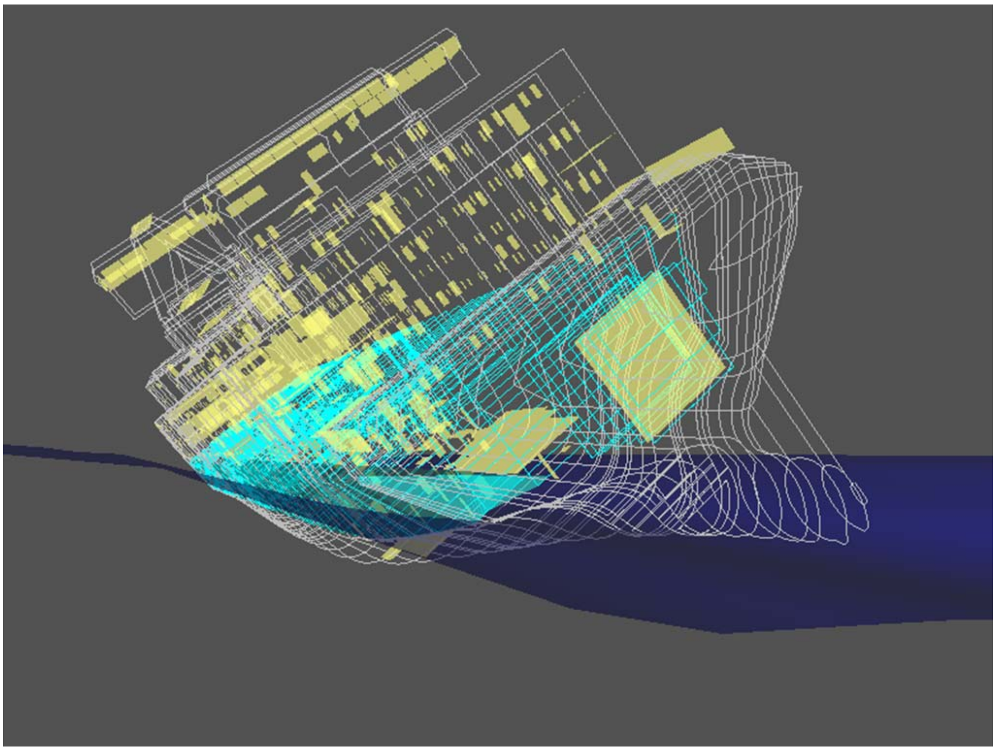
SSPA Research Report No. 134, 2008



Final Report-
Research Study on the Sinking Sequence of *MV Estonia*

SSPA Consortium

Project funded by VINNOVA:

The SSPA Consortium:

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PREFACE

This report is the final documentation from the SSPA Consortium on the “Research Study on the Sinking Sequence of MV Estonia”, which was funded by VINNOVA (The Swedish Governmental Agency for Innovation Systems) between March 2006 and May 2008 with 8.88 million SEK (about one million Euros). The VINNOVA Registration Number is 2005-02852 and the SSPA Project Number is 4006 4100.

The final and complete documentation consists of three DVDs with

- All 18 Project Reports (pdf format).
- Model test of the foundering of MV Estonia showing the most probable loss scenario, adjusted to full scale time (wmv-file).
- Computer animation of the most probable foundering scenario (avi-file).

All documentation is available for public downloading on the web site:

http://www.safety-at-sea.co.uk/mvestonia/ (Public Downloads) or www.sspa.se.

Many people and organisations have helped significantly with support, advice and assistance to this Consortium. Their contributions are gratefully acknowledged.

Lastly the SSPA Consortium wishes to express its deepest sympathy to the relatives and friends of those who perished in the accident.

5th of May, 2008

Claes Källström
Project Manager

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1 SUMMARY

A summary of work and results from "Research Study on the Sinking Sequence of MV Estonia" is given in this report. There are 17 more reports describing all details of the findings of the research project.

The "Research Study on the Sinking Sequence of MV Estonia" has combined a set of forensic, design, experimentation and analytical modelling to scrutinize and review the available evidence, to synthesise this into loss hypotheses, to test these hypotheses through first-principles modelling studies, and to finally demonstrate the established scenario of the loss.

It is concluded that the loss of 852 people on the night of 27/28th of September 1994 has resulted from a rapid loss of stability by MV Estonia. Therefore, all the circumstances and reasons for

- breach of hull integrity allowing unobstructed ingress of sea water into the spaces of MV Estonia
- inadequate stability to allow orderly ship evacuation and abandonment in case of such water ingress,

were considered as the causes of the disaster.

However, in view of the conclusion on the most likely sinking sequence of MV Estonia, it can confidently be stated that the lack of compliance with minimum SOLAS requirements on forward collision bulkhead by MV Estonia on the night of 27/28th of September 1994, was the main reason for unobstructed ingress of sea water into the car deck spaces and, therefore, that this was the main cause of the ship loss in the light of international maritime law.

The approach adopted in the research project was:

- To review evidence such as testimonies from survivors and observations from all available video recordings from diving and ROV (Remotely Operated Vehicle) investigations. Four diving team members from the wreck investigation were also interviewed.
- To form an International Panel of Experts (IPE) to assist the SSPA Consortium to suggest different loss hypotheses conformant with the evidence.

- To perform fundamental and systematic model experiments to derive data for numerical simulation models.
- To build comprehensive numerical models to describe the performance of the damaged MV Estonia during the initial foundering phase when it was manoeuvred and when drifting in wind and waves, as well as for the progressive flooding when water enters the ship.
- To evaluate the different loss scenarios and derive the most probable one using different numerical simulation methods.
- To substantiate the most probable scenario by computer simulations/animations and physical model experiments.
- To derive conclusions and to make recommendations for future safety improvements of passenger vessels.

The most probable foundering scenario as identified in the project is:

- The ramp is forced partially open by the bow visor prior to complete visor detachment from the vessel.
- Water is entering the car deck through the openings at the sides of the ramp resulting in a slowly increasing starboard heel angle.
- The ramp remained partially open until the bow visor detaches from the hull.
- The ramp fully opens and is crashing down onto the forepeak deck as the visor completely detaches from the vessel.
- Large amount of water is entering the car deck resulting in a rapidly growing starboard heel angle up to about 35-40 degrees.
- The ramp may be fluctuating up and down due to the interaction between waves and the pitch motions.
- Water is flooding down to the lower decks through vents and centre casing.
- The officer on the bridge is decreasing the ship speed and starts a port turn.
- After turning the ship heel is still increasing and the Main Engines stop.
- The heel is increasing and the Auxiliary Engines trip and stop when the heel angle is more than 45 degrees.
- The ship is now drifting in wind, waves and current and when the heel is about 80-85 degrees the Emergency Generator shuts down.
- The ship capsizes.
- The ship sinks with bow up.
- The aft part of the ship is hitting the seabed first.

The foundering sequence as described is estimated to take about one hour.

The conclusions on the most likely sinking sequence established on the basis of evidence available rest primarily on three key inferences:

- The first heel resulted from water on deck flooding through forward doors, and not from flooding through any other breach of hull integrity.

- The ramp opened completely and closed due to gravity after heeling beyond 90 deg angle.
- The large side windows on the decks above the car deck withstood substantial pressures before breaking.

To bring conclusions on the loss mechanisms to near certainty, it is highly recommended that the following further steps are taken:

- The whole hull of MV Estonia is inspected and documented in detail.
- The state of the ramp at the wreckage is inspected and documented in detail, and thereafter brought to surface for final confirmation of its state.
- At least three windows together with their frames are brought to surface and tested for breaking pressure.

Confirmation of the above key inferences would allow reaching a conclusion beyond reasonable doubt on the causes of the loss of MV Estonia.

2 BACKGROUND

2.1 The Accident

On 28th September 1994 the Estonian-flagged ro-ro passenger ship MV Estonia, having departed from Tallinn with 989 people onboard for a scheduled voyage to Stockholm, sank rapidly and disappeared from the radar screens of ships in the area at about 01:50 hrs. There were 852 fatalities and 137 survivors. The accident is considered to be the worst disaster at sea in post-war Europe.

Since the disaster, the Estonia foundering has continued to be a significant issue in Estonia, Finland and Sweden because the underlying causes of the loss were not very well described in the JAIC (The Joint Accident Investigation Commission of Estonia, Finland and Sweden) report, see [1] in Chapter 15 “References”. This has also resulted in extensive discussions and speculations around the world.

Based on the JAIC report the foundering is briefly described as:

The Estonian-flagged ro-ro passenger ship MV Estonia departed from Tallinn on 27th September 1994 for a scheduled voyage to Stockholm. At about 0115 hrs, Estonian time, the visor separated from the bow, due to heavy wave loads, and tilted over the stem. The ramp was pulled fully open, allowing large amounts of water to enter the car deck. Very rapidly the ship took on a heavy starboard list. She was turned to port and slowed down. The four main engines stopped and the ship was now drifting. The list to starboard increased and water started to enter the accommodation decks. The ship sank rapidly.

2.2 The VINNOVA Call

The Swedish Government decided in March 2005 that VINNOVA (The Swedish Governmental Agency for Innovation Systems) in its capacity as the authority responsible for the Swedish Maritime Safety Programme, should commission a research study about the sinking sequence of the MV Estonia.

The objectives of the Call were defined as:

- To shed light on the sequence of the sinking of MV Estonia.

- To develop knowledge to improve maritime safety for ships in Swedish waters and internationally.

Further in the Call text:

> "The loss of the MV Estonia with the consequent devastating events and loss of lives is a major reason to use all possible means to try to understand the underlying causes for what happened and to find ways to improve ship safety especially for ships carrying a large number of passengers. It is also important to understand the factors associated with the time taken for a ship to sink and/or capsize when in catastrophic distress and to make the right conclusions for the future."

The following restriction was also given:

"Diving on and ROV-surveying of the MV Estonia's wreck is not permitted, due to Swedish law and an agreement between Estonia, Finland and Sweden to consider the location of the wreck as a final place of rest."

2.3 The SSPA Consortium

To respond to the VINNOVA call, the SSPA Consortium was established with the following four partners:

- SSPA Sweden, Göteborg, Sweden (Project Management),
- Safety at Sea, Glasgow, UK (Scientific/Technical Coordination),
- Chalmers University of Technology, Göteborg, Sweden,
- Maritime Research Institute Netherlands, Wageningen, The Netherlands.

In March 2006 two consortia were awarded grants to investigate the sinking sequence and explain the underlying causes of the loss, namely the SSPA Consortium and the HSVA Consortium.

3 THE RESEARCH PROJECT

3.1 Project Documentation

The research carried out by the SSPA Consortium within "Research Study on the Sinking Sequence of MV Estonia" is documented in 18 reports and two video sequences "Model test of the foundering of MV Estonia showing the most probable loss scenario" and "Computer animation of the most probable foundering scenario", see Appendix A and C. A list of all 18 Projects Reports is given in Appendix A. This report presents an overall summary of the entire project and all the Project Reports, while the Project Report No. 17 by the Scientific/Technical Coordinator gives a technical summary of the investigation.

3.2 Objectives

The SSPA Consortium formulated following objectives for the research study:

The key objectives are to understand the sequence and explain the underlying causes of the loss of MV Estonia and to derive suitable recommendations on design and operation of passenger vessels in order to prevent such tragedy from happening again.

It is important to emphasize that this research study is not an accident investigation.

3.3 Approach Adopted

The approach adopted combines a set of forensic, design, experimentation and analytical modelling expertise deployed to scrutinize and review the available evidence, to synthesise this into loss hypotheses, to test these hypotheses through first-principles modelling studies, and to finally demonstrate the established scenario of the loss.

In more detail the approach adopted can be described as:

- To review evidence such as testimonies from survivors and observations from all available video recordings from diving and ROV (Remotely Operated Vehicle) investigations, see Project Reports No. 2 and No, 5 in Appendix A. Four divers from the wreck investigations were also interviewed, see Project Report No. 5.

- To form an International Panel of Experts (IPE) to assist the SSPA Consortium to suggest different loss hypotheses conformant with the evidence. The names and organisations are given in Appendix B.
- To perform fundamental and systematic model experiments to derive data for numerical simulation models, see Project Reports Nos. 3, 4, 6, 9, 8 and 12 in Appendix A.
- To build comprehensive numerical models to describe the performance of the damaged MV Estonia during the initial foundering phase when it was manoeuvred and when drifting in wind and waves, as well as for the progressive flooding when water enters the ship. See Project Reports Nos. 1, 7, 9, 10, 11, 13 and 14.
- To evaluate the different loss scenarios and derive the most probable one using different numerical simulation methods, see Project Report Nos. 14 and 17.
- To substantiate the most probable scenario by computer simulations/animations and physical model experiments, see Project Reports Nos. 12, 14 and 15.
- To derive conclusions and to make recommendations for future safety improvements of passenger vessels, see Project Report No. 16.

4 BASIC SHIP AND ENVIRONMENTAL INFORMATION

Basic ship data and meteorological information were collected from JAIC [1]. A short summary is given in this Chapter, while a more comprehensive presentation can be found in Project Report No. 16. The virtual model used in the research study is shown in Fig. 1.

Fig. 1. A virtual model of MV Estonia, from Project Report No. 17.

The ship particulars and conditions of MV Estonia at the time of the accident are summarized in Table 1.

Length between perpendiculars L_{bp}	137.4 m
Beam B	24.2 m
Displacement	11 930 m^3
Draught, mean	5.39 m
Draught, forward	5.17 m
Draught, aft	5.61 m
Metacentric Height GM	1.17 m

Table 1. Ship particulars of MV Estonia.

The General Arrangement of MV Estonia is shown in Fig. 2. The ship was equipped with a twin propeller and twin rudder arrangement and two forward tunnel thrusters. An anti-heeling tank system and a pair of active stabilizing folding fins were used for reducing the roll motions.

The environmental conditions at the time of accident are summarized in Table 2.

Significant wave height H1/3	4.0 – 4.4 m
Wave peak period Tp	7.8 – 8.7 s
Wave from direction	214 – 260 degrees
Mean wind	12 – 20 m/s
Wind from direction	225 – 270 degrees (SW – W)
Current	0.2 – 0.6 knots
Current from direction	225 – 270 degrees (SW – W)

Table 2. Summary of environmental conditions at the time of the accident, from JAIC [1].

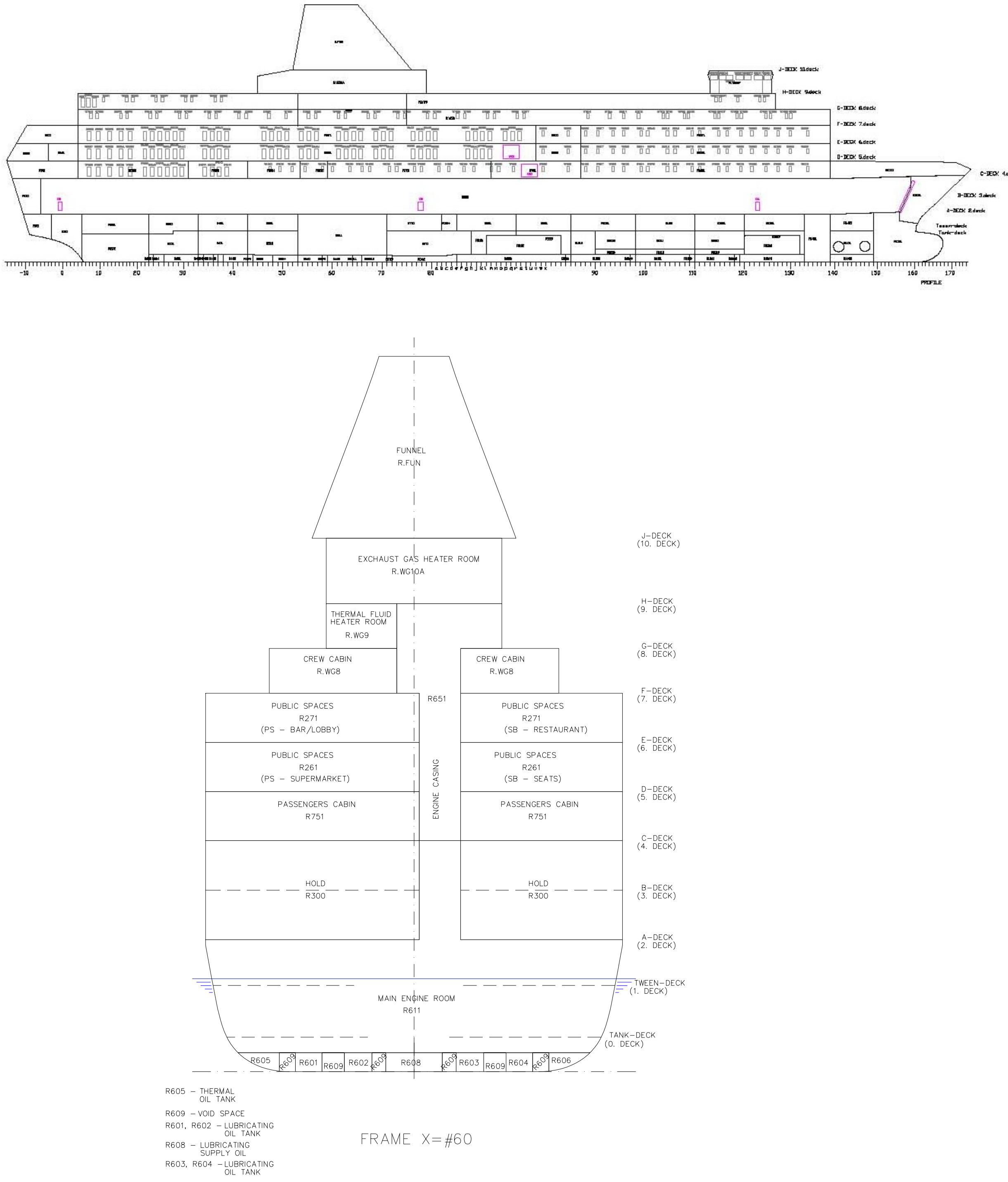


Fig. 2. The General Arrangement of MV Estonia, used both in numerical modelling and scale model manufacture.

