged Ship on New Track, Bow Damage Only—Statistical Approach

5.1. Introduction

The results presented in this section deal with the roll response of the damaged ship with visor lost, ramp fully open, but without NSD and with all up-to-date inputs. For the other openings, where no updates were made, such as the ramp and the ventilation ducts to the vehicle deck and the spaces below, the conditions described in [5] were applied without modifications. All numerical simulations start at the moment in time the visor is lost, at 01:00 ship time on 28 September 1994.

Figures 8–10 show the roll motion of the damaged ship under exactly the same 100 different wave sequences for the three center casing opening conditions; "Reference", "All closed", and "All open". In each figure, the left graph displays the time-histories of the roll angle, with capsized cases highlighted in shades of blue. The right graph displays the unconditional exceedance probability of capsize timing, POE(T), according to Equation (1).

According to the sinking and capsizing process based on survivors' testimonies and previous investigations, the vessel started to flood when the visor dropped off and pulled the ramp fully open. Within approximately 300 s, the rapid inflow of water contributed to the sudden heeling to starboard. Around 1200 s after the initial massive water ingress at the bow, the vessel gradually lost its stability, reaching heeling angles over 60° and began sinking towards the seabed.

To provide a clearer understanding of the capsizing trends observed in the time–history results, the time-sequenced course of events is briefly summarized below:

- 0–235 s: Straight course at 14.4 kn (bow-quartering waves);
- 235–665 s: Turning phase, speed reduction from 14.4 kn to 5 kn;
- 665–2500 s: After turning, speed reduction from 5 kn to 0.8 kn (stern-quartering waves).

5.2. "Reference" Condition

As presented in Figure 8, the damaged ship with the reference center casing door opening conditions capsizes in 50 out of 100 cases, each using a different wave sequence reproducing the JONSWAP spectrum sea state with H_s = 4.2 m and T_p = 8.3 s.

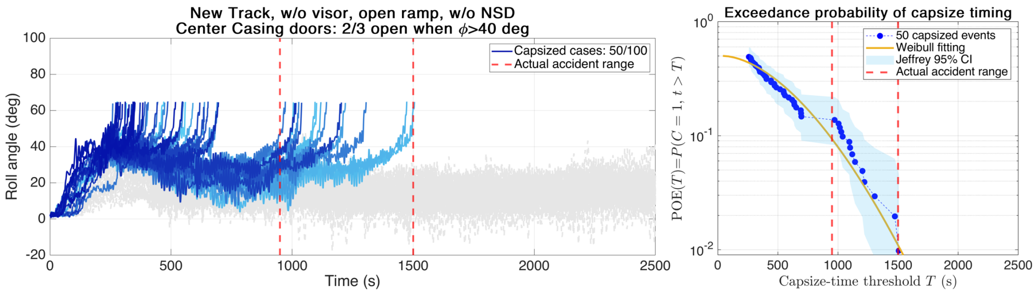

Figure 8. "Reference" condition: center casing doors 2/3 open when ϕ>40°. Weibull fit (shape = 1.74, scale = 674.10).

The capsize time distribution of these 50 capsize cases is fairly distinct and clear:

- 33% (i.e., 33 capsizes out of 100) occurring during the turn (235–665 s);
- 3% occurred in the post-turning phase (665–950 s);
- **14% occurred within the time range comparable to the actual accident (950–1500 s);**
- 0% occurred later than 1800 s;
- 50% of cases survived (i.e., the ship survived the remaining 50 cases out of 100).

During turning, the combined influence of flood water dynamics, cargo shift, and centrifugal force induced rapid roll motion through additional heeling moments, substantially increasing the risk of capsize. Depending on the wave sequence and center casing conditions, a partial stabilization may occur; however, the initial 4–5 min after flooding still appear to be the most critical period for the survival of the vessel.

The majority of capsize cases (36/50) occur during the turn, yet a number of cases (14/50) closely resemble the actual heeling and sinking process. Within the capsize range of 950–1500 s in Figure 8, there are some cases, in which the ship appears to stabilize temporarily, with the roll motion reduced below 20° after the turn, but which subsequently capsize, likely due to encountering unfavorable wave sequences.

The probability of exceedance (POE) distribution of the capsize times for these 50 cases is also presented in Figure 8. Each capsize event is considered independent, such that each has the probability of "1/number of capsized events". Given the strong nonlinearity in the numerical simulations, capsize events that deviate significantly from the main curve may represent "extreme cases" or "non-dominant capsizing patterns", arising from rare wave conditions and nonlinear interactions.

Based on the unconditional POE distribution of the capsize times for the 50 events under the 2/3 door opening conditions, with no significant deviations among individual events and a continuous occurrence of capsize times up to 1500 s, the 2/3 opening conditions appear physically reasonable and largely reproduce the actual accident scenario. The 3-parameter Weibull fit also closely follows the empirical distribution, indicating a high likelihood of capsize within the actual accident time range (950–1500 s).

https://doi.org/10.3390/jmse14050503

5.3. "All Closed" Condition

In the "All closed" opening condition all unknown doors (see yellow rectangles in Figure 7) are assumed to remain closed throughout the simulation. Flood water entering the vehicle deck through the open bow is restricted from flowing down on to the interconnected lower deck compartments via the center casing.

As shown in Figure 9, the capsize probability (P_{capsize}) under the "All closed" opening condition in 100 different wave sequences is 22%, which is significantly lower than under the "Reference" condition (50%). Most capsize events occur during the turning phase, with only one case observed after the turn, at around 900 s. Thus, although the risk of capsize is significantly reduced compared to scenarios with some center casing doors open, the timing and pattern of the 22 capsized cases are not comparable to the actual accident.

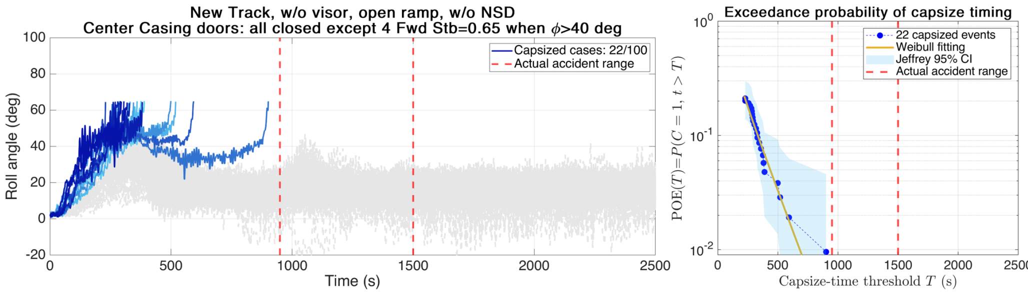

Figure 9. "All closed" condition: All unknown doors closed, with other surveyed door conditions as observed. Weibull fit (shape = 0.97, scale = 143.51).

Due to water accumulating mainly on the vehicle deck in the "All closed" condition, the draft increase from the additional weight is smaller than in the reference condition. The flood water is largely confined to the vehicle deck and can flow back out at the bow, limiting the draft increase. This reduces the likelihood of waves continuing to surge into the vessel thereby increasing the vessel's survivability. Nonetheless, 22 capsize events occur during the turn.

For the remaining cases, in which the damaged vessel survives the turning phase, it maintains a starboard list of about 20° and survives also past the end of the simulation. As the speed decreases below 5 kn and the wave encounter angle shifts to a stern-quartering condition, net water ingress through the open ramp is reduced, while the vessel's pitch motion facilitates egress of the previously accumulated water on the vehicle deck.

In the POE distribution of the limited number of capsize events under the "All closed" condition, only the last event in the tail slightly deviates from the main trend, representing an outlier. Up to the POE level of 0.02, the distribution shows generally a low scatter, indicating that if the damaged ship under the "All closed" opening condition does capsize, it most likely occurs within the time range of 230–600 s. This suggests that the center casing doors were likely not in the "All closed" condition at the time of the accident.

5.4. "All Open" Condition

The simulation under the "All open" condition uses the same initial door configuration as the "Reference" condition. Once the roll response exceeds 40°, all doors, except those observed closed (green boxes in Figure 7), are assumed fully open with a discharge coefficient C_d of 0.65, differing from the "Reference" condition only in the C_d values of the four aft starboard doors.

As shown in Figure 10, a total of 43 capsize events in the "All open" condition are observed, fewer than the 50 events under the 2/3 open condition, suggesting that the large volume of water entering the lower compartments leads to a relatively slower reduction in stability over time, thereby contributing to survival in certain wave sequences. Regarding capsize timing, it extends up to 1500 s, exhibiting a trend comparable to that of the 2/3 open condition.