5 REVIEW OF EVIDENCE

A preliminary review of evidence was given in Project Report No. 2 and the final review can be found in Project Report No. 5. A summary is given in this Chapter. This task was carried out by Chalmers.

The objective was to summarize the evaluation of the compiled material of evidential character condensed into a, from a witness testimonies perspective, conceivable "Course of Events" hypothesis. It should be noted that it is not the intention to present one single and in all details "true" Course of Events, which based on the available information is not achievable. The review of evidence evaluation work is comprehensively detailed in Project Report No. 5.

5.1 Course of Events

Based on the assessment of the available information the following conceivable "Course of Events" hypothesis can be established. It should be noted that the time references are sometimes estimation based on other interlinked observations. All time references within this Chapter are given in Ship Time = Estonian time = Central European Time CET +1 h. Times of special importance are denoted T0-T8 and they are also indicated in the graph of Fig, 1.

1994-Sep-27 19:00 hrs: MV Estonia departs from Tallinn. The ship is carrying full deck payload. Cars are not lashed to the deck, only the car parking break and in some cases a gear constitutes the securing. Some trucks and lorries are hindered from sliding by rubber chocks. Semi-trailers are lashed by four web-lashings. Heavy weather was forecasted. Due to an alleged bad cargo stowing plan, the MV Estonia departs having an offset in transverse centre of gravity resulting in 1-2° starboard list.

During the voyage when the ship is encountering full wind force the heeling angle is further increased. The inclination is to some extent compensated by means of water ballast. However, already within the first couple of hours the capacity of the heeling tank system is fully utilized and the ship continues her voyage at a starboard list of about 2-4°.

1994-Sep-28 00:00 hrs: the MV Estonia reaches the waypoint. After change in course, the wind is South-West veering to West and the waves are somewhat more westerly.

Following the passing of the waypoint engagement of the fin stabilizers is ordered and consequently the speed is reduced to 14.5 knots.

T0 00:45-00:50 hrs: the MV Estonia suffers a severe wave impact. Two, three heavy banging noises are heard from the bow when the visor hinges break. On his round the AB Seaman, C16, is standing just in the vicinity of the bow ramp when he suddenly experiences a deep pitch followed by a heavy impact that almost makes him fall backwards and a noise standing out from the other wave impacts. Prior to the severe impact the AB Seaman, C16, is noticed by the 3rd Engineer, C36, on a surveillance camera monitor.

In the Engine Control Room, ECR, the 3rd Engineer, C36, experiences two heavy impacts against the bow. Following the impacts the Motorman, C7, makes his way from the adjacent workshop to the ECR. He is then told by the 3rd Engineer, C36 that the situation is bad since the ramp was broken.

The Motorman, C7, states that; at 00:46 hrs he observes, on the ECR monitor, some water pouring in at the SB side of the ramp. (In later testimonies the Motorman withdraws this statement.) Following the first list, the Motorman was told by the 3rd Engineer that the situation was bad since the ramp had broken. The Motorman then looked into the monitor and saw a significant amount of water and even waves on the Main Deck. He stayed at the monitor and switched between various cameras directed towards different locations on the Main Deck until after the Main Engines had tripped and stopped.

The Systems Engineer, C33, who was in the Sewage Treatment Room at the onset, testified that he, about to 00:50, experienced two-three heavy impacts where after the Ship took a slight list that caused some barrels started to slide on the deck. After the following impact the barrels which had stopped now continued all the way to the side shell. At that point the Systems Engineer realised that something was amiss and rushed to the ECR, a walk that would normally take about 1-2 minutes but due to the severe ship motions and the increasing list this path may according to the Systems Engineer have required a somewhat longer duration. When entering the ECR the Systems Engineer was told that water had flooded into the garage on the Main Deck. When he looked in the monitor he saw large quantities of water entering at the ramp. The Systems Engineer then strives to reach the ECR phone in order to contact the Chief Engineer but falls at the table which is sheered off at its welds, apparently due to a significant increase of the inclination. After this incident the Systems Engineer does not look again on the ECR monitor.

00:50-01:05 hrs: During the labour of the visor lug plates when cutting through the F'Cle Deck and the Deck Transverse at #159, the ramp housing hits the tip of the ramp. The ramp locks break under the force of the visor and the ramp falls into and rests on the upper "cross bracing" in the visor structure. See [4] in Chapter 15 "References". Water is pressed at the sides of the partly opened ramp and onto the Main Deck, Dk 2. A starboard list is developed and increases as more and more water is entering the garage on Main Deck.

It must be considered as quite plausible that the three witnesses in ECR may have observed water ingress at ramp sides prior to a full separation of the visor and hence when the ramp is resting onto the visor structure. Scoring marks on the visor upper cross bracing confirm contact with the ramp grillage structure. Furthermore, if the Systems Engineer, C33, is correct the ramp had not been fully open prior to his escape, since the sketch made by him indicates a tarpaulin at the top of the ramp which is still there when the crew is watching the monitor.

The Security Officer, C28, overhears a walkie-talkie conversation in which the AB Seaman, C16, reported to the navigation bridge about water on the Car Deck, prior to a significant permanent list. This conversation is also overhead by the 3rd Engineer, C36, in the ECR.

T1 01:05 hrs: The visor is lost and the ramp falls down onto the Fore Peak Deck, allowing dramatically increased water ingress through the bow opening. The ship immediately heels deeper and remains at a significant starboard list exceeding 20°, making loose items to fall. Among other items one alarm clock that stops 12:02AM when the battery falls off. Some witnesses wake up by falling off their beds and many others fall where they stand including the receptionist at the information desk

A port turn is initiated and the engine control levers on the Navigation Bridge are pulled to zero.

After waking up due to the developing list, the 2nd Engineer, C38, gets dressed and looks out into the companionway in the Crew Accommodation, where he sees the 1st Engineer and the Refrig. Engineer, C42. The 1st Engineer then states that the visor was “smashed up” and that the ship should better be grounded.

T2 01:07 hrs: The alarm “Häire, Häire” is announced from the Information Desk on Deck 5. The list is now about 25-30°.

Probably one of the last survivors from the accommodation on Deck No. 1 hears the “Häire, Häire” in his cabin and still manages to ascend without any experience of massive flooding.

T3 01:08 hrs: In an attempt to follow the MV Estonia’s Safety Manual the Water Tight WT-doors are remotely released from the Navigation Bridge. Immediately thereafter the cryptic “Mr. Skylight to number One and Two” alert is announced from the Navigaation Bridge.

A first distress call is sent out and heard on VHF channel 16 by an AB Seaman onboard a vessel in the vicinity. The call comprises only three Mayday, Mayday, Mayday, hence no identification of the ship in distress can be made. When informing the officer in command on the bridge the AB Seaman is told that the vessel in distress would certainly repeat the call.

T4 01:10 hrs: Due to list and consequently loss of LO-pressure Port Main Engines (ME:s) trip and stop. Shortly after also the starboard ME:s stop. The list is now close to 35°.

While still in the ECR prior to ascending up to Deck No. 8, the System Engineer, C33, has the impression that the Officers on the Navigation Bridge are informed about water ingress somewhere into the buoyant hull and that the bilge pumps therefore are running.

The Systems Engineer, C33, and the Motorman, C7, are ordered by the 3rd Engineer to evacuate. On their escape they have to pass a WT-door *(at #71)* which is closed. Later also the 3rd Engineer, C36, has to operate the WT-door when he leaves the ECR.

T5 01:17 hrs: The Auxiliary Engines (AE:s) trip and stop and consequently the lights flicker for a second until the Emergency Genset starts. The list is now exceeding 45°.

01:22 hrs: First officially recorded Mayday is transmitted from MV Estonia. It states "Mayday, Mayday ESTONIA Please.

01:25 hrs: During the distress traffic MV Estonia declares having a Black-Out. Passenger, P76, notices two crew members climbing out of some trunk in the vicinity of the funnel, one of which is shouting in English: "Water coming up from Car Deck".

T6 01:27 hrs: The Emergency Generator shuts down. The list is now about 80-85°

01:29 hrs: The last message in the distress traffic from MV Estonia is transmitted.

T7 01:31 hrs: The ship is on her side and an aft trim is developing. The ship's whistle is sounded; a sound that "drowns" in the water.

A majority of the survivors are washed overboard by waves when the list is close to or even more than 90°. When Passenger, P49, is washed off, his wrist watch is smashed and stops at 01:31.

Many survivors also note an increasing trim by the stern and in some cases also a "beach line" developing, below which the afterbody of the ship is already immersed.

01:35 hrs: The radio station clock (BHD mounted) in the chart room of the Navigation Bridge stops at 23:35 UTC.

During the development of the disaster, eventually the bow ramp is closed either by wave impact or by gravity when the list is exceeding 90°, leaving just a small gap. Structural damages on the bottom of the ramp are noted by two survivors, P3 and P34, when they are climbing down the closed ramp at a list exceeding 90°.

T8 01:48 hrs: MV Estonia disappears from the radar screen at Utö Radar Station.

A graph of the plausible list development is shown in Fig, 3.

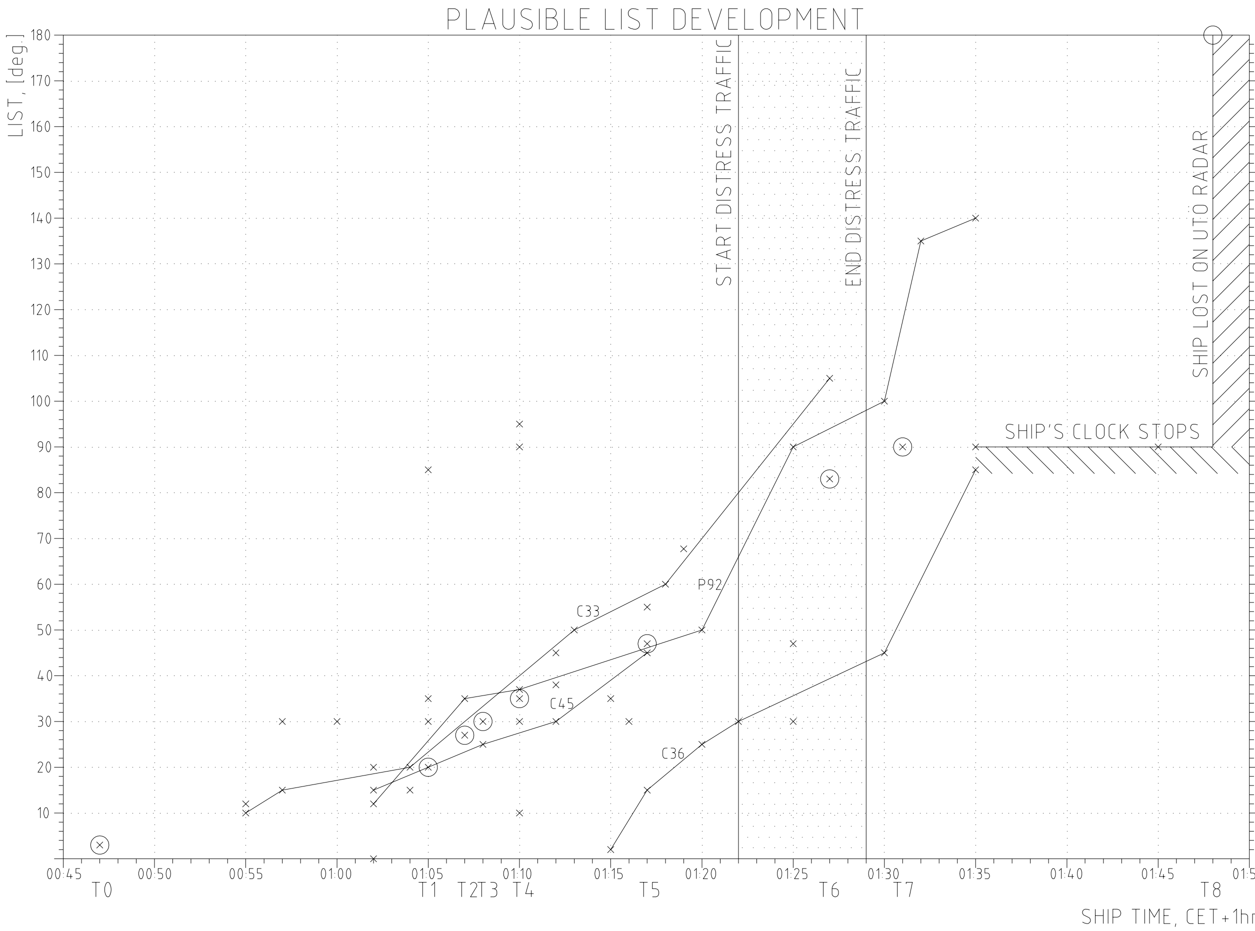


Fig. 3. Plausible list development, from Project Report No. 5.

5.2 Interview of Diving Team Members

In Project Report No. 5, Chapter 4.6, a summary is given of interviews of four diving team members from the Rockwater staff, who carried out the diving investigations on the wreck between 2-5 December 1994. The aim with these interviews was to find out if there were observations that were not reported in JAIC Supplement [2]. The following persons were interviewed:

a. The manager of subsea activities at Rockwater
b. The Onshore Project Manager
c. The Onboard Project Manager
d. The Onboard Survey Operations Coordinator and Dive Supervisor

From these contacts it was concluded that the Rockwater team took very seriously upon their task and carried out the operation with highest professionalism. No hole or breach into the hull was ever observed by the team.

6 POSSIBLE FOUNDERING SCENARIOS

During the project a large number of possible foundering scenarios were considered and investigated, see Project Report No 14. The scenarios were to a large extent suggested and constructed by assistance of the International Panel of Experts, see Appendix B.

The main scenarios considered were (combinations possible):

1. Bow visor falls off, car deck floods, heel angle increases, flooding below through central casing, sinking with bow up (the JAIC scenario [1]).
2. Bow visor falls off, car deck floods, heel angle increases, vents break under pressure, flooding below through the vents (suggested in [3]).
3. Stabilizing fins break off or hull damage occur through other means, lower decks flood, bow visor falls off, car deck floods, heel angle increases, flooding below, sinking with bow up.
4. Stabilizing fins break off or hull damage occur through other means, lower decks flood, water reaches car deck from below, heel angle increases, sinking with bow up.
5. 5a. Collision with other object, hull damage at deck 0/1 level, lower decks flood, bow visor falls off, car deck floods, heel angle increases, flooding below, sinking with bow up.
   5b. Collision with other object, hull damage at deck 0/1 level, lower decks flood, water reaches car deck from below, heel angle increases, sinking with bow up.
6. 6a-6c. Car deck floods through opening in the ship's side or through pilot door or through stern ramp, heel angle increases, flooding below, sinking with bow up.

The hydrodynamic analysis of the different scenarios can be divided into three cases:

1. Foundering by flooding car deck
2. Foundering by flooding deck 0/1
3. Foundering by flooding car deck and deck 0/1

The analysis by use of the PROTEUS3 simulation program can be found in Project Report No. 14. A summary is given in Chapter 9.4.

7 FUNDAMENTAL MODEL EXPERIMENTS RELATED TO THE FOUNDERING

Comprehensive scale model tests were performed by SSPA and MARIN, aiming at:

- A deeper knowledge of the dynamics of flooding into an accommodation deck.
- A deeper knowledge of the dynamics of water flow through a bow ramp opening into a car deck.
- Establish the sea keeping and manoeuvring characteristics of a damaged ship with large list angles and water inflow.
- Collecting data for upgrading and validation of mathematical simulation models.

The following fundamental model experiments were carried out in the project:

- Flooding of Superstructure Deck No. 4 (see Chapter 7.1 below and Project Report Nos. 6, 8 and 9.
- Bow ramp flooding, manoeuvring and sea keeping tests (see Chapter 7.2 below and Project Reports Nos. 3 and 4)

7.1 Model Experiments on Flooding of Superstructure Deck No. 4

7.1.1 Objectives and technical approach

This study is in fulfilment of the task "Flooding through complex internal spaces", see Project Report No. 6, where the results are presented of the model experiments that were done on the flooding of accommodation deck No. 4 of MV Estonia.

The objective of the study was to obtain physical model data that was to be used to compare and to validate the results of the numerical codes employed for the full computational simulation of the sinking sequence of MV Estonia.

To meet this objective a model of deck No. 4 was built in transparent plastic and completely filled with water from a container. The model was flooded from one corner and the time it would take for the various compartments to be completely filled up with water as well as the progression of the flooding through the various compartments was the main result of this investigation.

The experiments were carried out on the platform of the Seakeeping and Manoeuvring Basin (SMB) of MARIN. For these model experiments the following assumptions were made:

- A model was built at scale 1:20 which was considered to be large enough for the purpose.
- Only accommodation deck No. 4 was modelled.
- The internal compartmentization of deck No.4 was simplified.
- Door openings were modelled, there were no doors.
- The deck model was sitting fixed and level.
- Neither downflooding nor upflooding was required, although eventually a few stairwell openings were opened to see the effect of downflooding.
- All spaces were ventilated to the outside atmosphere.
- The inlet pressure head was kept constant during the flooding process, based on an assumed collapse pressure of the big windows.
- Water levels were measured in many locations and often in the middle of the compartments to monitor the dynamic flooding process over time.

7.1.2 Experimental setup

The experimental setup is shown in Fig. 4 and 5.

Fig. 4. The MV Estonia test set-up on the platform of the SMB basin of MARIN.

- The transparent model of the MV Estonia deck No. 4 filled with green water sits in the middle, supported by flat yellow transducers underneath.
- The big blue containers contain the supply of dyed (green) water.
- The white container sitting lower equalizes the water head at the model inlet.
- The scaffolding holds the video camera's hanging overhead.
- Electronic logging equipment is to the right.

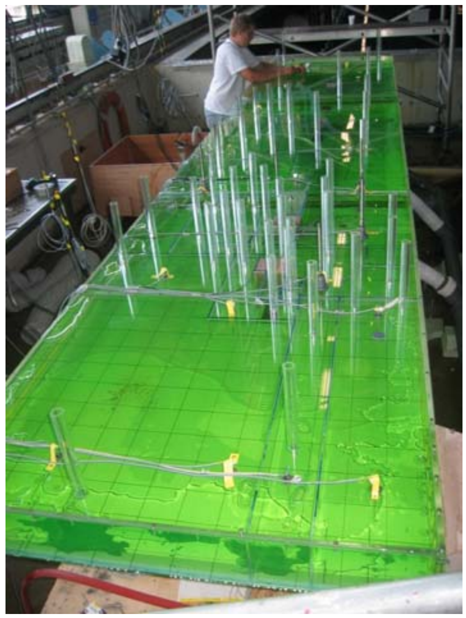


Fig. 5. Some details of the experimental setup:
- Air vent pipes on all major compartments.
- Electronic measurement probes for water height under the yellow tape.
- 2*2 m grid lines on the base plate.
- The inlet is in the right bottom corner, just outside the photograph.

7.1.3 Results and conclusions

Basically the test program called for only one single test condition, the nominal case. However, having gone through the trouble and expense of all the preparations, it is good laboratory practice to do a number of repeat tests. Therefore the tests were repeated 5 times. This gave an impression of the influence of the variability of initial conditions on the final results. The results are reported in detail in the Project Report No. 6. Some typical results are shown in Fig. 6.

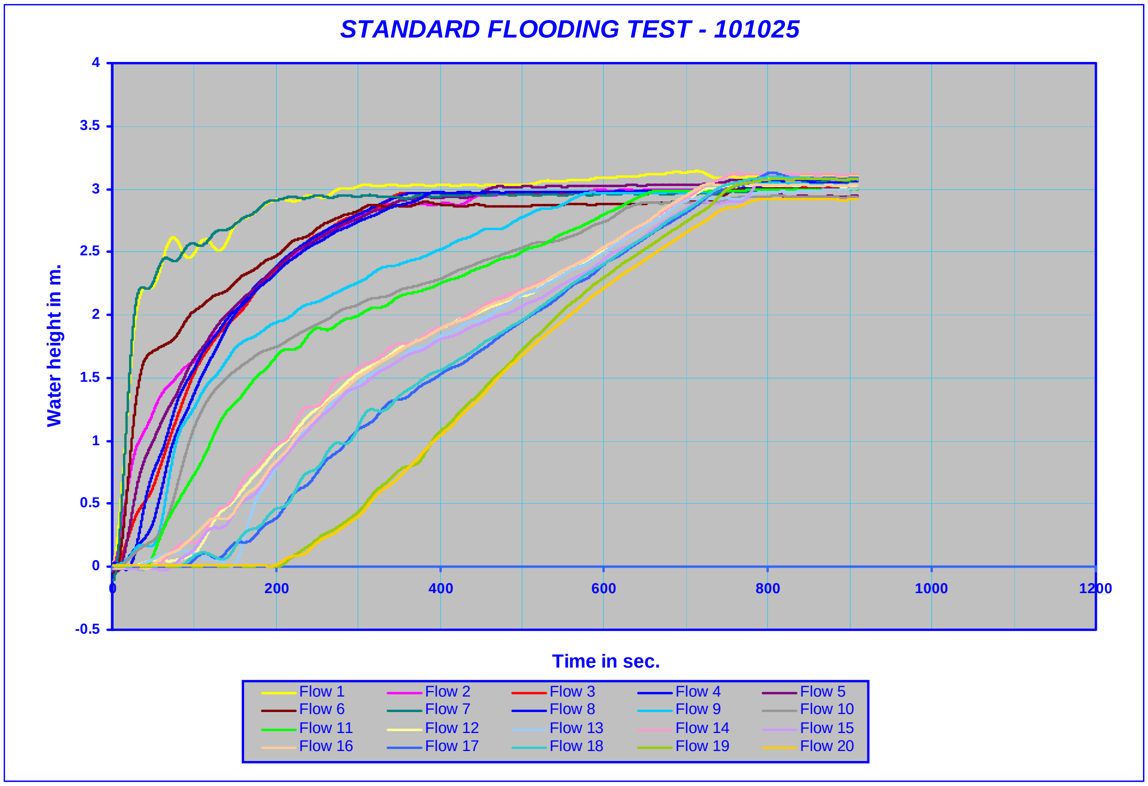


Fig. 6. The flooding of the various interior compartments in succession exhibits a trend that can easily be understood. The more upstream compartments fill up first and they fill up very rapidly. The more downstream compartments are flooded later and more slowly.

Some flow details are shown in Fig.7 and 8.

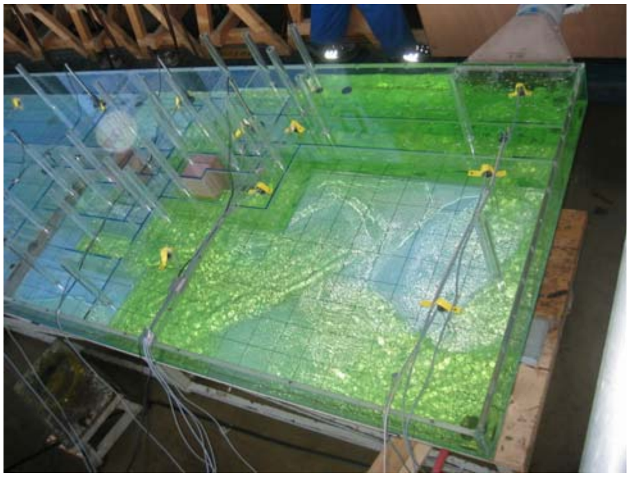


Fig. 7. Flow details from experiment:
- The water inlet is in the right top corner.

- Here there are 5 big windows that are supposed to be bashed in by water pressure at the same time.
- The conference area and the adjacent corridor are filled almost instantaneously, within the blink of an eye on model scale (4.5 times faster that reality).
- The wide expanse of the accommodation in the right bottom corner fills up more gradually.
- The flooding water is already rushing to the left through the labyrinth of compartments following a number of different routes.
- The compartments are visible by the blue stripes, indicating the sub-dividing walls.

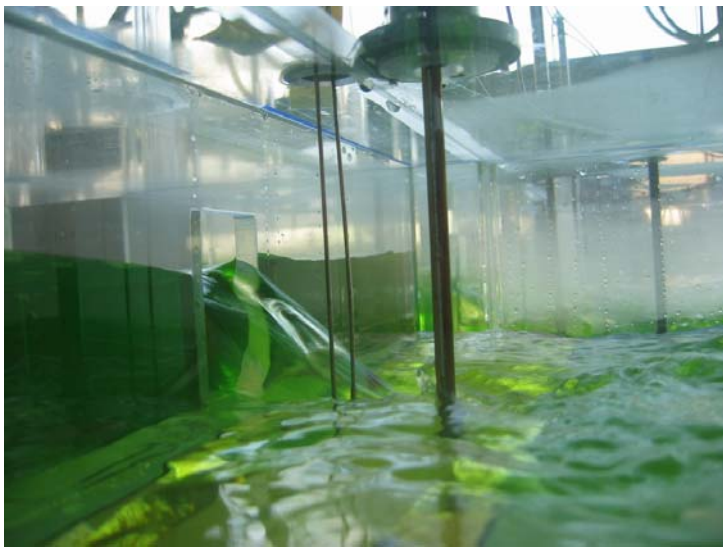


Fig. 8. Flow details from experiment:
- The floodwater cascades through the interior and the door openings are serious obstructions to the flow, thereby causing a considerable difference in pressure head between the compartments.
- Pressure head on the upstream side is maintained all the way into the door opening.
- The wide expanses of large compartments fill up in a quasi-static way.
- Water level probes (twin wires).
- Water force probe calibrated against flow velocity.

The results of these experiments justify the following overall conclusions:

- Progressive flooding experiments on a scale 1:20 model of an accommodation deck produce results that appear to be physically logical and understandable.
- From observation the flow behaviour is judged to be mainly governed by potential flow effects.
- From observation the flow was seen to mostly behave in a quasi-static manner, i.e. compartments would fill up gradually and with level water surface. Only near the inlet compartment the water was seen to burst into the first few compartments.

- The water level measured by wire probes in the various compartments corresponded with the weight of the water inside the model to a high degree of accuracy, supporting the use of the water level data as a reliable basis for follow-on evaluation and correlation.
- The data have also shown that the discharge coefficient for the door openings is anything but constant over time and anything but similar for all geometries of opening.
- The effects of parameter variations (pressure head and stairwell openings) gave logical results.
- The repeatability of the experiments was excellent.

7.2 Bow Ramp Flooding, Manoeuvring and Sea Keeping Tests

As a base for the extensive computer simulations carried out within the project manoeuvring tests in calm water and in waves, and flooding tests through the bow ramp, were carried out both in upright and heeled conditions with a model of MV Estonia in the SSPA manoeuvring and sea keeping basin (Maritime Dynamics Laboratory MDL), see Project Report No. 3. A few initial tests of flooding were also carried out in SSPA's towing tank and to further illustrate the flooding through the bow ramp. See Project Report No. 4. Tests were also performed with the model radio controlled in SSPA's towing tank. All tests in waves were carried out using the significant wave height H1/3=4.3 m and the peak wave period Tp=8.3 s.

7.2.1 Scale model of MV Estonia

A scale model of MV Estonia with a scale factor of 1:40 was used for these tests. The following main dimensions of the model (for more detailed information, see Project Report No. 3):

Lbp	[m]	3.435
Beam	[m]	0.605
Draft, aft	[m]	0.140
Draft, fwd	[m]	0.129
Displacement	[kg]	186.4

A photo of the scale model is shown in Fig. 9. The model was ballasted properly to achieve the correct performance.

Fig. 9. Photo of model of MV Estonia used for the manoeuvring and sea keeping tests.

7.2.2 Flooding tests

The flooding tests were carried out for speeds varying from 5 to 14.5 knots and for different headings from head sea to bow quartering sea (30 degrees from bow sea). Tests were also performed with forward and aft trim and with the model heeled to 25 degrees. Most tests were carried out with the ramp completely open, but also a few tests with the ramp open 1 m (full scale). The aim of these tests was to measure the initial inflow to the car deck. The trim of the model was kept constant for all tests since all water entering the ship model was instantly pumped out of the model. However, due to unexpectedly high inflows at high speeds some tests had to be limited in speed range to keep the trim constant.

An example of a flooding test with the bow ramp fully open and a list angle of 25 degrees is shown in Fig. 10.

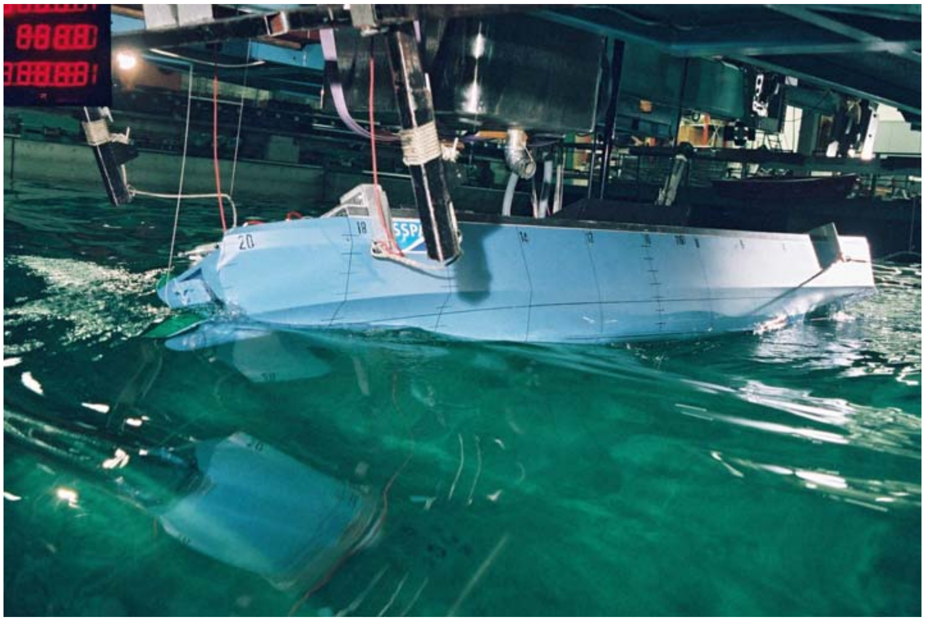


Fig. 10. Flooding test in waves with bow ramp fully open and a list angle of 25 degrees.

7.2.3 Summary of flooding test results

To summarize the results from the initial inflow tests, it can be estimated that if the visor fell off and opened the ramp completely at a speed of about 14 knots, 1500-1800 tons per minute would enter the car deck initially depending on the heading. If the speed should remain at 14 knots, within a short time a heel angle of 25 degrees would be reached, and due to the heel the inflow would increase significantly more. Due to problems with pump capacity it was not possible to measure this at 14 knots, but in the speed range 8-9 knots the increase due to 25 degrees heel was in the order of 20-30 %. If this is the case also at 14 knots, the inflow would reach the order of 2000-2500 tons/min. A forward trim could then increase the inflow even more. If the ramp is only partly open, maybe with the visor still on, the inflow can vary from a few tons per minute up to the order of 100 tons per minute.

During all tests in MDL the ramp was forced to stay open by use of a magnet. From tests in the towing tank without the magnet it was obvious that the waves managed to close the ramp frequently. The ramp was as the ship model scaled regarding shape and weight, but the friction of the hinges was probably lower for the model. Anyway, with the ramp fluctuating, the inflow decreased to some extent, but still a heel angle of about 25 degrees was obtained within a minute (full scale time), see Project Report No. 4. This means that depending on the position of the ramp (slightly opened, fluctuating or completely open) and the condition of the ship (speed, heel angle, heading) the inflow can vary from a few tons per minute up to more than 2000 tons per minute.