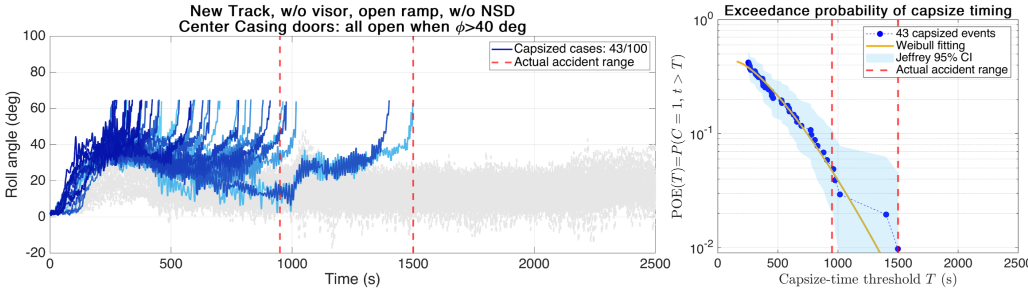

Figure 10. "All open" condition: All unknown doors open (C_d = 0.65 when ϕ > 40°), with other surveyed door conditions as observed. Weibull fit (shape = 1.37, scale = 444.48).

The time series results of the capsized cases indicate that large water ingress into the lower compartments generally tends to accelerate the sinking process. Specifically, while 14 capsize events occur between 950 s and 1500 s under the 2/3 open condition, this number decreases to 5 under the "All open" condition. Instead, more capsizes are observed between 665 s and 950 s, immediately after the turning phase.

Considering these somewhat opposing trends, shorter capsize times, but fewer occurrences under the "All open" condition, the simulation results show that the capsize behavior is highly sensitive to nonlinear interactions between the motions of the damaged vessel, flood water dynamics, and incident random waves.

Among the 43 capsize cases, 5 occur within the 950–1500 s range, although all these are positioned at the outer edges of this interval, according to the POE results in Figure 10. Compared to the "All closed" condition, the "All open" condition yields more plausible results, which better resemble the actual accident scenario, suggesting that it represents a more probable center casing opening configuration than the "All closed" condition.

6. Damaged Ship on New Track, Bow Damage and NSD—Statistical Approach

6.1. Introduction

As noted previously, the cause and timing of the NSD remain uncertain. Nonetheless, its occurrence is an established fact. Based on survivors' testimonies and all other available information, it cannot presently be closed out that the NSD could have come into being due to a collision between the fully detached, slowly sinking visor and the starboard side of the ship, which was advancing at 14–15 kn.

In order to investigate this scenario, the case study in this section applies the three center casing door opening conditions as described in Section 5 ("Reference", "All closed", and "All open"), with the addition of the NSD. All other variables, including the lost visor, open ramp, and updated inputs, remain unchanged. Since the NSD is positioned approximately 67 m behind the original visor location on the bow, its occurrence is assumed to take place 9 s after the start of the simulation, corresponding to the moment when the ramp is fully open. Through this case study, the likelihood of the NSD occurrence, while the ship was underway, is investigated.

6.2. "Reference" Condition with NSD

As shown in Figure 11 for the damaged vessel under the "Reference" condition with the NSD, a total of 69 capsize cases out of 100 are observed. This represents a notable increase compared to the same opening configuration without the NSD, exhibiting 50 capsize events (see Figure 8).

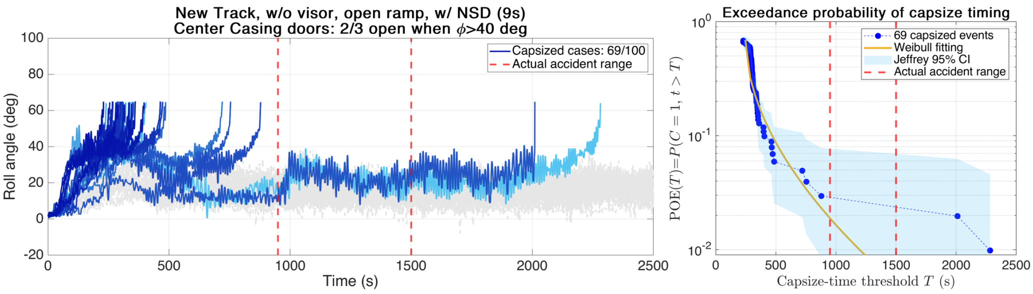

Figure 11. Roll response time–history for "Reference" condition with NSD. Weibull fit (shape = 0.54, scale = 66.33).

Most capsize events occur during the early stage of the turning phase, except for five cases. Although water ingress through the NSD is relatively small, its presence induces an additional heeling moment toward starboard. The resulting additional heeling angle causes the large volume of flood water on the vehicle deck, coming from the open bow, to flow toward starboard, contributing to an early and abrupt capsize.

Among the other 5 capsizing cases, in 3 cases the ship barely survives the turn, eventually capsizing within the time range of 720–880 s. The remaining 2 cases exhibit a stable heel response until 1800 s, after which a gradual increase is observed, ultimately leading to capsize after 2000 s. Such a delayed capsize seems to be primarily attributed to the wave sequences encountered.

The additional water ingress through the NSD opening ultimately causes 19 previous survival cases without NSD to capsize with NSD. Furthermore, for those cases that were already observed to capsize under the "Reference" condition without the NSD, the time to capsize in most cases is either significantly shortened to around 300 s or prolonged to approximately 2000 s. In both scenarios, these capsize times are far outside the timeframe of the actual accident. The capsize time distribution of the 69 capsized cases is as follows:

- 64% (i.e., 64 capsizes out of 100) occurred during the turn (235–665 s);
- 3% occurred in the post-turning phase (665–950 s);
- **0% occurred within the time range comparable to the actual accident (950–1500 s);**
- 2% occurred later than 1800 s;
- 31% cases survived.

In the ship motion simulations conducted with the 2/3 center casing doors open under 100 specific wave sequences, only one capsize case occurred relatively close to the actual time frame (around 900 s). With this result the likelihood that the NSD occurred while the damaged vessel was still afloat appears very low. The POE distribution of the capsize time, in which the last 2 points in the tail of the POE curve deviate from the rest, supports this claim. The Weibull fitting results also show that the capsizing process of the damaged vessel with this opening configuration is highly likely to conclude within 900 s.

6.3. "All Closed" Condition with NSD

Figure 12 shows the results of the "All closed" condition with the NSD. The number of capsizing incidents increases significantly from 22 to 70 compared to the same opening configuration without the NSD (see Figure 9), while the overall trend in capsize timing remains largely unchanged, with most cases occurring during the turning maneuver.

Considering the vertical position of the NSD, which is normally partially submerged below the waterline, the substantial water volume already taken in through the bow, and the additional heeling moments induced by turning, the NSD is likely to submerge deeper during the maneuver. This increases the hydrostatic pressure at the submerged inlet, thereby enhancing water ingress through the NSD and acting as a trigger that further reduces the vessel's stability. The same situation may have occurred in other cases applying the NSD, but it appears particularly prominent in this case.

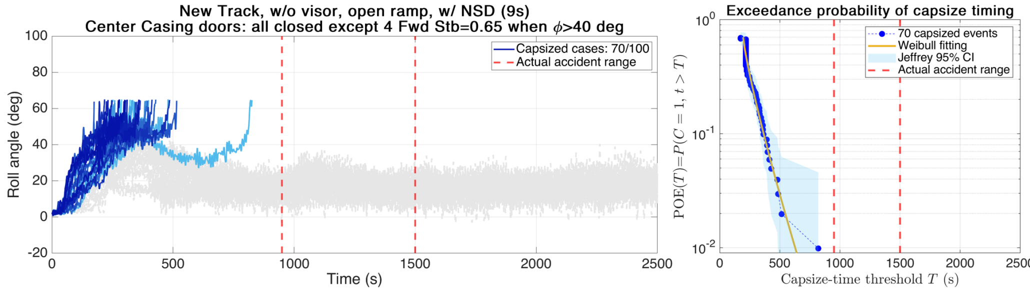

Figure 12. Roll response time–history for "All closed" condition with NSD. Weibull fit (shape = 0.84, scale = 77.00).

Regarding the POE distribution in Figure 12, all capsize events except the last in the tail exhibit a smooth probability distribution, suggesting that under the 2/3 center casing door opening condition with the NSD, capsize is highly likely to occur within 500 s. Thus, when the NSD occurs in the "All closed" condition, reproducing a scenario similar to the actual accident is extremely unlikely.

6.4. "All Open" Condition with NSD

Figure 13 shows the simulation results for the "All open" condition with the NSD reaching a total of 70 capsize events. As observed also in other cases with the NSD, a significant increase in the number of capsizing events is shown compared to the case without the NSD (43 capsize events, see Figure 10).