7.2.4 Manoeuvring and sea keeping tests

The aim with these tests was to obtain data for the simulation of the initial phase of the foundering. To map the manoeuvring properties of the ship, conventional manoeuvring tests, such as turning circle tests and zig-zag tests in calm water, were carried out. To investigate the manoeuvring properties in waves different turning tests with varying rudder settings and with heel angle was performed at different speeds. Also sea keeping tests in the same headings as for the inflow tests, with and without heel angle, and for varying speeds were done. A photo from the set-up of a manoeuvring test with a heel angle of 25 degrees is shown in Fig. 11.

Fig. 11. Model set-up for turning tests. At 25 degrees heel angle the port shaft is in the waterline and the port rudder half out of water, which significantly influences the behaviour of the ship.

An example of a test result is shown in Fig. 12, when the heel angle was 25 degrees starboard down. The initial speed was 7 knots and waves were coming from 30 degrees from port. Port rudder of 30 degrees was given and when the model had made a 180 degree turn the rudders were set to zero. Due to the heel and the waves and keeping the propellers running, the model continued to turn to port. In order to keep the starboard side towards the waves, as indicated in some testimonies from survivors, the propeller thrust must be reduced when the model is in beam seas not to continue the port turn.

Overall more than 30 different tests were done to give a thorough background to the simulations. All the results are presented in Project Report No. 3.

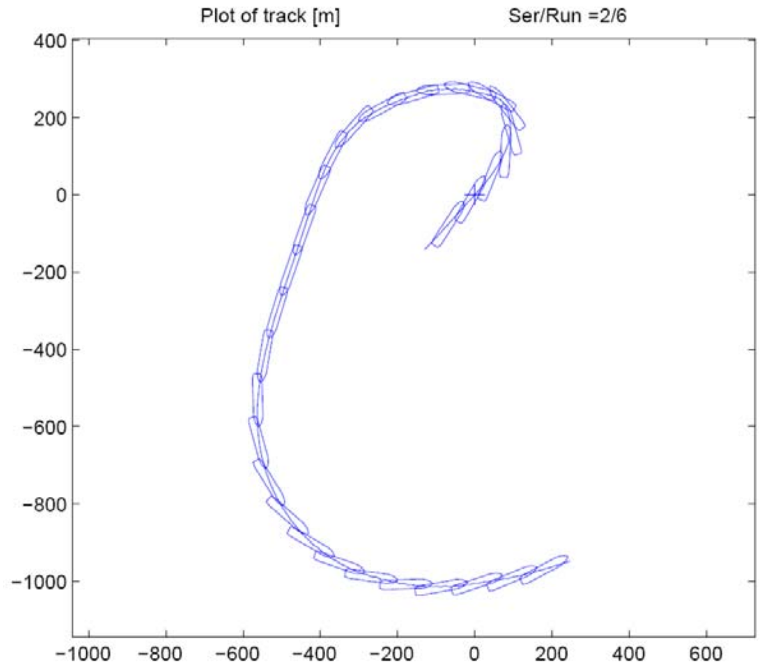


Fig. 12. Example of a turning test in waves and with a heel angle of 25 degrees starboard down.

8 VALIDATION OF NUMERICAL MODELS

8.1 Validation of the SEAMAN Simulation Model

The simulation program SEAMAN, designed for simulation of ship dynamics in all six degrees of freedom, was used as a basis for development of special modules to investigate the course of events before the foundering of MV Estonia. The modules describe:

- Bow ramp opening with assumed water inflow
- Model of flooded water on main deck
- Model for flooded water in ventilation pipes
- Model for flooded water in centre line casing

The model tests described in Project Reports Nos [3], [4] and [12] and in Chapter 7.2 were used for validation of the SEAMAN simulation model. The details of the validation can be found in Appendix 2 of the Project Report No. 11.

Based on the mathematical modelling approach and the validation studies it was concluded that the validity of the used mathematical model is in the region up to list angles of about 90 degrees. In order to avoid violation of this validity region, all simulations with SEAMAN were stopped at a list angle of 90 degrees.

It was concluded that the SEAMAN simulation model represents the ship dynamics well within the validity region as is shown in extensive comparisons with model tests.

8.2 Validation of the FREDYN Computation Model

8.2.1 Objectives and technical approach

This study is in fulfilment of the task “PIV measurements”, where PIV means Particle Image Velocimetry. In the Project Report No. 8 the results of the model experiments are presented. Tests were done on the flooding of accommodation deck No. 4 of MV Estonia for the purpose of obtaining PIV measurements.

The objectives of this study were:

- to get insight into the flow of model of deck model during flooding,
- to obtain physical model data that is to can be used to validate numerical modelling.

To meet these objectives PIV tests were performed on the scale 1:20 transparent model of deck No. 4 of MV Estonia that was also used for the investigation for the flooding experiments. This model was completely filled with water from a set of containers. The model was flooded from one corner and the time it would take for the various compartments to be completely filled up with water. The progression of the flooding through the various compartments was the main result of the MARIN experimental and numerical investigation.

The present study involved an additional series of tests that was carried out separately. In these tests the emphasis was placed on the local details of the flow upstream and downstream a number of door openings and the rate of flow through these openings. The measurements were performed using PIV techniques in which the whole flow field becomes available as a vector field at a great many time instances.

In addition to the assumptions made for the first series of model experiments outlined in Chapter 7.1, there were the following assumptions made for the present series of tests:

- The seeded particles travel with the flow and have the same velocity as the surrounding fluid.
- The flow structure in the immediate vicinity of the door opening may be taken as representative of the flow in the door opening.

8.2.2 Results and conclusions

Basically the PIV measurements involved the one nominal test condition in which the flow through 2 door openings was monitored in detail. The tests were repeated many times and the equipment was moved to monitor both doors in succession. The detailed results are given in Project Report No. 8.

Typical test results are shown in Fig. 13 and 14.

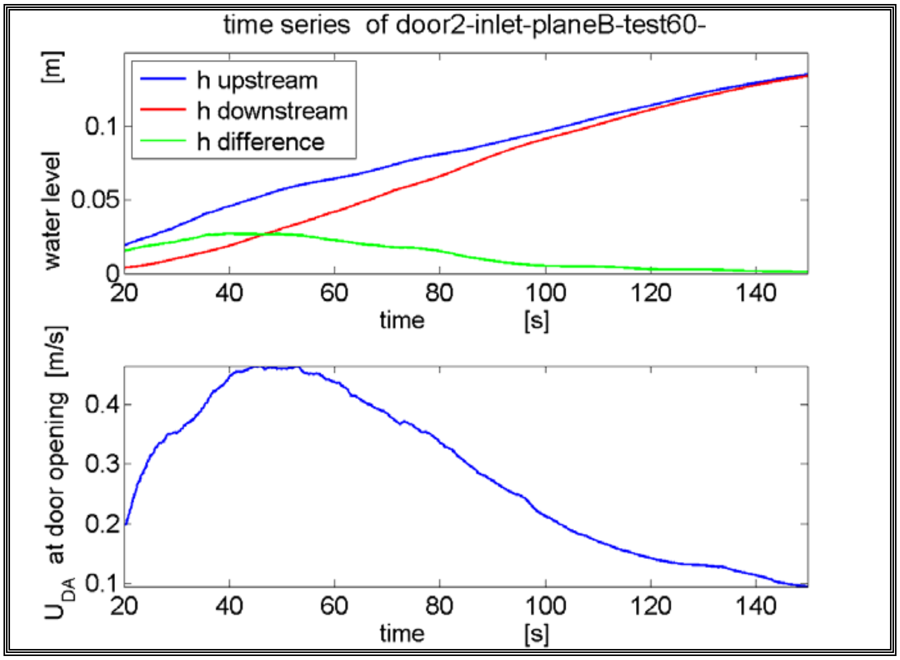


Fig. 13. The flow through a door opening exhibits a trend that can easily be understood. As time progresses from left to right, the waterlevel on both the upstream and the downstream side of the door opening rises, eventually to the ceiling. Because there exists a difference in pressure head there is a flow through the door opening, the average flow velocity being intimately related to, and in fact driven by, the difference in pressure head.

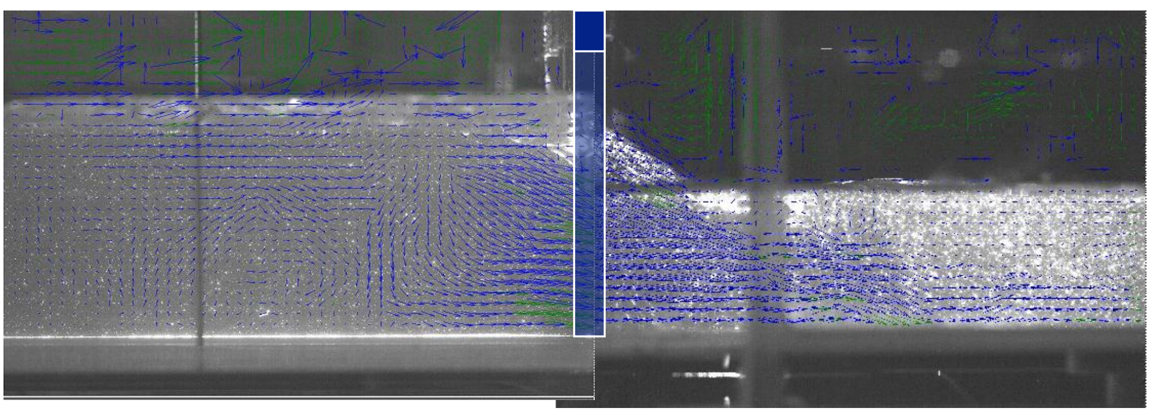


Fig. 14. The flow of water is seen to cascade through a door opening from left to right. The clouds of minutely little seeding particles moving with the flow are illuminated by a laser sheet from below and they show up as bright silvery specks. The results of the analysis is given in terms of a vector map overlaid on the photograph. The vector map was mathematically integrated in the vertical and horizontal sense to obtain the average flow velocity through the door opening. This would give a quantity to be compared to the earlier model experiments and to the simulations.

The results of the PIV experiments justify the following overall conclusions:

- In a qualitative sense the PIV measurements are a good tool to bring out the structure - both spatial and temporal- of the flow at some distance upstream and downstream of the door openings as well as very close to the door opening.
- In a quantitative sense the results of the PIV measurements, when properly integrated and averaged over the width of the door opening and over the 'wetted' height of the door, correspond well with the results of the Progressive Flooding Experiments of Series 1.
- The flow structures in the vicinity of the door openings, as brought to light by PIV, support the assumption on the preponderance of potential flow effects over viscous effects for that location.

8.3 Validation of the SIMCAP Computation Model

The SIMCAP model of MV Estonia was validated through comparison with static calculations made previously and within present project. Validation of dynamic properties of the model was made through comparison with model tests carried out by SSPA. The validation is described below and in detail in Project Report No. 10.

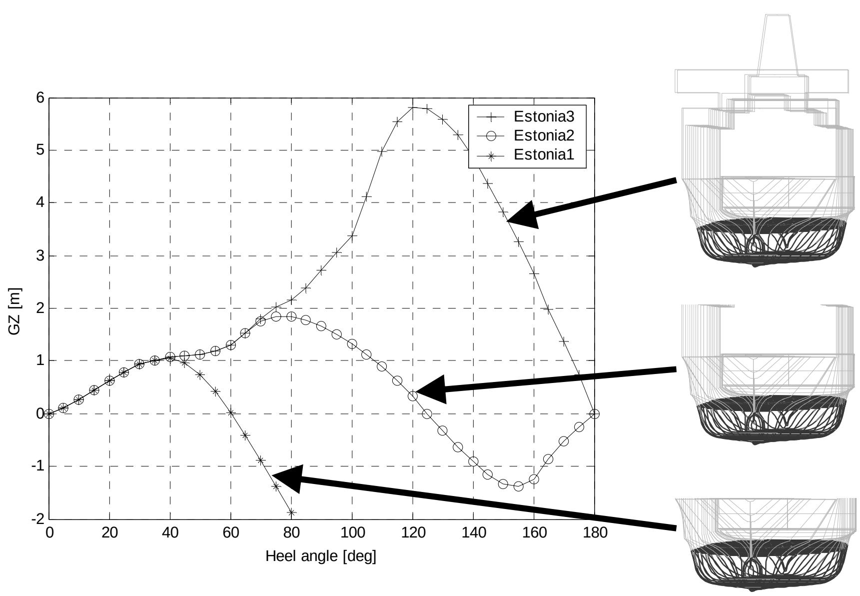


Fig. 15. Static stability curves.

8.3.1 Hydrostatic validation

The intact static GZ curve was calculated for three different hull realizations, Fig. 15. The lower curve corresponds to an intact stability calculation with a hull configuration up to and including deck 4. The intermediate curve corresponds to a hull configuration up to and including deck 7 and the upper curve correspond to the whole ship. All curves correspond well with calculations within present project and with calculations in the supplements of JAIC [2].

8.3.2 Dynamic validation

SSPA conducted a roll decay model test in zero forward speed which was used to tune the viscous roll damping of the SIMCAP numerical model. SSPA made a series of bow ramp opening inflow experiments. Simulations show an agreement with the trends in these experiments regarding inflow versus speed and heading. Quantitative comparison was however not possible due to the specific set up of the experiments. SSPA made two model experiments of flooding tests with the complete car deck modeled. Comparison with simulations shows reasonable agreement. The model tests are reported in Project Reports Nos. 3 and 4.

8.4 Validation of the PROTEUS3 and CFD Simulation Models

8.4.1 Objectives and technical approach

A numerical study on the flow through complex ship geometry was carried out by the Ship Stability Research Centre (SSRC) of the Universities of Glasgow and Strathclyde, see Project Report No. 13.

The study subject was a model of deck No 4 of MV Estonia subject to “numerical” flooding by sea water. The model was flooded from five windows in the starboard aft corner of deck 4. The model was kept in a fixed position with a constant head pressure at the damage openings. Main aim of the simulations were to find out how long it takes to completely fill the compartments with water, time-to-flood (TTF), and to investigate how the water progresses through various openings from compartment to compartment.

The project was realized with the software package GAMBIT, which has been used for the creation of the 3D geometry of the model while FLUENT has been applied for carrying out the flooding simulations. New methods have been developed and adopted to reflect an accurate scenario in a moderate time frame as this kind of RANSE simulations are usually extremely demanding to computational capacities.

8.4.2 Results and conclusions

For the CFD calculations as well as for the model tests (see Chapters 7.1 and 9.2, and Project Reports Nos. 6 and 8) a simplified geometry was chosen. All bulkheads including its openings were modelled, see Fig. 16.

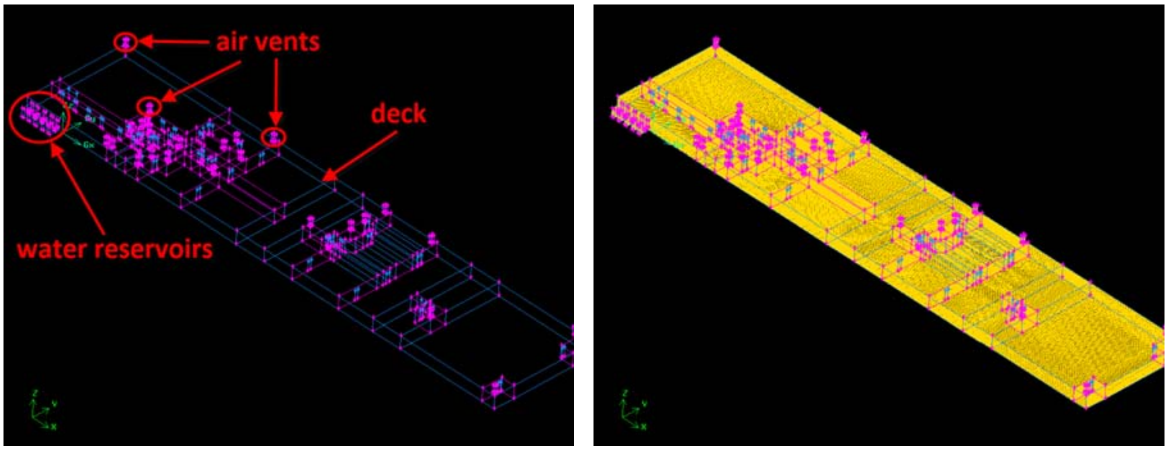


Fig. 16. Model of the volumes and meshed model.

The damage openings were connected to water reservoirs which were permanently refilled with water and which delivered a constant head pressure. Trapped air could escape through air vent shafts.

FLUENT was run on an eight nodes dual core cluster and all eight nodes (16 CPUs) were used for the calculation. Governing equations were solved with state-of-the-art algorithms like volume of fluid (VOF) and the standard k-ε turbulence model. After two months of calculation time and one month of data processing following representative results could be gained (Fig. 17 - 22). The results include a comparison with model tests and the numerical solver PROTEUS3.