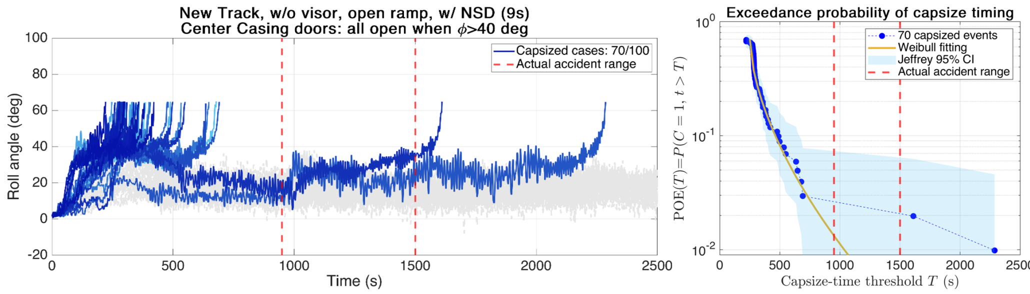

Figure 13. Roll response time–history for "All open" condition with NSD. Weibull fit (shape = 0.60, scale = 69.21).

The impact of additional water ingress through the NSD on the capsizing process is substantial, as seen in other cases, 68 capsizing events occur during turning, while the remaining 2 occur much later around 1600 s and 2300 s.

Notably, the roll response trend due to the application of the NSD closely resembles that of the 2/3 door open condition with the NSD (see Figure 11). The POE distribution indicates that if capsize occurs under this opening condition, it is highly likely to happen within 700 s, although in rare cases it may occur after 1600 s. This also suggests that the simultaneous occurrence of the bow opening and NSD under this condition is unlikely.

7. Damaged Ship with NSD Only

7.1. Introduction

The NSD is assumed to be the only damage on the outer hull of the vessel, letting water in. The visor is lost, but the ramp at the ship bow is assumed to be closed. Since the NSD-only configuration allows only a small amount of flood water into the vessel, the opening conditions of the center casing doors is not expected to significantly affect the results: For simplicity, only the 2/3 door-open condition is applied.

Simulations are performed both on a straight course and on the new track. In particular, the straight course simulations aim to determine whether the resulting heel develops rapidly enough to force the crew on the bridge to take action to turn the ship or to reduce speed. For the straight course simulations, two speed conditions are considered: maintaining the initial speed of 14.4 kn or applying the decreasing speed profile used on the new track. For the new track simulations, the ship speed decreases from 14.4 kn to 0.8 kn.

In order to ensure comparability with the first scenario in Section 6, it is assumed that the NSD opens 9 s after the start of the simulation. Any differences in simulation results therefore arise solely from the presence of the NSD or changes in the vessel's track or speed, with all other modeling parameters unchanged. From the perspective of numerical modeling, the two scenarios are effectively equivalent.

7.2. Straight Course, NSD Only, Constant Speed

Figure 14 shows the simulation results for the damaged vessel experiencing water ingress solely through the NSD under 100 different wave sequences at a constant speed of 14.4 kn. The individual roll responses, shown as gray curves, indicate that variations among wave sequences do not lead to significant differences in ship motion, and the overall response trends remain similar.

The red curve, the mean roll response of all realizations, indicates a steady roll increase of approximately 10° due to water ingress during the initial phase of the simulation, lasting up to around 700 s. After this period, the rate of increase slows down, and the ship stabilizes at approximately 10°, with only minor fluctuations in the heeling angle until around 5000 s. Between 5000 s and 7000 s, the heel increases steadily again, reaching a peak of about 25°. After 6500 s, that is, almost after two hours, although the magnitude of roll variations induced by various wave scenarios increases, these fluctuations can be regarded as negligible in assessing, whether the actual accident was caused solely by NSD. After reaching its peak, the damaged vessel gradually stabilizes, maintaining a roll angle below 20° for the remainder of the simulation.

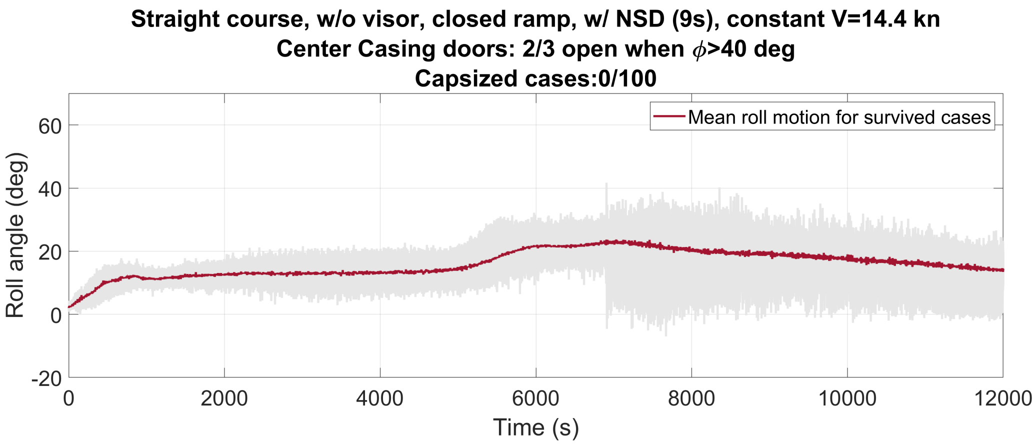

Figure 14. Ship on a straight course with lost visor, intact ramp, and NSD at constant speed.

The roll response in Figure 14 between 0 s and 250 s shows an increase of 3–4° (from the initial 2° to approximately 5–6°), which is much less than in the actual accident. Such a small increase can be considered insufficient for the bridge crew to initiate a rapid turn while on a straight course. Furthermore, as shown in the period between 0 s and 4000 s, where the heeling angle remains around 10° with almost no increase, the computed results suggest that the water ingress through the NSD alone does not induce sufficient heeling to cause the damaged vessel traveling on a straight course to capsize.

7.3. Straight Course, NSD Only, Decreasing Speed

The same damage configuration as in Section 7.2 is applied, but with a speed reduction from 14.4 kn to 0.8 kn, as on the new track. The results are presented in Figure 15.

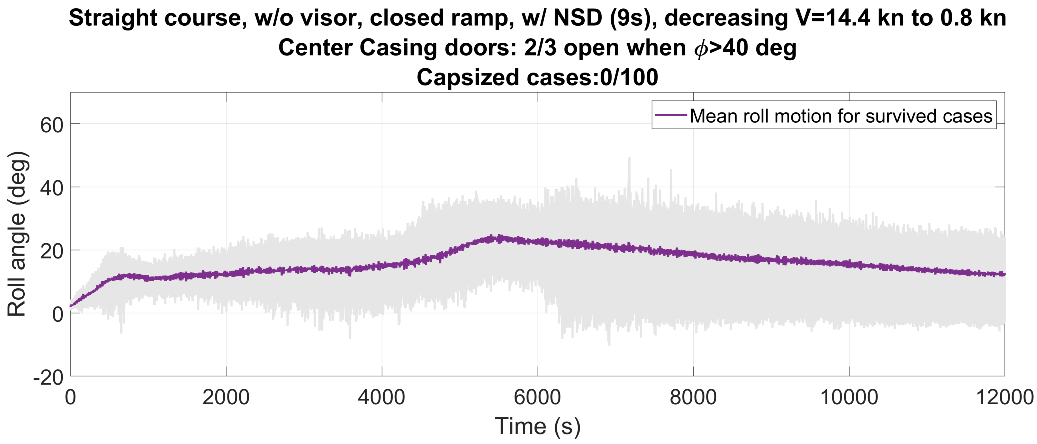

Figure 15. Ship on a straight course with lost visor, intact ramp, and NSD at decreasing speed.

Up to 4000 s, the trend of mean roll response is observed to be fairly similar to that of the ship traveling on a straight course at constant speed in Figure 14. However, after 4000 s, the roll increase becomes more pronounced, reaching its peak around 5500 s, which is slightly earlier. Afterwards, the roll response gradually decreases and the damaged vessel stabilizes with the roll response of below 20°.

Overall, it can be said that flooding due to the NSD alone on the damaged vessel traveling on a straight course does not create a situation in which the bridge crew would be forced to execute a turn to avoid the eventual capsizing.

7.4. New Track, NSD Only, Decreasing Speed

The simulation results for the damaged vessel, having the water ingress solely from the NSD, on the new track are presented in Figure 16.

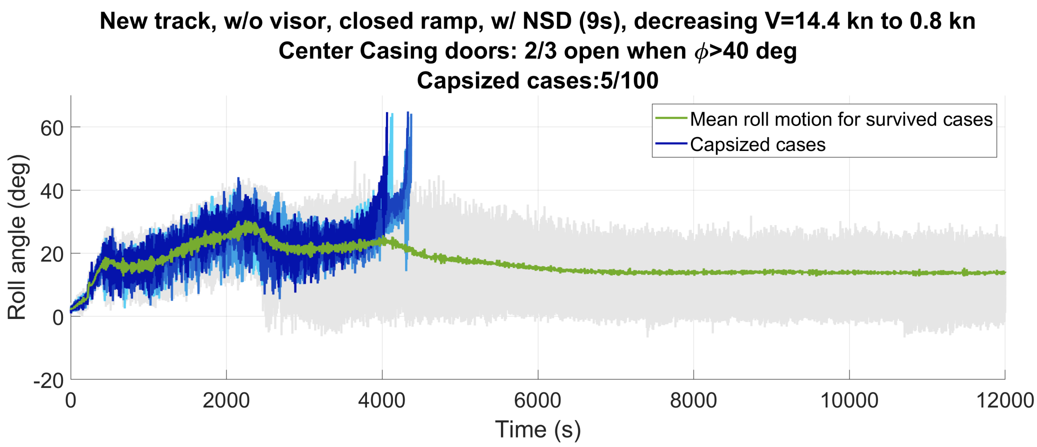

Figure 16. Ship on the New Track, with lost visor, intact ramp, and NSD at decreasing speed.

In the time period before the turning phase (0–250 s), the mean roll response reaches nearly 10° and continues to increase, reaching approximately 20° during the initial turning phase (250–500 s). The peak response, reaching approximately 30° (mean value), is observed around 2300 s, before the heeling angle begins to continuously decrease until 3000 s.

After 3000 s, the mean roll response of the damaged vessel shows an increase by 4100 s before stabilizing again, remaining around 15° for the rest of the simulation. At the time range near 4100 s, the damaged vessel appears to encounter unfavorable wave sequences in some cases, leading to its roll response exceeding 40° or even capsizing in 5 specific wave scenarios.

Compared to results on a straight course (see Figures 14 and 15), the overall response appears to develop faster, and it is more pronounced in terms of its magnitude and timing of peak response occurrence. Furthermore, given the 5 capsize cases, applying the same opening conditions, but running on the new track appears to be more prone to induce capsizing scenarios.

The starboard NSD, initially on the lee side, becomes exposed to environmental conditions on the wave side as the vessel turns, directly facing first the bow-quartering waves and later the stern-quartering waves. In addition, dynamic loads from cargo shift, centrifugal force, and accumulated water during the turn act to submerge the NSD further below the free surface, increasing water pressure at the damaged opening. This more vulnerable positioning in terms of water ingress through the NSD alone contributes to the overall higher roll development seen in the results.

Nevertheless, considering the 95 survival cases and 5 capsizing cases observed near 4100 s, which is far later than the timeframe of the actual accident reported by survivors, the damage case with the NSD only on the vessel running on the new track appears rather unlikely.

8. The Effect of Speed and Course on Ship Survivability

8.1. Introduction

According to the simulation results of the previous section for water ingress solely through the NSD on a straight course, as shown in Figures 14 and 15, the damaged vessel survives in all computed wave sequences. When the vessel under the same opening conditions is advancing on the new track, some capsize cases are observed. Thus, the turning of the damaged vessel appears to have an adverse effect on its survivability.

This raises the question of how the capsizing tendency changes, if the vessel maintains a straight course instead of turning, in a situation where the bow damage opening occurs first, followed by the NSD opening, as applied in Section 6. The objective is to investigate how the time–history of the heeling angle of the vessel changes and whether the decision to turn, made to ensure the survival of the vessel from an operational perspective, would be the best course of action. Two scenarios are studied, in which the damaged vessel (visor lost, ramp open, 2/3 center casing doors open, with or without NSD) runs on a straight course at either constant or decreasing speed.

8.2. Straight Course, Bow Damage and NSD, Constant and Decreasing Speeds

Figure 17 presents the results of this scenario on a straight course at constant speed. It can be observed that capsizing occurs in all 100 cases, with the bow ramp and the NSD open leading to a capsize mostly between 250 s and 750 s. In a few cases, capsizing occurs later, around 800 s to 900 s.

In this straight-course scenario, the vessel continuously encounters bow-quartering waves. This circumstance allows a significant amount of water to flow in at constant ship speed through the open bow, resulting in inevitable capsize regardless of the particular wave sequence. This situation is considered the most critical in every aspect.

Figure 18 presents the results of this scenario on a straight course at decreasing speed. The only difference from Figure 11 is that the vessel continues straight instead of turning on the new track. On a straight course, capsizing occurs in 65 cases, compared with 69 cases on the new track out of 100. The difference is small, slightly favoring the straight course with decreasing speed.

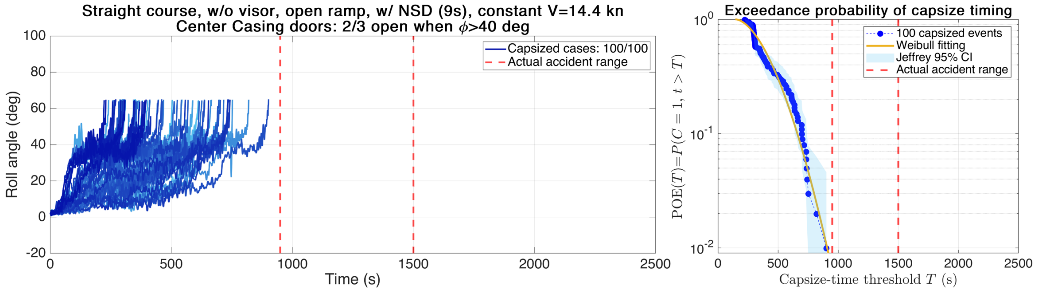

Figure 17. Ship on a straight course with a lost visor, open ramp, and NSD at constant speed. Weibull fit (shape = 1.76, scale = 321.35).

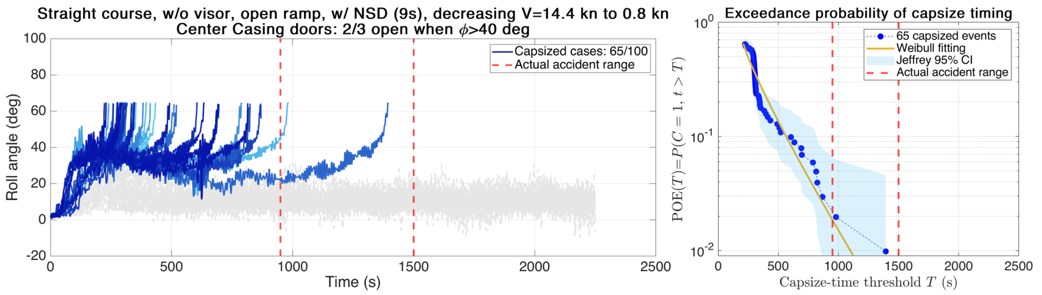

Figure 18. Ship on a straight course with lost visor, open ramp, and NSD at decreasing speed. Weibull fit (shape = 0.88, scale = 174.32).

Comparing straight ahead results at constant speed (100 capsizes, see Figure 17) to the straight ahead results at decreasing speed (65 capsizes, see Figure 18), the very clear positive effect of reducing ship speed on the survivability of the vessel is observed. A major reason for this is the reduced speed of the water inflow at the open bow.

Thus altogether, based on the simulations, here with both the bow damage and the NSD, the effect of reducing speed appears to be a more effective measure against rapid stability loss and capsize, than turning the vessel.

8.3. Straight Course, Bow Damage Only, Constant and Decreasing Speeds

This section aims to assess the influence of the course of the MV Estonia with bow damage only under the "Reference" center casing door open condition, which is considered the most probable opening configuration the vessel would have experienced during the accident. The analysis seeks to evaluate whether a turning maneuver of the damaged vessel was an optimal decision to try to improve survivability, with the intent of providing insight for further discussion and conclusions.

Figure 19 presents the results for the MV Estonia with bow damage only, 2/3 center casing doors open, without NSD, traveling on a straight course at a constant speed of 14.4 kn. Capsizing occurs in all 100 wave sequences, mostly between 240 and 850 s, with a few cases observed later around 940–1100 s. Compared to the scenario with NSD (see Figure 17), the timing of capsizing is slightly delayed, as expected.

Figure 20 presents the results of this scenario on a straight course at decreasing speed. This enables a direct comparison with the results presented in Figure 8, where the vessel follows the new track with the same speed decrease.

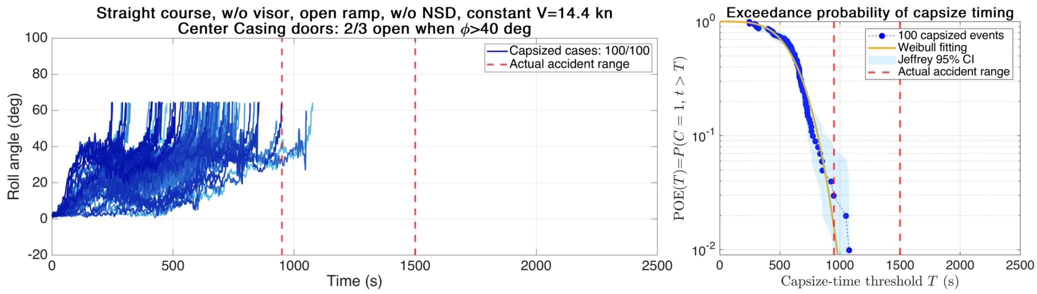

Figure 19. Ship on a straight course with lost visor, open ramp, and no NSD at constant speed. Weibull fit (shape = 3.94, scale = 669.81).