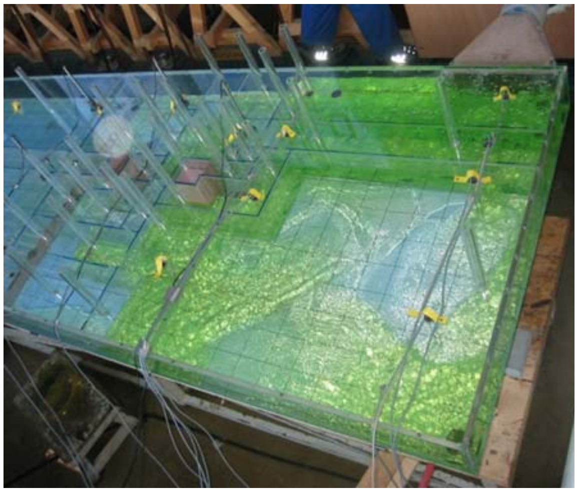


Fig. 17. Model test after 33 seconds.

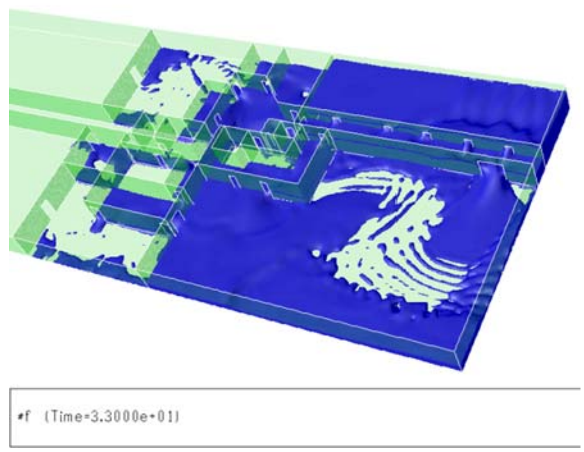


Fig. 18. CFD ISO surfaces after 33 seconds.

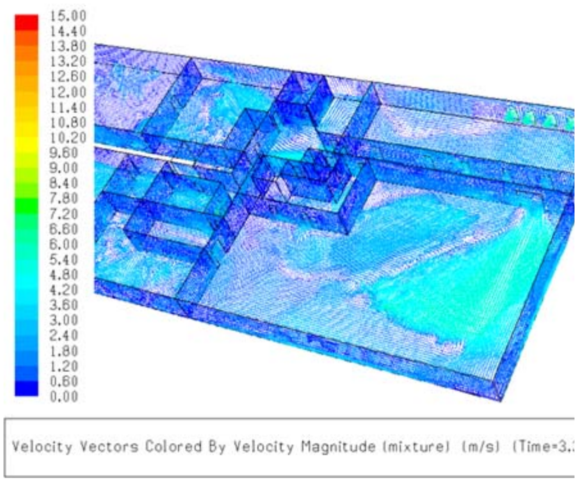


Fig. 19. CFD velocity vectors after 33 seconds

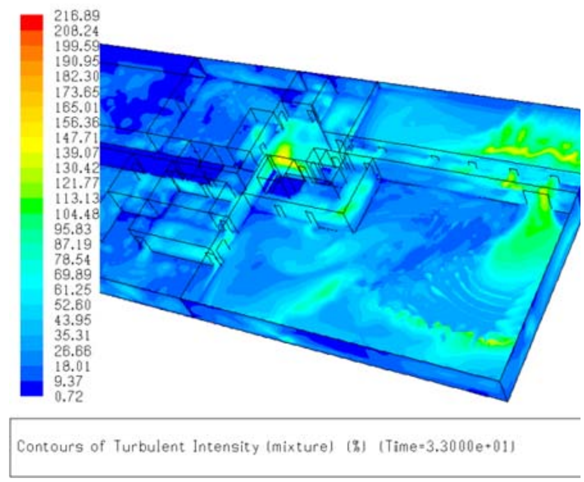


Fig. 20. CFD turbulence intensity after 33 seconds

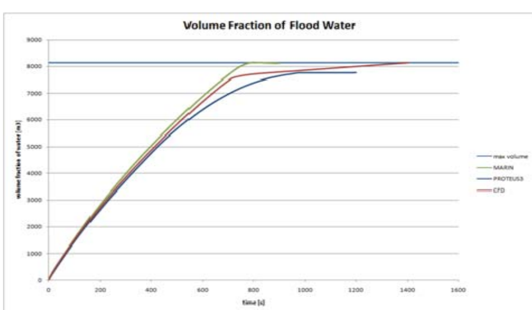


Fig. 21. CFD velocity vectors after 33 seconds

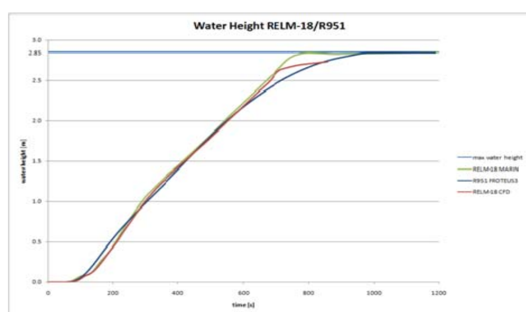


Fig. 22. CFD turbulence intensity after 33 seconds

The flooding behaviour in the various compartments took course according to the physics of basic fluid dynamics. All flooding curves exhibited an exponential behaviour and agreed very well with the model tests. Especially, highly turbulent areas like the regions around the damage opening could be simulated with very good accuracy. When water hits the ceiling of a compartment some numerical instabilities can be observed due to trapped air which cannot escape but it can be avoided by lowering the time step size. In terms of time it takes roughly between three and four months to get results with CFD which drastically limits the amount of trying different flooding cases.

9 SIMULATIONS OF FOUNDERING SCENARIOS

9.1 SEAMAN Simulations of Course of Events before Foundering

9.1.1 Assumptions

A simulation study by use of SEAMAN was carried out for the course of events, from the moment when the water started to enter into the ship and until the ship list was about 90 degrees. All details of these simulations are presented in Project Report No. 11 and a summary is given below.

The following environmental conditions were assumed in the simulations:

Wind: SW 18 m/s mean wind

Current: 0.5 knots going to ENE

Waves: Significant wave height of 4.0 with a peak period of 8.3 s, in one of the simulations 4.3 m was tested. The waves were modeled according to a Jonswap spectrum and assumed to come from WSW.

The ship was, in the simulations, controlled by an autopilot keeping the ship on course before the drop of the visor and providing the port turn after. The roll stabilizing fins were assumed to be active, and port heeling tank was initially filled with water, but was after a certain time emptied (at which time the starboard tank was filled). In each simulation carried out, the ambition has been to pass close to the debris positions indicated in Fig. 23 and in the track plots. The simulations were stopped when the heel angle exceeded 90 deg, with a drifting direction towards the wreck, see also sonar plot in Fig. 23.

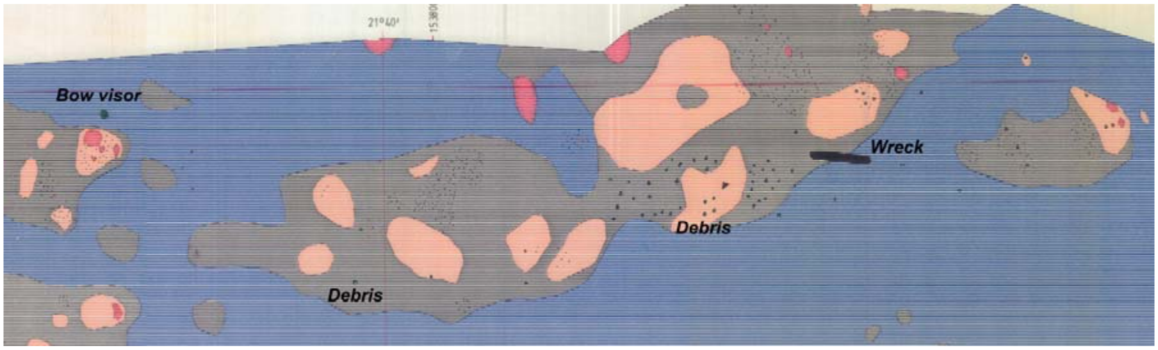


Fig. 23. Sonar plot of seabed. Courtesy of Dr. Nuorteva, Supplement No. 501 of [2]. "Debris" indicates possible lost material from MV Estonia.

To sum up, the following information from the sonar plot and different witnesses have been used as guide lines:

- The bow visor was located 1667 m west and 81 m north of the wreck.
- The time between loss of bow visor to a list of 90 deg is about 1560 sec.
- Before the loss of the visor, water was slowly flooding in through the bow ramp, entailing a list of not more that 10-15 deg at the time of the loss of the visor.

Furthermore the windows on the upper decks are assumed to break at a pressure corresponding to 5 m pressure height.

9.1.2 Simulations

The simulations are summarized in Project Report No. 11 with variations of initial heading and speed, wave height, and the time for change of rudder and engine set points. The simulation shown in Figs. 24 to 26 is the one that coincide best with witness statements (cf. Fig. 3) and the sonar plot of Fig. 23.

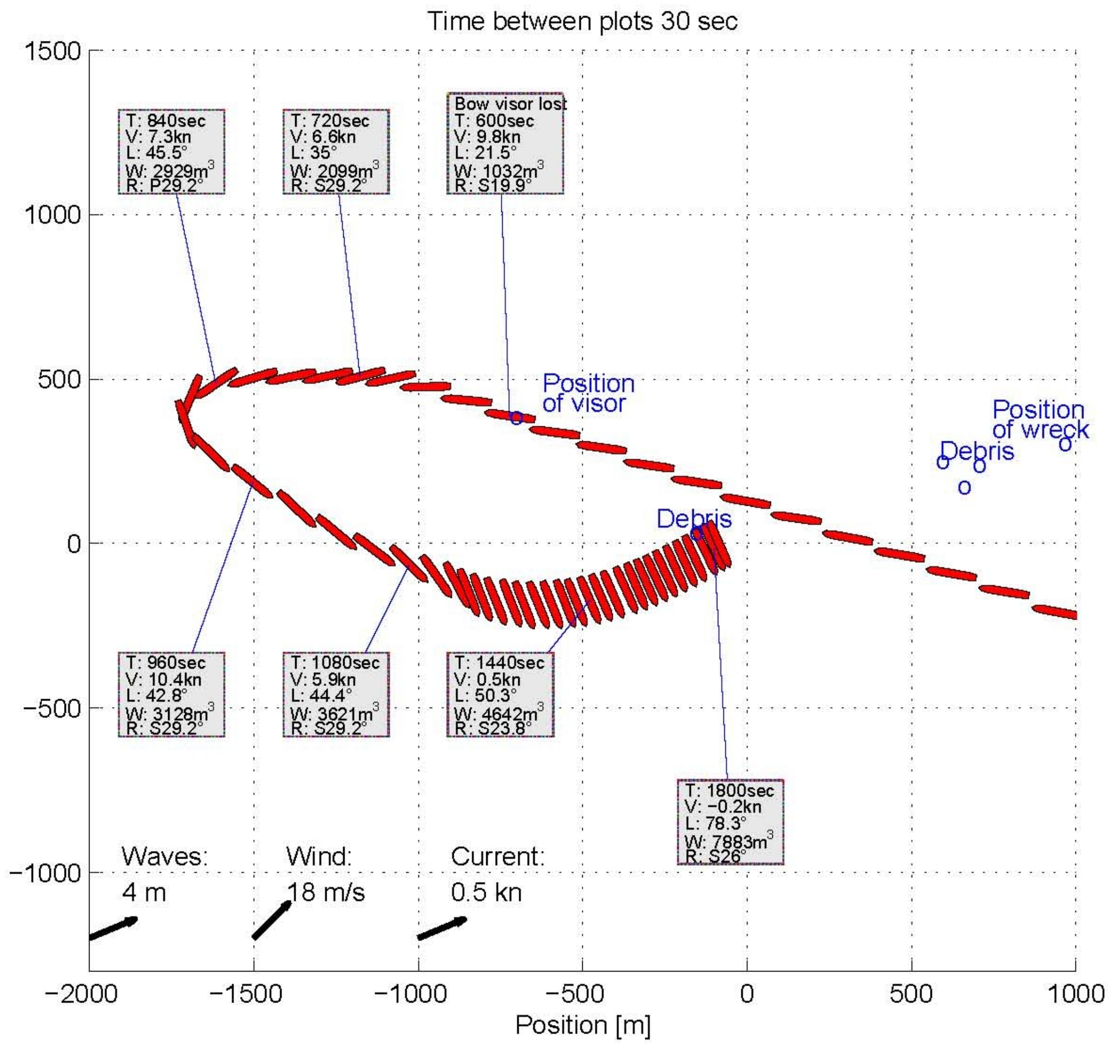


Fig. 24. The track of MV Estonia before the foundering, from simulation No. 6 (COE6) in Appendix 3 of Project Report No. 11.

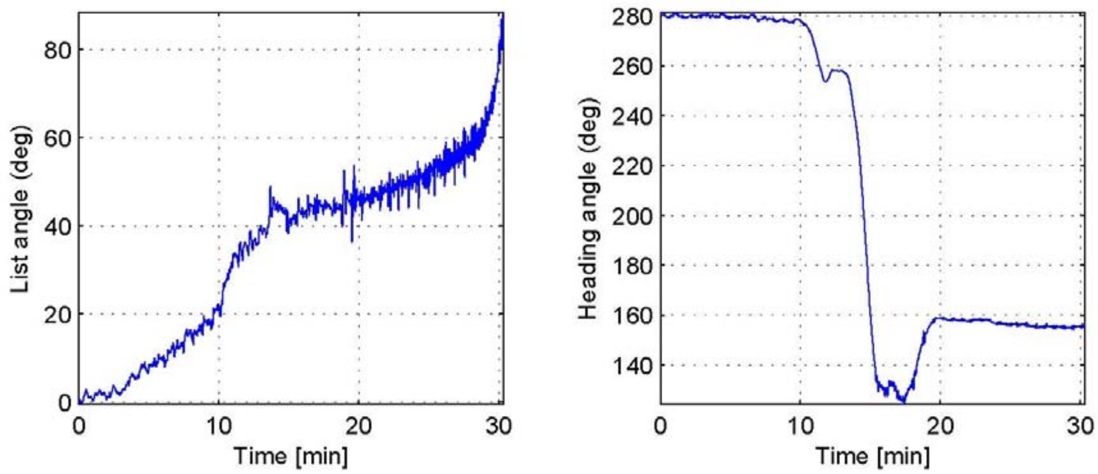


Fig. 25. Time histories of List and Heading Angles, from simulation No. 6 (COE6) in Appendix 3 of Project Report No. 11.

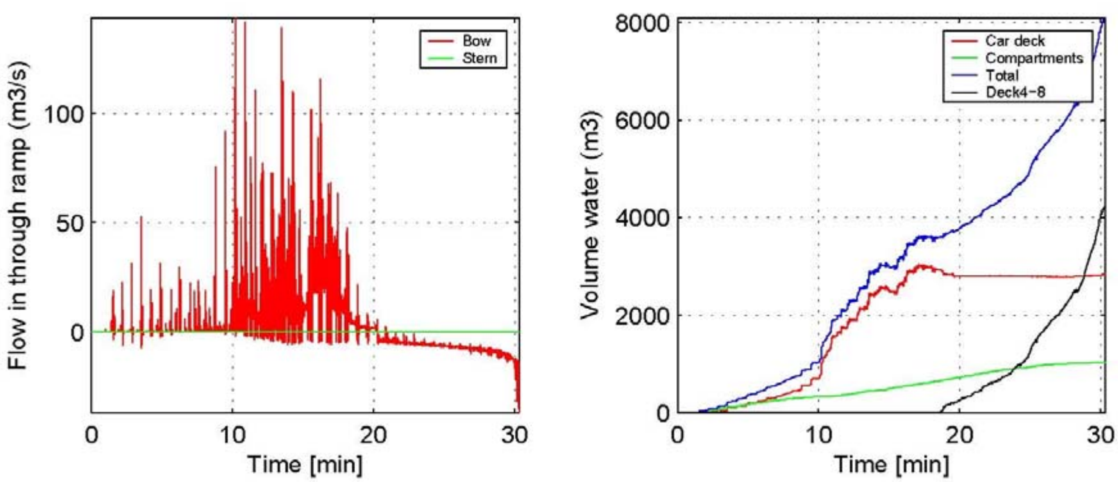


Fig. 26. Time histories of Flow and Volume water, from simulation No. 6 (COE6) in Appendix 3 of Project Report No. 11. Compartments means compartments below car deck.

9.1.3 Conclusions

The following conclusions can be drawn from the simulation study with SEAMAN:

- The simulation model used represents the ship dynamics well as is shown in comparisons with model tests.