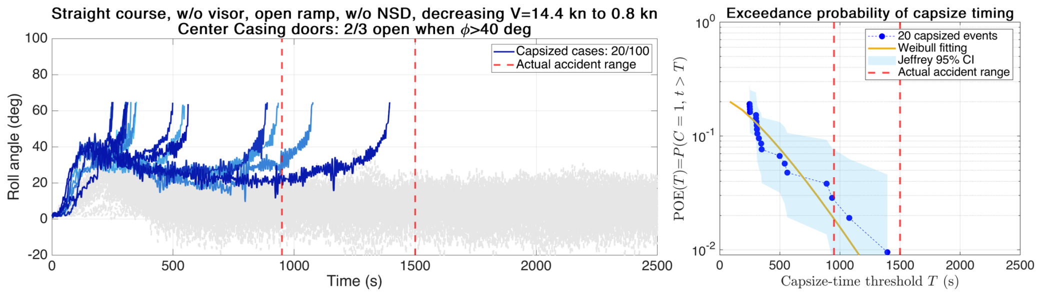

Figure 20. Ship on a straight course with lost visor, open ramp, and no NSD at decreasing speed. Weibull fit (shape = 1.24, scale = 432.97).

The only difference to Figure 8 is going straight ahead instead of turning on the new track. On a straight course, capsizing occurs in 20 cases, compared with 50 cases on the new track out of 100. There is a clear difference in favor of continuing on straight course, but reducing speed, as on the new track.

Similar to the case with bow damage and NSD open (see Figures 17 and 18), the comparison of straight-ahead results at constant speed (100 capsizes, see Figure 19) and at decreasing speed (20 capsizes, see Figure 20) clearly demonstrates the remarkable positive effect of speed reduction on vessel survivability.

Thus, altogether, based on the simulations, here with the bow damage only, the effect of reducing speed appears to be a clearly more effective measure against rapid stability loss and capsize, than turning the vessel. As the scenario of the MV Estonia having the bow damage only on the new track best corresponds to the real case that took place, this comparison also shows what would have most likely happened to the MV Estonia, if it would have just continued straight ahead with constant speed, just reduced speed or carried out like it did in the real case.

9. The Representative Sinking Scenario from the Statistical Analysis

9.1. Introduction

With the statistical approach, the 2/3 center casing door opening condition without NSD was confirmed as the most plausible damage configuration. A specific wave sequence that most closely reproduces the actual sinking process was then selected from 100 simulation runs as the representative scenario. In this section, the effects of the NSD, center casing door opening conditions, ship speed, and track on the sinking process are analyzed in detail using this single wave sequence.

9.2. The MV Estonia on the Old Track with Original Input Data and on the New Track with All Updates

As shown in Figure 21, altogether the simulation on the new track with updated input data provides a very similar heeling behavior of the ship to that on the old track with original (2008) [5] input data. Differences between the heeling behavior are more due to the random character of the waves than to the small differences between the two tracks used.

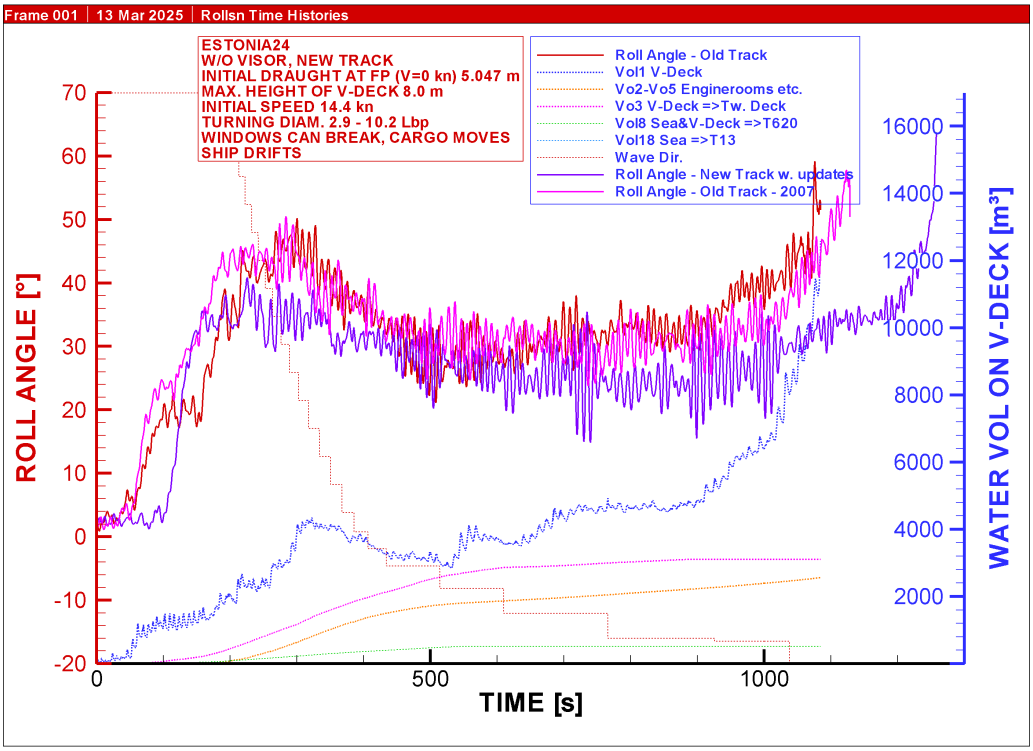

Figure 21. Heeling angle and water volumes on the vehicle deck, lower deck, and machinery spaces as a function of time. Cargo shift and ship drift are included. Red curve: old track computed with the current compiler and computer. Blue curve: new HSVA track. Purple curve: old track from HSVA Estonia Investigation, 2008.

Figure 22 shows the development of the heeling angle according to HSVA (2008), TUHH (2008), and JAIC (1997), based on survivors' testimonies and according to numerical simulations. The black curve shows the development of the heeling angle, including the rapid sudden heeling in the beginning, as described by many survivors. This curve is a suitable reference curve for dynamic simulations. The red curve does not show this initial, dynamic heeling, and is suitable reference curve for quasi-hydrostatic calculations. The blue curve is the time–history concluded by JAIC after the accident.

Aside from older simulated time-histories (HSVA 2008), also the time–history of the heeling angle on the new HSVA track in the present study (HSVA 2025) is shown. The initial rise time of the heeling angle in the HSVA 2025 curve is reasonably comparable to that in earlier simulations from 2008, although the peak heeling angle is slightly lower. This may partly be due to the new track, but it is certainly also influenced by the different individual wave sequence used to describe the irregular seaway. As the new HSVA track represents an improvement over the older tracks, and the simulations does not reveal any significant deviations, the new HSVA track is adopted in all further simulations.

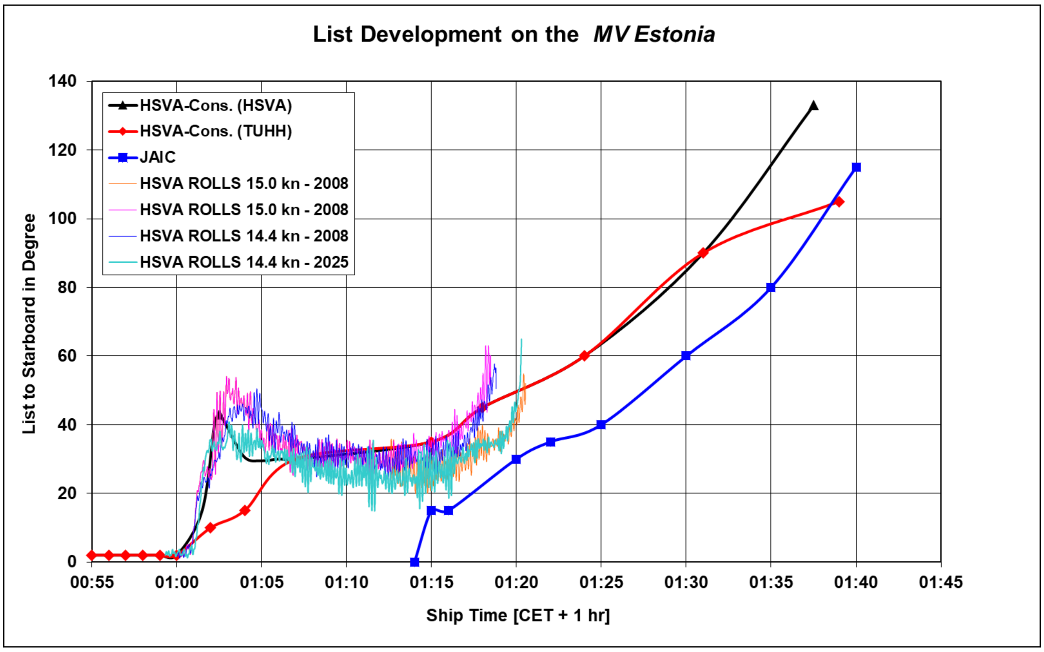

Figure 22. Development of list to starboard during the MV Estonia accident.

9.3. The MV Estonia on the New Track with NSD Under Center Casing Door Conditions "Reference", "All Closed", and "All Open"

Figure 23 shows the MV Estonia on the new HSVA track with and without new side damage (NSD) on the starboard side of the ship. The long red curve corresponds to the development of the heeling angle on the new HSVA track without the NSD. The much shorter pink curve shows this development with the NSD. Most plausible assumptions on the opening conditions (reference ≈ 2/3 open) of the center casing doors are used in computing this curve.

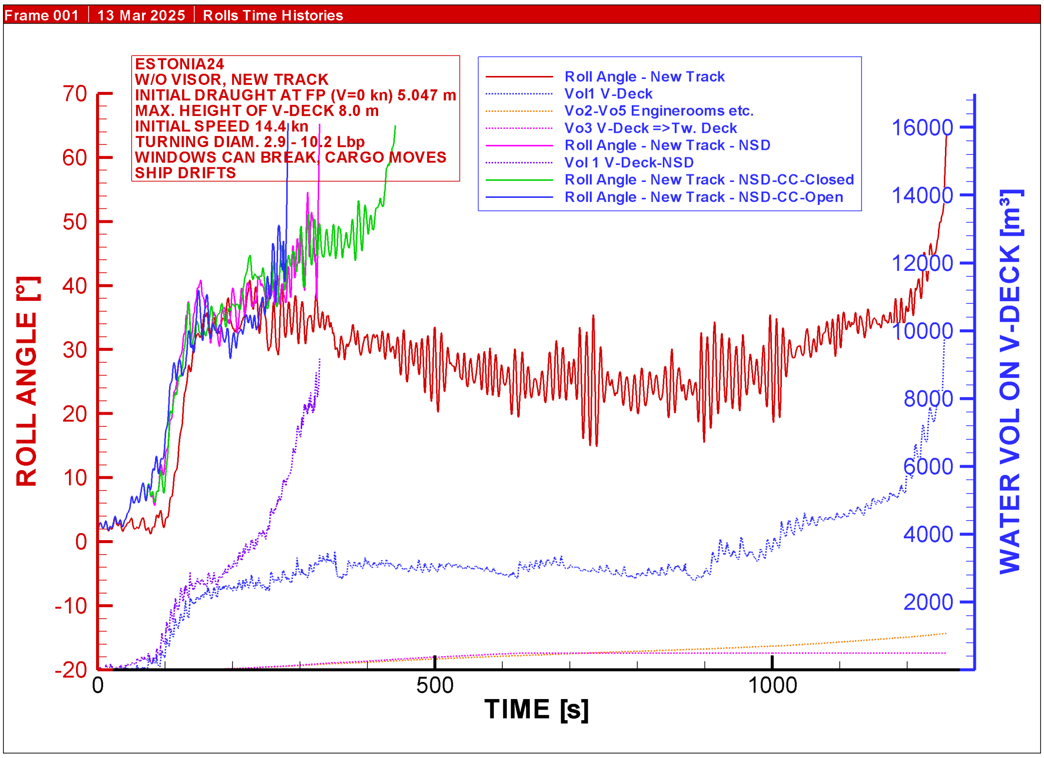

Figure 23. The MV Estonia with the bow damage on the new HSVA track with (blue, pink, green) and without the new side damage (red).

As the conditions of the port and starboard side center casing doors during the accident are not accurately known, two additional curves, one with open center casing doors (blue) and one with closed center casing doors (green) on both sides of the center casing were computed. As the blue and green curves show, the effect of opening or closing all center casing doors is not very large. Thus, the assumptions made in modeling the center casing doors do not appear to have a significant influence on the simulation results.

Altogether, regardless of the modeling of the center casing doors, the presence of the NSD leads to time-histories of the heeling angle in which the ship capsizes within 4–7 min. This, however, did not happen. These time-histories are clearly very different from the one constructed based on survivors' testimonies and other known facts about the accident. Based on these simulations, it is highly unlikely that the NSD was present on the ship hull shortly after the visor was lost.

9.4. MV Estonia on a Straight Course and on the New Track with the New Side Damage with and Without Speed Reduction

Figure 24 shows the heeling angle on the new HSVA track with the bow damage, with (pink) and without the NSD (red). In addition, two simulations with the NSD on a straight track with (yellow) and without (black) speed reduction are shown. In these cases, the presence of the NSD on the hull of the MV Estonia leads to a rather rapid capsize of the vessel, which did not take place. The speed reduction on a straight track is identical to the speed reduction on the new HSVA track.

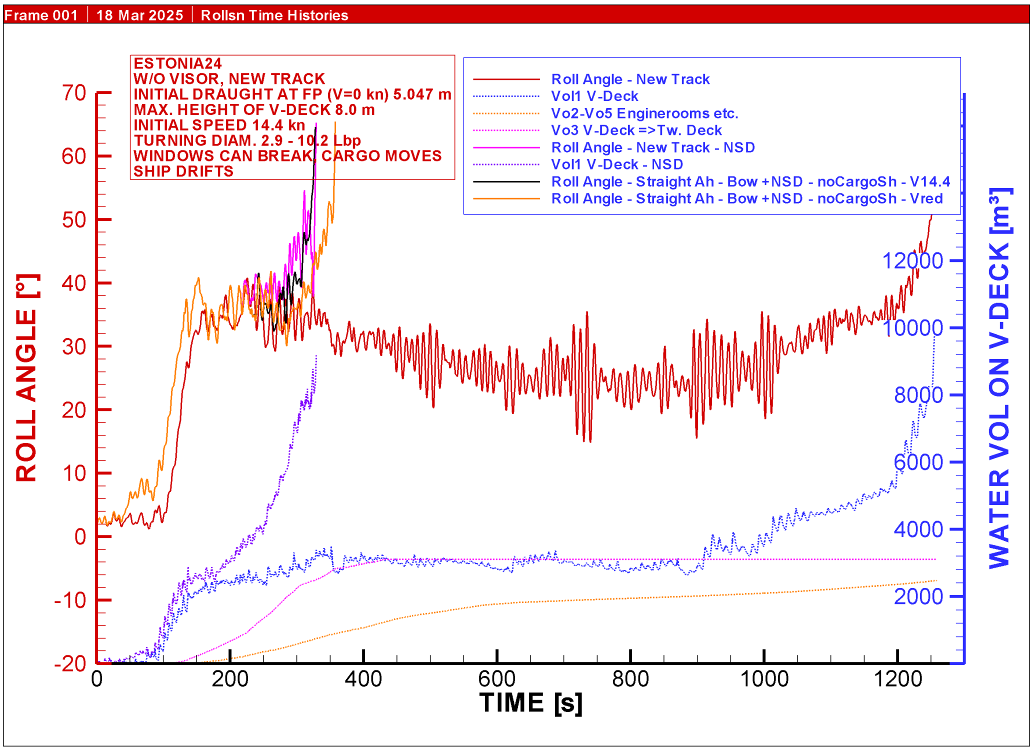

Figure 24. The MV Estonia with the bow damage on the new HSVA track with (pink) and without the NSD (red). The yellow and black curves show the ship behavior with the bow and new side damage on a straight track with and without speed reduction.

Thus summarizing, across all tested conditions—including different tracks, center casing door configurations, and speed assumptions—the presence of the NSD consistently results in a rapid capsize within approximately 4–7 min, a scenario that does not align with the actual accident sequence. These findings suggest that the NSD was unlikely to have been present during the ship capsizing process while still afloat.

9.5. MV Estonia Advancing on a Straight Course

9.5.1. Bow Damage Only on a Straight Course

One of the tasks in the present study is also to investigate the course of events, if the MV Estonia would have continued on a straight course with the side damage only. Thus, in this case, there is no damage on the ship bow opening to the vehicle deck, but there is side damage, as found in 2021 on the starboard side of the MV Estonia wreck lying on the seabed. In order to shed light on this issue, several simulations using the same wave sequence were carried out on both the HSVA new track and straight track: For comparison, the classical case of the MV Estonia with the bow damage only on a straight course is studied first.

Figure 25 illustrates the situation of the MV Estonia with the lost visor and bow ramp completely open on a straight course with and without speed reduction. The red curve in Figure 25 shows the heeling angle of the MV Estonia on the new HSVA track until capsize for comparison. The dotted curves show the computed water volumes on the vehicle deck, tween deck, and other compartments. The green curve shows the case with the MV Estonia on a straight course at a constant original speed of 14.4 kn, while the violet curve shows the speed as reduced along the new HSVA Track. There is no centrifugal acceleration on a straight course, and no cargo shift is modeled.