- Different approach headings have been tested and it is possible to achieve a track that corresponds with the established positions of visor, debris and wreck. This means that the heading angle at the time of loss of visor is not critical for the final outcome, however, it may change the rate of change of list.

- Before the turn and loss of visor, a starboard rudder angle is, due to the weather helm tendencies, required to maintain the heading. When the ship starts to heel over due to internal flooding, this tendency is increased since port propeller will eventually come above the water level. However, when the ship is turning into the wind, the direct wind moment to starboard will reduce the port turning tendencies. According to the simulations sufficient power on propellers is required to make the ship fulfil the turn. Thus the engines could not have been stopped before the turn through the wind.

- According to the simulations the visor must have dropped before the port turn of the ship, considering established positions as well as the development of the list. If the turn is initiated before the loss of the visor, there will not be sufficient inflow of the water for later capsize. In beam or following sea the inflow of water through the bow ramp is only marginal.

- When the visor is lost, the list increases rapidly up to a level of about 35 to 45 deg (as long as the ship is meeting the waves), after which it continues to increase, however more slowly. This agrees well with the final model tests carried out at SSPA and reported in Project Report No. 12.

- When the list has reached 60-70 deg, the list increases more rapidly until 90 deg, when the simulation is stopped.

The results from the two simulations 6 and 8 (COE6 and COE8 in Project Report No. 11) have been plotted in the diagram of Fig. 27, where the list angle development versus time is shown. In this diagram is also plotted a number of witness statements (cf. Fig. 3) as well as results from model tests of Project Report No. 12. In simulation 8 the initial heading angle was 240 deg instead of 281 deg.

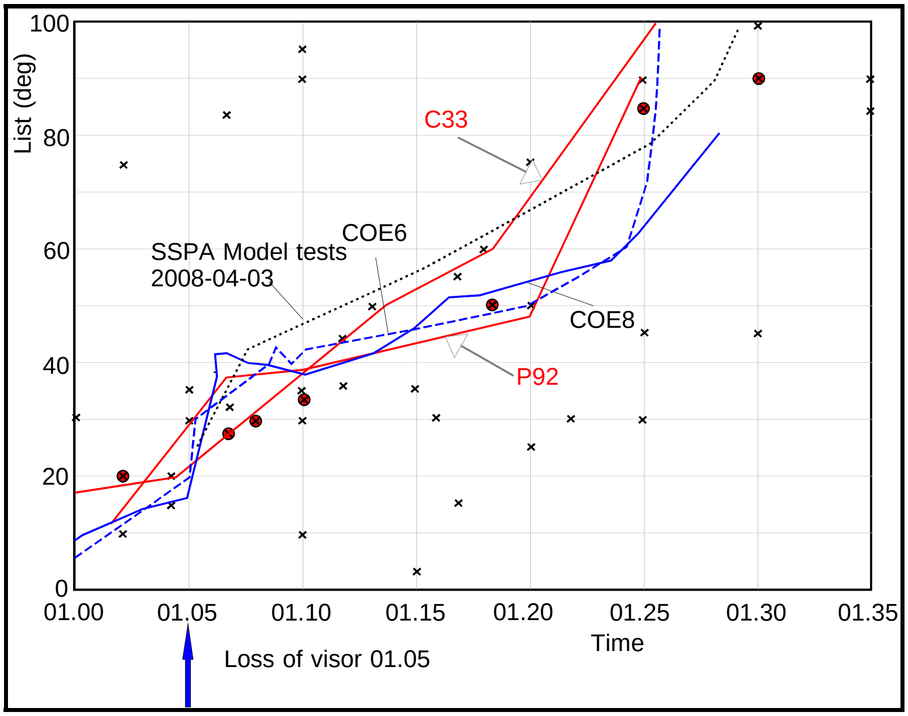


Fig. 27. List development versus time from witness statements C33 and P92 (cf. Fig. 3), SEAMAN simulations (COE6 and COE8), and model test.

9.2 Simulations of Flooding of Superstructure Deck No. 4, using FREDYN

9.2.1 Objectives and technical approach

The objective of the study was to obtain computer simulation results to be compared and to be validated against the results of the model experiments carried out for a specific test case, i.e. the flooding of accommodation deck No. 4. The successful correlation of such simulations would give confidence when it is employed for the full computational simulation of the sinking sequence of MV Estonia

The timewise simulation of the progressive flooding through a complex interior of a passengership is a daunting task. The currently feasible way of doing this is to set up the system of fluid flow equations for each compartment and for each connection. Then it shows that the equations are highly non-linear thus necessitating a time-stepping approach. In order to do so it is also required to make certain simplifying assumptions about the flow behaviour. As the compartments fill up with water the ship as a whole will sit deeper and obtain a heel angle which alters the flow through the connecting doors and through the compartments.

The numerical code employed at MARIN is the so-called FREDYN-Flooding module. It is based on many years of development in an international consortium, and has been validated quite extensively outside the current Estonia R&D investigation.

In the code a number of fundamental assumptions are made.

- Quasi-static flow description, so no travelling wave fronts.
- Potential theory, so no friction effects are present in the description other than the physics embedded in the concept of discharge coefficient.
- Bernoulli equation, to obtain the resultant velocity through a door opening.
- Fluid flow equations for fluid and gas (here: water and air)
- Through-flow in a door opening being based on the concept of discharge coefficient.
- For the present calculations it was further assumed that compartments were fully ventilated to the outside atmosphere (some extra runs were made separately to investigate the effect of air-pockets though).

9.2.2 Results and conclusions

In the present simulations the same cases were covered as for the experiments done for the Deck No. 4. The variation cases with a variation of pressure head, a variation of downflooding openings and a variation of air-ventilation were also simulated for comparison with the experiments.

Fig. 28 and 29 show some typical simulation results. The detailed results can be found in Project Report No. 7.

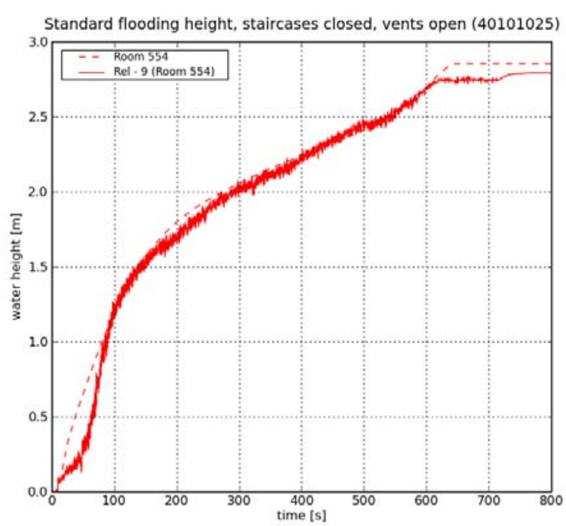


Fig. 28. Comparison between computer simulations (dashed line) and model experiments.

The two diagrams of Fig. 29 show the comparison between the experiments (wiggly lines) and the simulations (dashed lines).

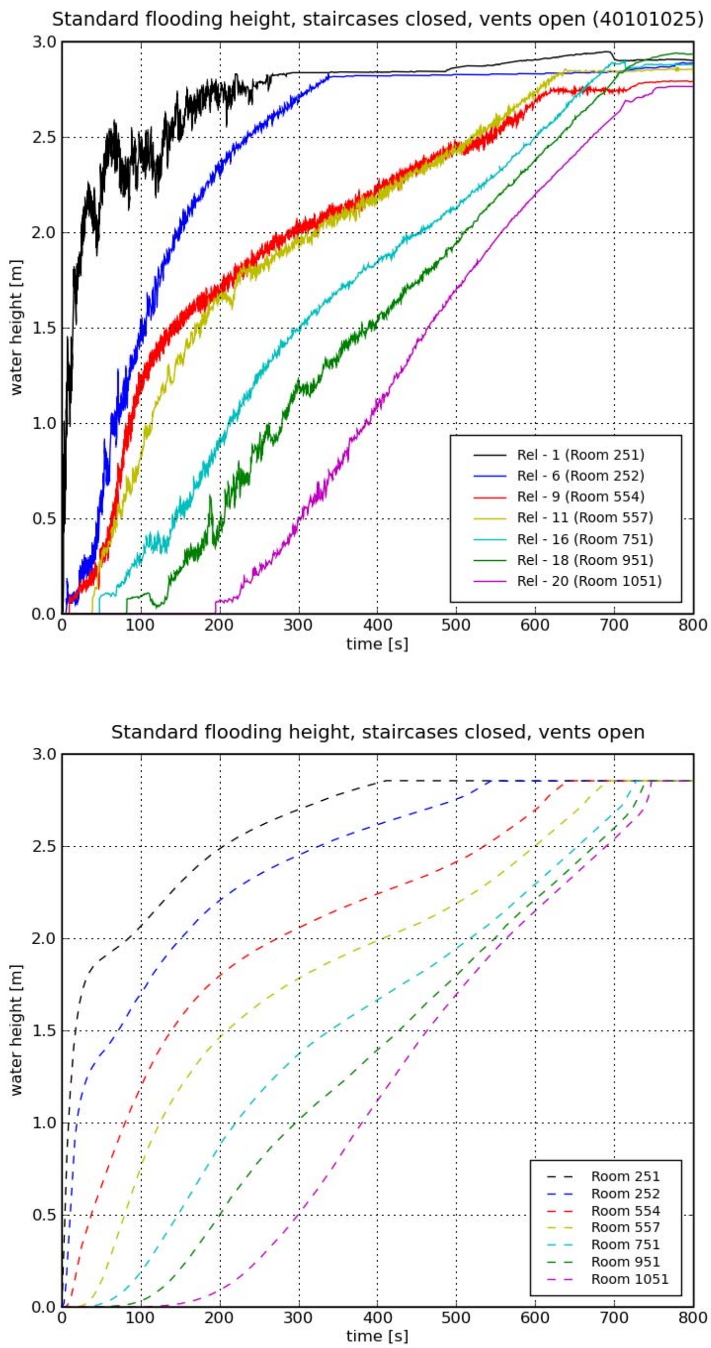


Fig. 29. Comparisons between experiments (wiggly lines) and the simulations (dashed lines).

The results of the calculations carried out for the present R&D project on Deck No. 4 justify the following overall conclusions:

- The results of the numerical calculations are supported and validated by the results of the progressive flooding experiments in the global sense and constitute a reliable tool for the investigation of the flooding rate of whole compartments and sequences of compartments.
- The numerical calculations are a very efficient tool -as regards time and costs- to investigate parameter variations that are difficult or too time-consuming to do in a physical experiment.
- The results are dependent on the assumption of the value of the discharge coefficient for the inlet and the door openings. The sensitivity of the final results to the Cd value is significant; in particular the Cd adopted for the inflow openings plays a crucial role.
- The Cd coefficients have a local effect on the throughflow of the door opening to which they are related; yet in addition they have an out of proportion cumulative effect on the flooding rates of the more downstream compartments.
- The Cd values assumed for the computations and the flooding rates coming out of these agree consistently with the values as evaluated from the model experiments. Even to the extent that the Cd values for the inflow windows were considerably different from the Cd values for the doors.

9.3 SIMCAP Simulations of the Foundering

9.3.1 Objectives and technical approach

Numerical simulations were carried out in order to better understand the sinking sequence during the loss of MV Estonia and to reveal key physical mechanisms pertinent to the foundering. This work is reported in Project Report No. 10.

An in-house numerical tool, SIMCAP, capable of simulating flooding and damage stability events for ships in a seaway has been used. During the project this tool has also been further developed in order to better capture processes of relevance to the foundering, e.g. refinement of water inflow model and capability of different ship headings and speed.

The simulations were divided into two stages; the initial stage, where the car deck was flooded through the bow ramp opening, see Chapter 3.1 of Project Report No. 10 and the final stage, which starts with a flooded car deck and ends with the capsize and sinking of the ship, see Chapter 3.2 of Project Report No. 10.

9.3.2 Initial stage simulations

In the initial stage simulations were made for different speeds and headings with a fully open bow ramp, see Fig. 30. The results are compared to model tests and further explained in Project Report No. 10. The work also includes a study of possible flow through the aft ramps.

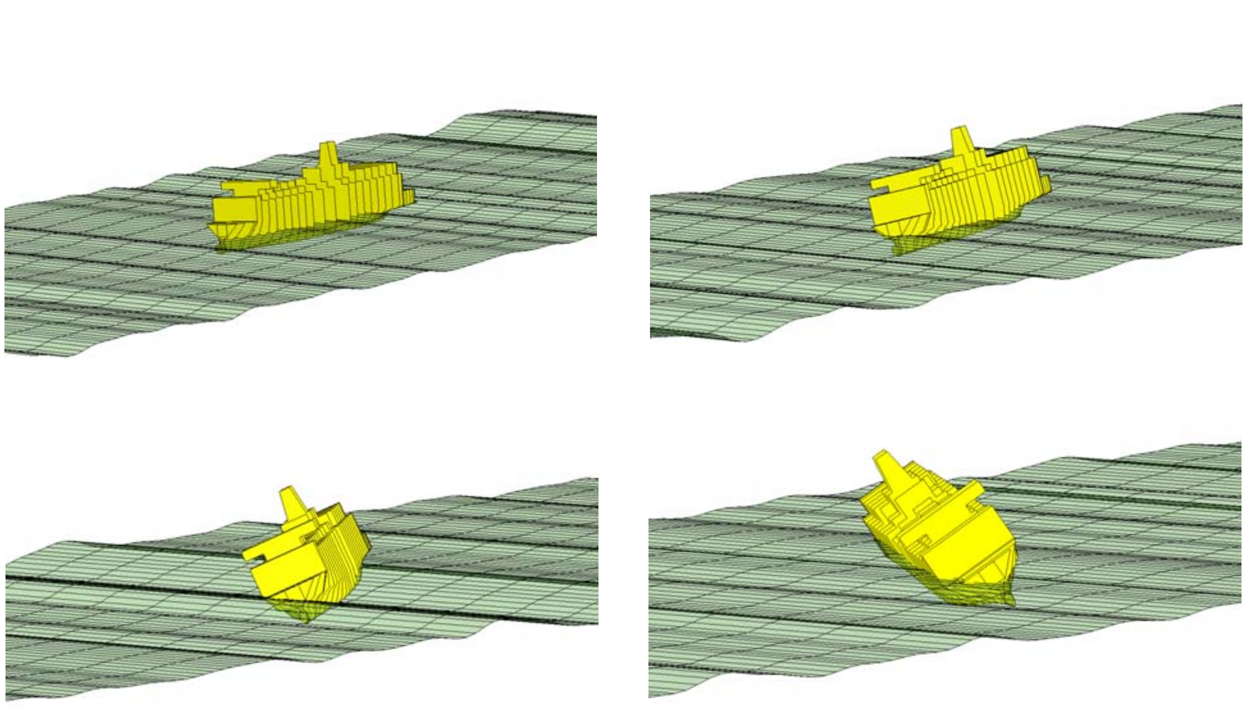


Fig. 30. Snap shots from initial stage simulations with flooding through bow ramp opening.

9.3.3 Final stage simulations

The simulations of the final stage starts with the assumption that the car deck is flooded with 2500 tonnes of water and the ship is drifting at beam seas. In Project Report No. 10 a time series representation of a final stage simulation is shown, where the ship capsizes and finally sinks after 21 minutes.

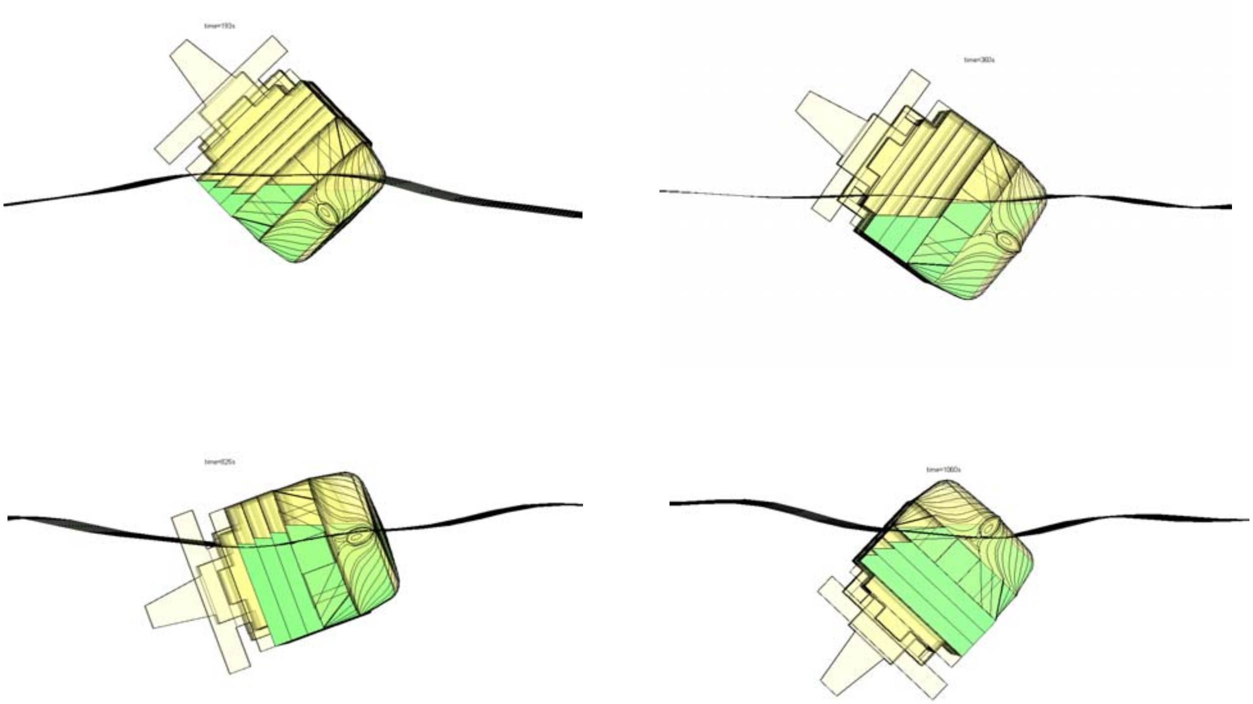


Fig. 31. Snap shots from a final stage simulation with flooded water in green color.