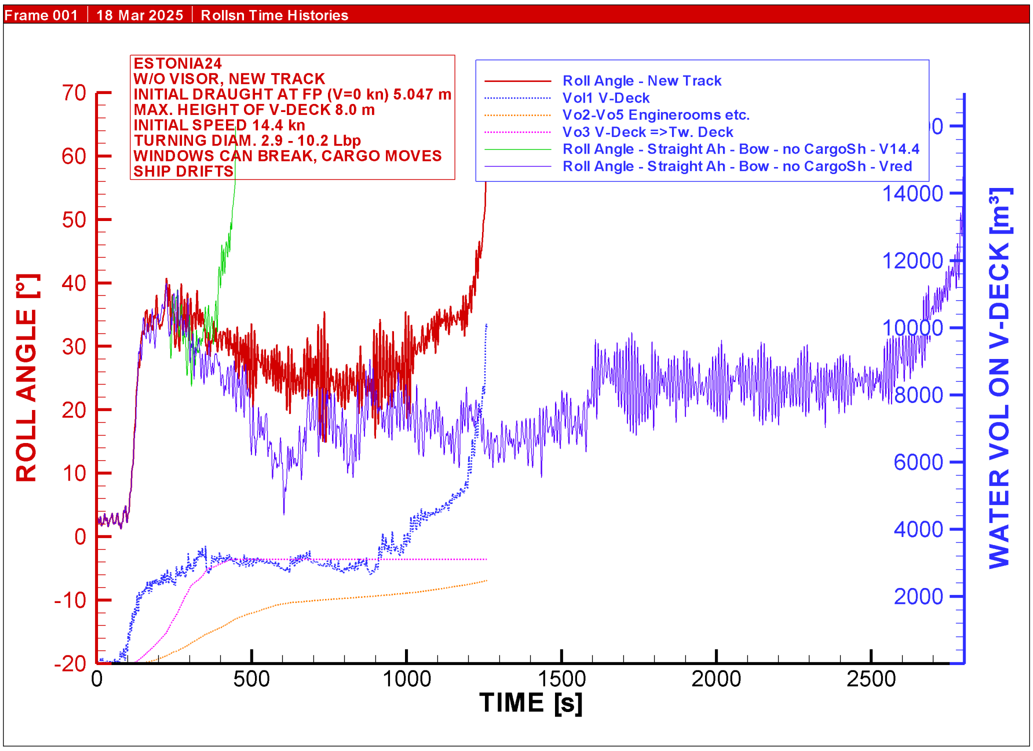

Figure 25. The MV Estonia on the new HSVA track and on a straight course with and without speed reduction, with lost visor and bow ramp completely open.

With only the original bow damage and no NSD, the heeling process and capsize are sped up, if the ship maintains the constant speed of 14.4 kn. If the speed is reduced as on the HSVA new track, the ship capsize is significantly postponed. These two simulated time-histories of the heeling angle do not correspond to that observed by the survivors (see Figure 22). The results in Figure 25 show the following: The speed reduction of the MV Estonia on a straight course leads to a clearly longer survival of the vessel than maintaining a constant speed. This is to be expected, as the inflow at the damaged bow is strongly dependent on the ship speed. The turning of the vessel towards the waves causes additional heeling and centrifugal forces, which have an adverse effect on the ship survival. Accordingly, the time to capsize on the new track is shorter than on a straight course.

9.5.2. NSD Only on a Straight Course

Figure 26 shows the time–history of the heeling angle of the MV Estonia on a straight track with NSD only, represented by the nearly horizontal red and purple curves. The red curve corresponds to the constant speed of 14.4 kn and the purple one to the speed reduction exactly as on the new HSVA track. For comparison, the case of the MV Estonia on the new HSVA track with the side damage only is shown with the light blue curve.

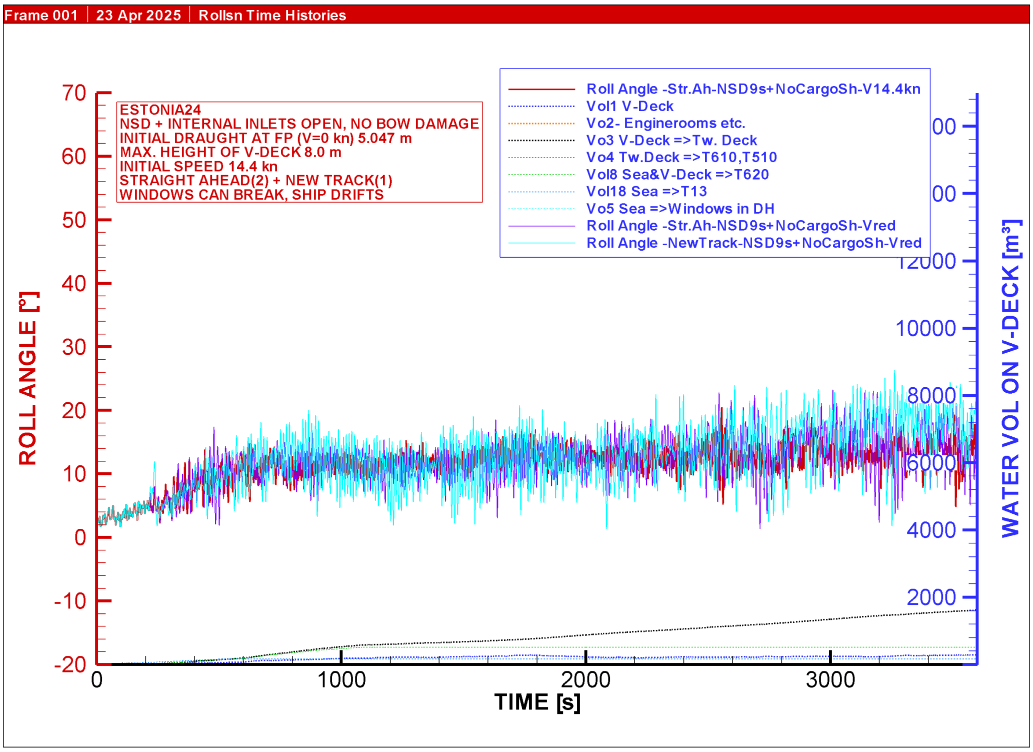

Figure 26. The MV Estonia on a straight course with (purple) and without (red) speed reduction, with the new side damage only. The light blue curve shows for comparison the heeling angle of the MV Estonia on the new track with the new side damage only.

For the two straight course results (red and purple curves), the heeling increases first very gradually, in a relatively steady manner for about 1–1.5 h, until it starts a long decrease towards its final value of about 10°. The ship survives the flooding with this final heeling angle in a stable floating position. The difference to the time–histories based on survivors' testimonies as shown in Figure 22 is very clear. Thus, the accident scenario of the MV Estonia on a straight track with new side damage only is very unlikely.

9.6. Conclusions Based on Individual Cases

- The computed results show very clearly that the damage scenario of the MV Estonia on the new HSVA track with both the bow damage and the side damage caused by the collision with the detached bow visor is a very unlikely damage scenario. Based on the computed results, it seems very reasonable to assume that the new side damage was not present during the ship heeling and capsize process.
- Any modeling assumptions regarding the center casing doors (all open, all closed, most plausible conditions) do not change this general result.
- If the ship would have advanced on the original straight course, with or without speed reduction, the general result as above does not change.

- The classical scenario with the bow damage only on the new HSVA track appears to be the most likely damage scenario.
- The scenario with the bow damage only on a straight course is not a likely damage scenario, but based on the simulated heeling processes it cannot be completely closed out. Based on the debris on the seabed, it can be closed out.
- The scenario with the new side damage NSD only on the new HSVA track as well as on a straight track leads to a ship heeling process, which is clearly different than the one constructed based on the known facts on the accident. The heeling remains fairly small and the ship survives. This is clearly not a possible, correct damage scenario.

10. Conclusions

10.1. Updated Simulation Code HSVA-Rolls and Input Data

The New HSVA Track

Based on the new information on the debris on the seabed provided by ESIB, a new HSVA track was constructed. The drift of floating objects caused by wind and current before setting on the seabed, and the speed reduction and possible turning radius of the MV Estonia were taken into account in this process. Altogether, the new track can be regarded as the best available reconstruction of the real MV Estonia track during the accident.

Updated input for numerical simulation

All new information available for modeling purposes, such as the updated window strength and the surveyed conditions of the center casing doors and cargo shift in the shipwreck lying on the seabed, was incorporated into the numerical model.

The MV Estonia on the new track, with bow damage only: Center casing door conditions upgraded.

As the actual state of the internal doors in the MV Estonia and the precise wave sequence encountered by the ship are not accurately known, the recently updated modeling of the center casing door conditions was fine-tuned. After this initial adjustment of the center casing door discharge coefficients, the majority of simulations fell into the desired Category 3, exhibiting behavior consistent with that of the MV Estonia during the accident. Subsequently, all simulations were conducted using these same input conditions. The variation of random waves within the sea state was thus employed to refine the center casing door conditions, increasing the likelihood of achieving realistic outcomes.

Epistemic uncertainty in the numerical model

All results from numerical simulations are subject to assumptions and input data used in the modeling. The effect of three important assumptions, made under some epistemic uncertainty, are commented as follows:

Test simulations showed that the behavior of the damaged ship is not very sensitive to the assumed opening time of the relatively small NSD, 9 s after the start of the simulation. The NSD at the starboard side is located near the actual waterline, and its effect becomes more pronounced only later, when the ship heels to starboard during the turn to port, which submerges the NSD deeper down and increases the pressure head at the damage opening.

The numerical model of the damaged ship contains altogether 38 modeled openings, with an effective cross-sectional area ($C_D * A$) of ca. 58 m^2. The open bow and access onto the open ramp make almost half of this area. The effective initial cross-sectional area of the center casing doors amounts to ca. 6 m^2, which is 10.3 percent of the total. Thus, the fine-tuning of the discharge coefficient values on the 16 center casing doors is limited to this fairly small portion of the total area of the openings. The effect of this adjustment on the reliability of the overall results is assumed to be very small.

A single sea state (H_s 4.2 m, T_p 8.3 s, JONSWAP-spectrum) as in the first HSVA study [5] was used also in this study. This ensures, in its part, consistent results between the present study and [5]. The selection of this sea state and variations thereof is dealt with already in [5]. The small uncertainty in the sea state encountered by MV Estonia is not expected to change the overall results and conclusions of the present study.

10.2. Conclusions Based on the Statistical Approach and the Computed Individual Cases

In order to considerably improve the reliability of the individual single cases, a statistical approach was used to study the behavior of the ship always in 100 different wave sequences for the given sea state.

Table 3 summarizes the simulation results, excluding NSD-only cases (see Figures 14–16), and shows that two aspects must be addressed: the overall likelihood of capsize, $P(C = 1)$, and the likelihood of reproducing the actual accident timing, $\Delta POE_{[950,1500]}$. While the inclusion of NSD generally increases $P(C = 1)$, it does not necessarily improve agreement with the actual accident time range (950 s < t < 1500 s).

Table 3. Summary of capsize occurrence probability and interval POE of capsize timing (950 s < t < 1500 s) for different opening conditions and scenarios. $P(C = 1)$: capsize probability, $\Delta POE_{cond,[950,1500]} = POE_{t|C=1}(950) - POE_{t|C=1}(1500)$: conditional POE given capsize, and $\Delta POE_{[950,1500]} = POE(950) - POE(1500)$: unconditional POE.

Course	Center Casing Doors	Ramp	NSD	V	$P(C=1)$	$\Delta POE_{cond,[950,1500]}$	$\Delta POE_{[950,1500]}$
New track	Reference	Open	w/o	Decreasing 14–0.8 kn	50.0%	28.0%	14.0%
	All closed				22.0%	0.0%	0.0%
	All open				43.0%	11.6%	5.0%
	Reference	Open	w/	Decreasing 14–0.8 kn	69.0%	0.0%	0.0%
	All closed				70.0%	0.0%	0.0%
	All open				70.0%	0.0%	0.0%
Straight course	Reference	Open	w/	Constant 14 kn	100.0%	0.0%	0.0%
				Decreasing 14–0.8 kn	65.0%	3.1%	2.0%
		Open	w/o	Constant 14 kn	100.0%	3.0%	3.0%
				Decreasing 14–0.8 kn	20.0%	10.0%	2.0%

Among the considered cases, the new track reference condition without NSD provides the best match to the accident timing, with $\Delta POE_{[950,1500]}$ = 14% and a conditional interval POE of 28%. By contrast, the other new track cases show an unconditional interval POE of 0%, regardless of whether the NSD is applied or not. The only exception is the "All open" case without NSD, which yields 5% and remains relatively less plausible than the reference case.

Although ship speed is confirmed to be a critical parameter in straight-course simulations, the straight-course scenarios do not agree with the testimonies and can therefore be excluded. Detailed discussions of each condition are provided in the following sections.

The likelihood of extreme center casing door conditions with 100 wave realizations

Simulations using three sets of center casing door conditions were employed to assess their effect on the behavior of the damaged ship. In the reference condition of the center casing doors, 14 capsize cases fall within the time frame of the actual accident. In the "All closed" condition, zero capsize cases occur within this period, while in the "All open" condition, five cases do so. Thus, the reference condition appears to be the most likely scenario.

The "All closed" condition can be ruled out, whereas the "All open" condition is less likely than the reference condition but cannot be excluded based on the numerical simulations.

The MV Estonia with the bow damage and NSD on the new HSVA track

The computed results clearly show that the damage scenario of the MV Estonia on the new HSVA track with both the bow damage and the NSD caused by the collision with the detached bow visor is highly unlikely. In all center casing door cases "Reference", "All closed", and "All open", not a single simulation yields a capsize time falling between 950 s to 1500 s, as observed in the actual MV Estonia accident. Thus, the alternative modeling assumptions regarding the center casing doors do not change this general result. Most of the capsize cases take place in a much shorter time. Based on the computed results, it seems very reasonable to assume that the NSD was not present during the ship heeling and capsize process on the track constructed based on the debris on the seabed and other real facts on the MV Estonia accident. Also, if the ship would have advanced on the original straight course, with or without speed reduction, this general result does not change.

The MV Estonia with bow damage only on the new track

The classical scenario with the bow damage only on the new HSVA track appears to be the most likely damage scenario. The new HSVA track based on the debris locations on the seabed is an improvement in comparison with the tracks used earlier. The corresponding time-histories of the heeling angle, however, remain very similar.

The MV Estonia with bow damage only on the original straight course

The scenario with the bow damage only on the original straight course is not a likely damage scenario, but based on the simulated heeling processes, it cannot be completely closed out. Based on the debris on the seabed, this scenario can, however, be closed out.

The MV Estonia with NSD only on the original straight course and on the new HSVA track

The scenario of the MV Estonia with only the NSD on a straight course as well as on the new HSVA track leads to a ship heeling process, which is clearly different than the one constructed based on the known facts of the accident. The heeling remains in all cases fairly small. On a straight course, the ship survives, both at constant and at decreasing speeds. On the new track, the ship capsized in 5 cases out of 100 cases in different wave sequences. In these 5 cases the capsize takes place much later than in the real MV Estonia accident. Thus, the damage case with the NSD only is altogether extremely unlikely.

10.3. Conclusions on the Effects of Speed Reduction and Turning on the Survivability of the MV Estonia

The effects of the speed reduction and turning of the ship on the survival times of the MV Estonia were studied in two cases: (1) MV Estonia in the hypothetical case with both the bow damage and the new side damage; (2) MV Estonia in the classical case with only the bow damage.

In both conditions, MV Estonia advancing straight ahead with the bow damage and with or without the NSD, reducing speed clearly and significantly improves the vessel's survivability compared to maintaining a constant speed.

In both conditions, MV Estonia with the bow damage, with or without the NSD, turning the damaged vessel introduces additional dynamic heeling moments, which adversely affect the vessel's survivability compared to maintaining the original straight course. In the classical case of the MV Estonia with the bow damage only, turning of the vessel leads to significantly lower survivability.

Overall, the computations carried out for the ship with the open bow show that maintaining a straight course and reducing speed, without turning, appears to offer the highest level of survivability for the vessel.

10.4. The Benefit of Numerical Simulations of Past or Potential Marine Accidents

More than 30 years after the MV Estonia accident, the numerical simulations show in terms of capsize probabilities to which consequences the alternative courses of action by the crew on the bridge during the accident would have led.

During the accident, the crew on the bridge had to make their decisions very fast, most likely without full knowledge of what was happening. Now, much later, it has become possible, with a high degree of reliability, to study alternative courses of action with the help of numerical simulation.

Numerical simulations like the ones presented could be used for educational purposes to show beforehand what happens in a potential damage case, when different courses of action are taken. This could help to further improve the safety of the passenger and RoPax ship operation.

Author Contributions: Conceptualization, methodology, software, validation, formal analysis, investigation, resources, data curation, P.V. and S.K.; writing—original draft preparation, S.K.; writing—review and editing, P.V.; supervision, P.V. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Estonian Safety Investigation Bureau (ESIB) Public Procurement No 277489. The writing of this paper was financed by HSVA.

Data Availability Statement: The data presented in this study are not publicly available due to commercial confidentiality.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the writing of the manuscript.

Abbreviations

The following abbreviations are used in this manuscript:

BE	Bernoulli Equation
DOE	Dynamic Orifice Equation
ECR	Engine Control Room
ESIB	Estonian Safety Investigation Bureau
HSVA	Hamburg Ship Model Basin
JAIC	Joint Accident Investigation Committee
NSD	New Side Damage
POE	Probability of Exceedance
SSPA	RISE—SSPA Maritime Centre, a research institute in Sweden
UIF	Unified Internal Flow

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