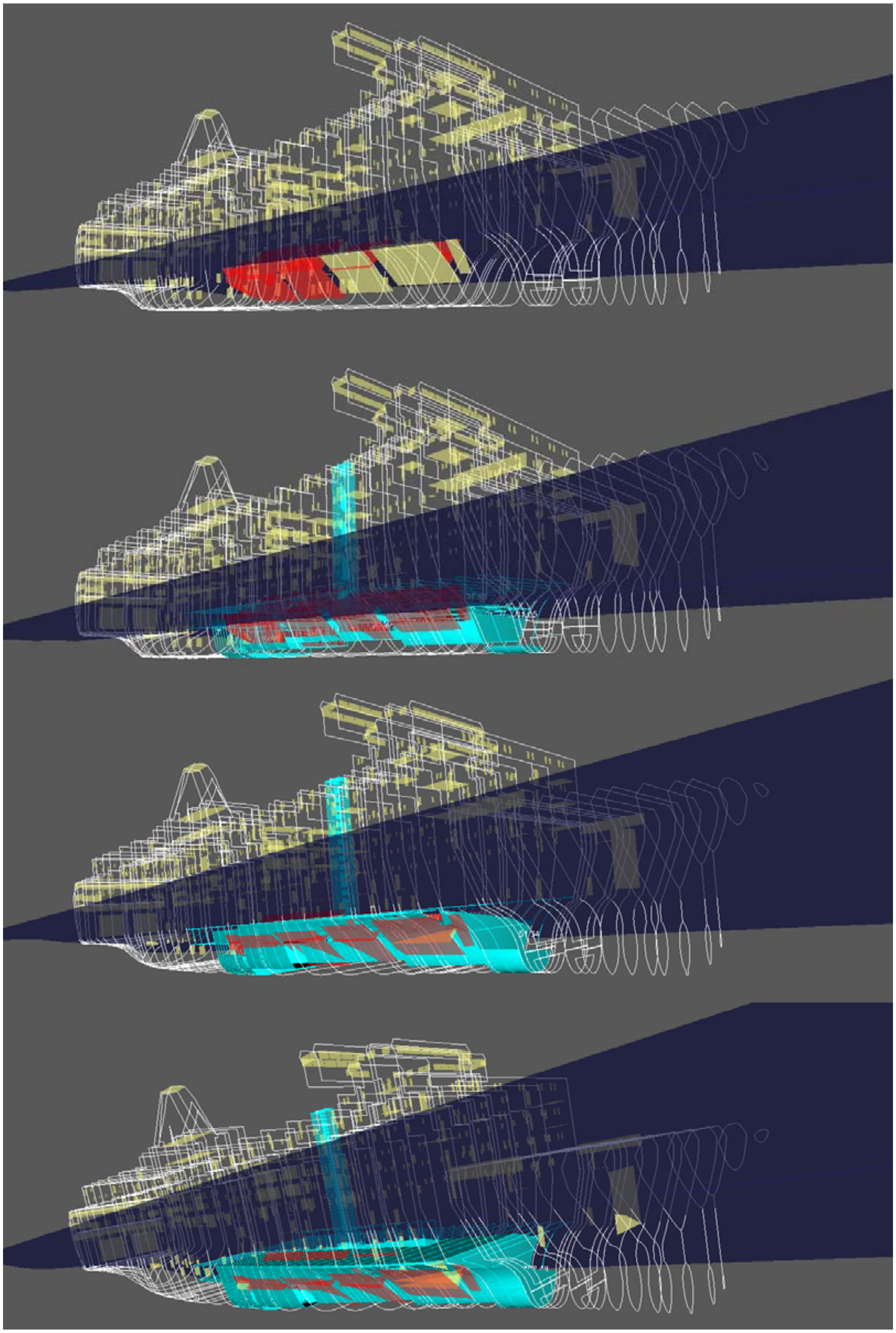
Fig. 31 shows snapshots from a final stage simulation. Physical mechanisms of importance to the foundering are explained in connection with similar snap shots in Chapter 3.2.1 of Project Report No. 10.

The SIMCAP simulations should not be seen as an exact description of the foundering. The importance of the simulations is rather in the revealing and explaining of the physical mechanisms that explain and support the possibility of a similar scenario.

9.4 PROTEUS3 Simulations of the Foundering

Safety at Sea's PROTEUS3 simulation program was used to analyze different scenarios, see Project Report No. 14. The main scenarios are also described in Chapter 6.

Fig. 32 shows a sample snapshot of the PROTEUS3 simulation of flooding of spaces on Deck 0/1 forward.



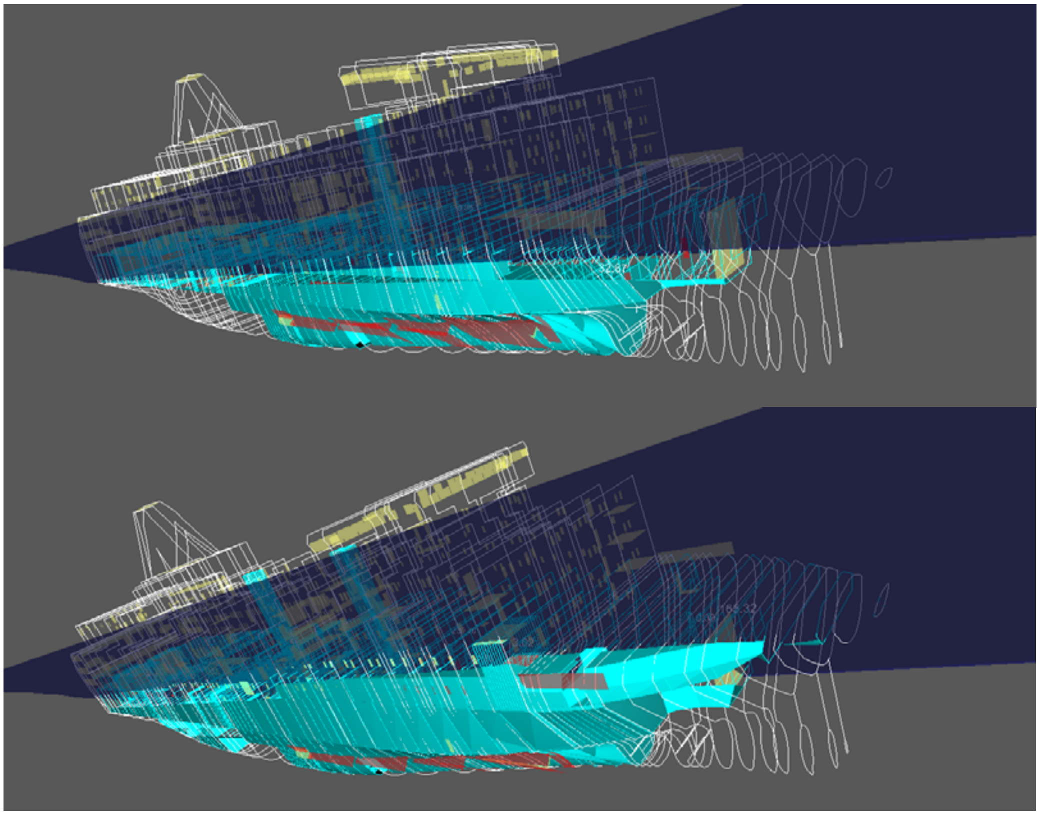


Fig. 32. Six snapshots of the PROTEUS3 simulation of flooding of spaces on Deck 0/1 forward, subsequent up-flooding of car deck and development of large angle of heel. Up-flooding can only take place in case of substantial or nearly complete flooding of the lower spaces subject to direct flooding from the sea.

10 DESCRIPTION OF THE MOST PROBABLE FOUNDERING SCENARIO

The possible foundering scenarios summarized in Chapter 6 and described in detail in Project Report No. 17 were analysed by use of the different tools reviewed in Chapters 7-9.

The most probable foundering scenario of MV Estonia, as concluded in Project Report No. 17, is:

- The ramp is forced partially open by the bow visor prior to complete visor detachment from the vessel, cf. [4].
- Water is entering the car deck through the openings at the sides of the ramp resulting in a slowly increasing starboard heel angle.
- The ramp remained partially open with broken lockings, port hinges and actuating cylinders until the bow visor detaches from the hull.
- The ramp fully opens and is crashing down onto the forepeak deck as the visor completely detaches from the vessel.
- Large amount of water is entering the car deck resulting in a rapidly growing starboard heel angle up to about 35-40 degrees.
- The ramp may be fluctuating up and down due to the interaction between waves and the pitch motions.
- Water is flooding down to the lower decks through vents and centre casing.
- The officer on the bridge is decreasing the ship speed and starts a port turn.
- After turning the ship heel is still increasing and the Port Main Engine, and after a short while also the Starboard Main Engine, trips and stops.
- The heel is increasing and the Auxiliary Engines trip and stop when the heel angle is more than 45 degrees.
- The ship is now drifting in wind, waves and current and when the heel is about 80-85 degrees the Emergency Generator shuts down.
- The ship capsizes.
- The ship sinks with bow up.
- The aft part of the ship is hitting the seabed first.

The foundering sequence as described is estimated to take about one hour. The scenario is demonstrated and verified by the scale model tests described in Chapter 11 and a computer animation of the sequence is described in Chapter 12.

11 MODEL EXPERIMENT OF THE MOST PROBABLE FOUNDERING SCENARIO

Foundering tests were carried out with a complete model of MV Estonia based on the model used in the manoeuvring and bow ramp flooding tests, see Project Report No. 3. The aim with these tests was twofold: to validate the simulations carried out within the project, and to strengthen the understanding of the foundering by use of physical experiments. The experiments are described in detail in Project Report No. 12 and a video (36 min) "Model test of the foundering of MV Estonia showing the most probable loss scenario, adjusted to full scale time", see Appendix C, is a part of the final project documentation.

11.1 The Scale Model

A photo of the model, scale 1:40, of MV Estonia is shown in Fig. 33.

Fig. 33. The ship model used for the foundering tests. In the background the SSPA's Maritime Dynamics Laboratory with the wind battery is shown.

The model was in these tests radio controlled. Two electrical motors were driving the propellers and the rudders were remote controlled like two valves placed in the bottom of the model, one fore and one aft, to be able to adjust for air compressibility in model scale. Also the ramp was remote controlled. When the ramp was open it was forced to stay open by use of a magnetic plate. The same waves as in the previous experiments were used, see Chapter 7.2.

The interior of the model was as detailed as possible. Complete drawings are shown in Project Report No. 12. All decks and main bulkheads were represented in the ship model, except Deck No 3 (hanging car deck) and the small parts of Deck No 5, 6 and 7 located behind the superstructure. All compartments could be filled with water during the foundering, except a number of tanks that were regarded as void spaces.

When building the model for the foundering there were three main tasks to consider:

- the displacement of the model has to be correct
- the permeability of the model must be as full scale like as possible
- the scaling of air compressibility model/full scale has to be handled like the ventilation of air

The first demand, correct displacement, is relatively easy to accomplish. However, the permeability of the MV Estonia is not completely known. Because of this, it was decided that the permeability of MV Estonia when she foundered was taken according to IMO's regulations for performing damage stability tests. This gives, taking into consideration the void spaces that cannot be filled, that the permeability for the three main parts of the ship is:

Below car deck:	0.88
Car deck:	0.90
Superstructure:	0.95

Due to strength reasons the model permeability was little bit too low in the lower decks of the model, but compensated in the higher decks to give a correct permeability figure overall.

11.2 Air Compressibility

The air compressibility must be considered in scale model tests of foundering scenarios. In the foundering air is trapped. A number of tests were carried out where the model capsized, trapped air and remained floating upside down. The volume of this trapped air was measured, and a mean value was found to be around 40 litres. Also the pressure of the trapped air was measured. The scaling laws give for the present situation that about 20% of the trapped air should be evacuated to give a proper remaining amount of trapped air in the model, see Project Report No. 12, Appendix 1. In this case around 8 litres could be let out in order to fulfil the scale laws. The two valves in the bottom of the model were calibrated giving a flow of 6.7 litres each per minute at the actual pressure. This means that one valve could be held open a little more than 1minute during the test.

11.3 Flooding

In the foundering tests all watertight doors were open except the one aft of the engine control room. Each room in the model could be flooded through the different doors, staircases, lifts, emergency exits, ventilation systems etc. according to the full scale ship. The most important ventilation shafts for the water ingress was the ones going down from the both sides of the ship just below deck 4 (first deck in the superstructure), inside car deck and down to tank deck. These shafts were scaled and they were also important for air evacuation. Flooding into Deck No 4, 5 and 6 could take place through two open large windows in the aft part on each deck.

11.4 Test Results

The depth of the basin corresponded to 90 m in full scale. The tests started with the model close to the end of the basin and steamed against the waves with an angle of approximately 10 degrees from port side. The wind came also from port side with an approximate angle of 40 degrees. When the model reached the position +10 m (10 m south of the midpoint in the basin) the ramp was opened and the propeller thrust was somewhat reduced, in the order of 10%. Immediately the heel increased due to the water entering on car deck, and starboard rudder was used to keep her on course. When the model reached a heel angle of approximately 25 degrees a port turn was initiated. The heel increased all the time in the turn and when the turn had reach around 100 degrees the propellers were stopped. The model then stopped very quickly and started to drift in wind and waves 90 degrees to the waves.

Several tests under the same conditions were carried out to assure the repeatability of the tests. In the final phase of the foundering, when the model had reach a heel angle of 150-160 degrees the aft valve was opened less then one minute to compensate for air compressibility.

Fig. 34. Ship model in heel angle 150-160 degrees. Due to scale effects in air compressibility air was ejected from a calibrated valve at the stern of the model.

Figs. 34 to 36 show the final phase of the foundering. The ship model sank with stern first and rested with the aft part of the superstructure on the bottom of the basin. The forward part of the ship model with the bulb was now still above the surface. In this position the forward valve was opened a few seconds and now also the bow sank. This means that the amount of air ejected from the model was in the order of 8 litres.

In Fig. 37 the heel angle development during the foundering test is shown.

Fig. 35. Final phase of the foundering. The stern has rested at the bottom of the basin and air is escaping from the car deck. Due to practical reasons the ramp was forced open during the tests, but would have been closed by gravity by now.

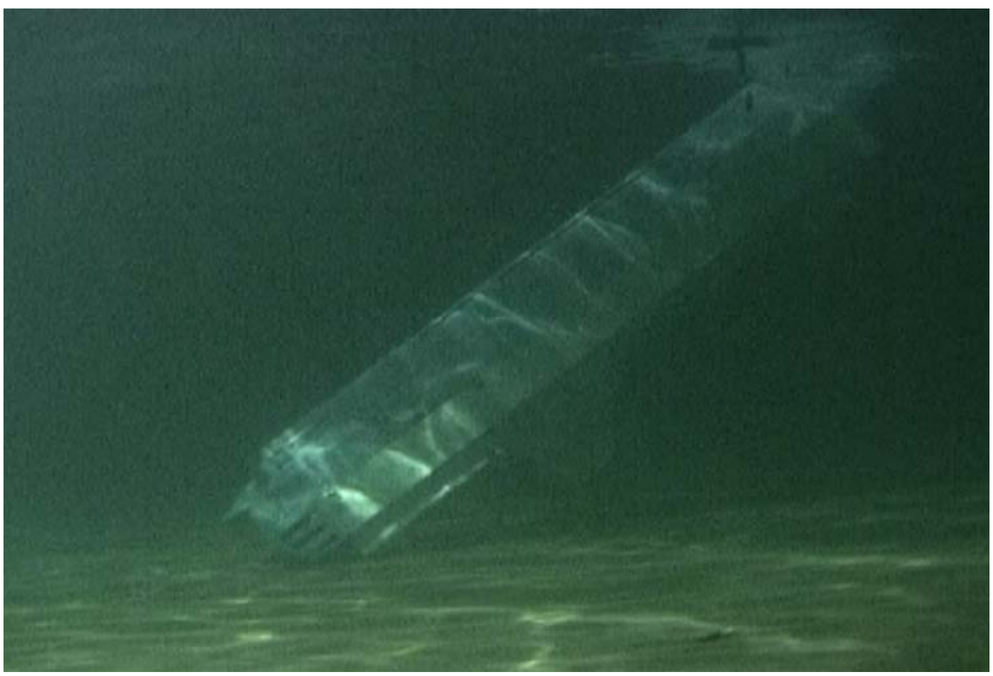


Fig. 36. Final phase of the foundering. The aft part is hitting the bottom.

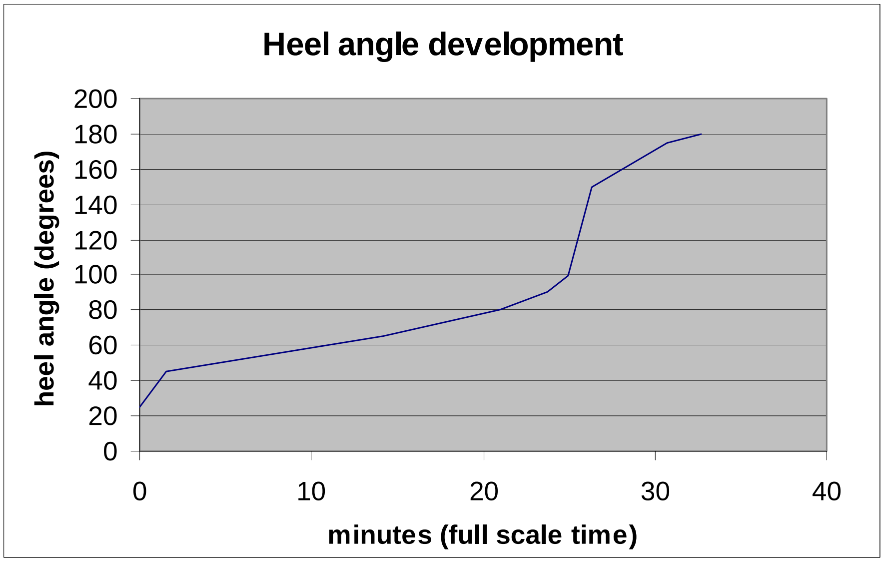


Fig. 37. The heel angle development. As soon as the model reached a heel angle of about 40 degrees water started to fill the aft rooms on tank deck through the ventilation shafts. At the same time water flooded Deck No 4. This explains the relatively slow increase in heel angle until the model reach 90-100 degrees. From this point the heel increases rapidly up to about 150 degrees.

12 COMPUTER VISUALIZATION OF THE MOST PROBABLE FOUNDERING SCENARIO

A virtual demonstrator was designed within the project by Safety at Sea, see Project Report No. 15. The demonstrator was used for illustrating the most probable foundering scenario as established by the SSPA Consortium. A video animation showing the sinking sequence is a part of the delivery from this project, see Appendix C.

Fig. 38, and Fig. 1, show illustrations from the virtual demonstrator.

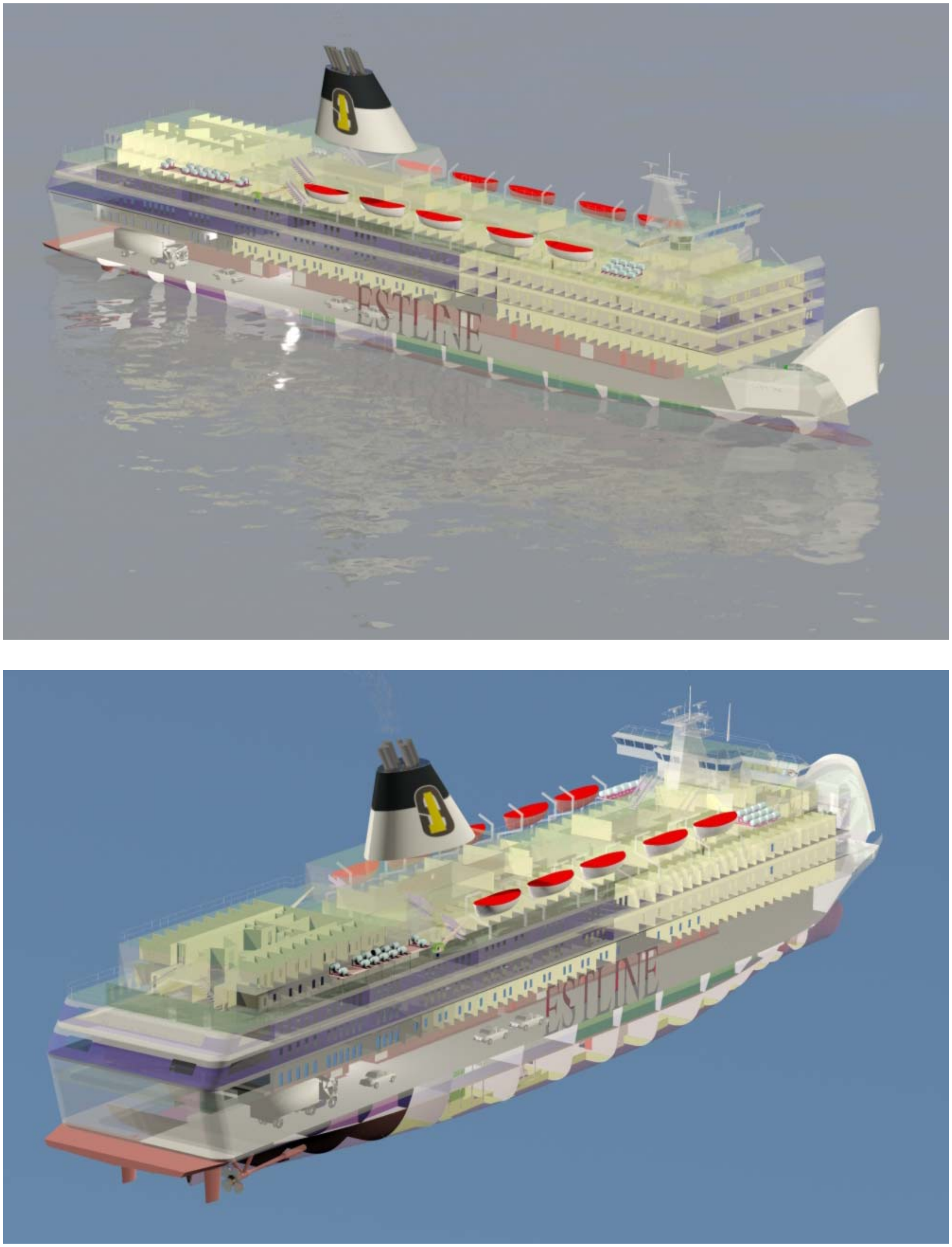


Fig. 38. Pictures of MV Estonia from the virtual demonstrator.

13 RECOMMENDATIONS

There are many ongoing and recently completed research projects aiming at improving ship safety. Within the SURSHIP (SURvivability of SHIPs) programme, about 25 national-funded research projects are running, and there are a number of EU Framework Programme Projects that focus on ship safety. The Swedish Research Project "DESSO-Design for survival onboard" [5] presented a concept ship, the DESSO Ship, with the ability to stay upright and afloat by use of wide side casings.

This Chapter contains recommendations from the SSPA Consortium with respect to ship safety and development of tools and methodology.

13.1 Recommendations on Ship Safety

In Chapter 7 "Safety onboard passenger ships" of Project Report No. 17 is a brief overview of the regulatory system, the function of which was to prevent accidents such as the MV Estonia disaster. A summary is given in this Chapter. An analysis of the stability of MV Estonia is presented in Project Report No. 16.

13.1.1 System of safety provision

The provision of safety is implemented in maritime industry by compliance with prescriptive, history-driven rules and regulations, used by designers/builders/operators, verified by Flag State Administrations, which can use Class Societies, and policed by Port State Controls, during every stage of ship life.

The development of maritime rules is driven by accidents, whereby the industry is forced to respond to societal concerns arising when accidents occur.

Therefore, the society is part of a system in which it plays significant role, namely that of requesting of its governments to mobilize of resources adequate for development and enforcement of safety standards, which would be commensurate with the societal safety expectations.

Every accident unacceptable to the society is a demonstration that safety standards are not sufficiently reflective of societal expectations.

13.1.2 Historical trends

Sixteen flooding accidents with a total loss of nearly 3,000 lives have taken place since the MV Estonia disaster, see Project Report No. 17. The underlying cause of such loss of life is rapid loss of stability by a ship when subject to flooding.

While it has not been possible to determine if all of these ships have complied with statutory requirements on stability, at least MV Estonia has complied with stability standards of SOLAS.

There are strong indications that most modern stability standards do not raise the level of required stability much higher beyond those which MV Estonia complied with.

13.1.3 Recommendations on Safety Standards

In the MV Estonian disaster a heavy loss of lives was caused by a rapid **loss of stability**.

The loss of stability resulted most likely from water inflow onto the car deck through the bow doors. However, there are several other possibilities of **dangerous water ingress** into a ship which can bring about complete and rapid loss of her stability, very often, **despite compliance** with all international regulations in force.

Although considerable efforts have been spent on increasing the stability standards and subsequently agreed to be adopted in Europe after sinking of MV Estonia, it is progressively becoming clear that even the most contemporary standards on stability are not sufficient to prevent a disaster of MV Estonia dimension from happening again.

Therefore, it is recommended that a goal is adopted without delay that the rate with which catastrophic ship flooding accidents occur is lowered significantly, to reach a level in line with other risks in society. This level is yet to be defined.

Attainment of such a goal requires predominantly that steps are taken swiftly on **raising ship stability standards** beyond today’s levels.

13.2 Recommendations on Development of Tools and Methodology

To improve the maritime safety, in essence and in perception, it is of paramount importance to learn from accidents through extensive forensic investigation. Validated experimental and numerical tools as well as a proven methodology are of crucial importance. Some recommendations are given below.

13.2.1 Recommendations on the role of simulation

When the forensic investigation has led to the development of a hypothesis on a certain 'scenario' i.e. a logical sequence of events constituting a logical and interlinked system of cause and effect, then a 'reconstruction' in the real world or a 'simulation' in the virtual world can be helpful to study and to test the hypothesis.

A scientific simulation study, employing all available modern techniques for model experiments and computer simulation, is no substitute for a forensic investigation of the wreck and of the site of the accident and scrutiny of all the relevant technical information on the ship and its cargo.

If the simulation upholds the hypothesis, if all the shackles of the chain of events hold even under a modest variation of the -inevitable- technical assumptions, then all we can conclude is that the hypothesis cannot be rejected. It may then be concluded that it could have happened this way.

However, due consideration is to be given to the development of alternative hypotheses and scenarios that would embrace a different sub-set of the evidence and might equally well have happened.

13.2.2 Recommendations on the development of ship design tools

It is recommended that the safety against capsize and sinking can be expressed in quantitative terms. For this to happen, the R&D on this subject needs to get a boost from the industry and regulatory bodies.

The R&D on fluid flow <u>external</u> to the ship's hull -in the well-known fields of hydrodynamics of ship resistance and propulsion- has made great progress since the basic laws were formulated by William Froude in the 1870's.

Even though the R&D in the field of fluid flow <u>inside</u> a ship's hull (i.e. progressive flooding) has benefited greatly from that century of development, it is no exaggeration to estimate that it will take decades rather than years for this scientific field of internal flow to become fully mature to the extent that the flow details are understood sufficiently to predict progressive ship flooding and capsizing as a function of time with sufficient degree of confidence.

Notwithstanding this satisfactory point of departure and the satisfactory progress in recent times, it cannot be taken for granted that the computational method as currently implemented will stand up to the task of prediction of the progressive flooding, capsizing and eventual sinking process of a complete ship with sufficient degree of accuracy.
There are simply too many aspects yet to be investigated.

It is therefore recommended to undertake extensive and detailed studies on a great many subjects for which the scientific technical knowledge is presently lacking:

- Behaviour of the ship moving in 6 degrees of freedom over large amplitudes,
- Behaviour of water sloshing in and out through a damage opening in the hull,
- Effects of down-flooding and up-flooding through stairwells and other openings,
- Quantification of Discharge Coefficients (Cd's) used for through-flow through openings that could possibly be dependent upon flow geometry, magnitude of flow velocity and eventually also on size and shape of the wetted opening,
- Effect of air ventilation of compartments and development of air-pockets,
- Quantification of the strength and collapse behaviour of interior rigid sub-division and doors,
- Quantification of the strength and collapse behaviour of windows,
- Retarding effect of furniture and fittings in interior spaces.

It is therefore recommended that the currently existing tools, both computational and experimental, will get an impetus from industry and regulatory bodies to bring them on the level necessary to qualify and to quantify the hydrodynamic safety of passenger ships.

Even when the numerical codes have become sufficiently robust in the future to deal with all conceivable and realistic internal fluid flow effects, it still remains to be investigated whether the sheer accuracy of the results is sufficient to deal with ships in their most delicate and difficult condition: being on the verge of capsizing.

Having the tool is only the first step, the next, and probably more challenging step is to develop the required methodology of how to assess the – marginal – stability of a damaged ship in waves. In all these fields there are hosts of questions to be answered and a great deal of research yet to be carried out.

13.3 Specific Research Recommendation

In the research project "DESSO- Design for survival onboard" [5] was a concept ship with very high survivability designed. By combining the findings from "Research Study on the Sinking Sequence of MV Estonia" and the DESSO project and develop the concept ship further towards a real ship, together with the tools and methodologies mentioned in Chapter 13.2, a significant step for improved ship safety would be within reach.

14 CONCLUSIONS AND FURTHER WORK

The “Research Study on the Sinking Sequence of MV Estonia” has combined a set of forensic, design, experimentation and analytical modelling to scrutinize and review the available evidence, to synthesise this into loss hypotheses, to test these hypotheses through first-principles modelling studies, and to finally demonstrate the established scenario of the loss.

The loss of 852 people on the night of 27/28th of September 1994 has resulted from a rapid loss of stability by MV Estonia. Therefore, all the circumstances and reasons for

- breach of hull integrity allowing unobstructed ingress of sea water into the spaces of MV Estonia
- inadequate stability to allow orderly ship evacuation and abandonment in case of such water ingress,

have to be considered as the causes of the disaster.

There are many such reasons and circumstances, all of which contributed to greater or lesser extent to the loss. Clear identification of all of them specifically in relation to the loss of MV Estonia was beyond the scope of this project, and is therefore, left for future investigations.

However, in view of the conclusion on the most likely sinking sequence of MV Estonia, it can confidently be stated that the lack of compliance with minimum SOLAS requirements on forward collision bulkhead by MV Estonia on the night of 27/28th of September 1994, was the main reason for unobstructed ingress of sea water into the car deck spaces and, therefore, that this was the main cause of the ship loss in the light of international maritime law.

In more detail the approach adopted in the research project was:

- To review evidence such as testimonies from survivors and observations from all available video recordings from diving and ROV (Remotely Operated Vehicle) investigations. Four diving team members from the wreck investigation were also interviewed.
- To form an International Panel of Experts (IPE) to assist the SSPA Consortium to suggest different loss hypotheses conformant with the evidence.
- To perform fundamental and systematic model experiments to derive data for numerical simulation models.

- To build comprehensive numerical models to describe the performance of the damaged MV Estonia during the initial foundering phase when it was manoeuvred and when drifting in wind and waves, as well as for the progressive flooding when water enters the ship.
- To evaluate the different loss scenarios and derive the most probable one using different numerical simulation methods.
- To substantiate the most probable scenario by computer simulations/animations and physical model experiments.
- To derive conclusions and to make recommendations for future safety improvements of passenger vessels.

The most probable foundering scenario as identified in the project is:

- The ramp is forced partially open by the bow visor prior to complete visor detachment from the vessel.
- Water is entering the car deck through the openings at the sides of the ramp resulting in a slowly increasing starboard heel angle.
- The ramp remained partially open until the bow visor detaches from the hull.
- The ramp fully opens and is crashing down onto the forepeak deck as the visor completely detaches from the vessel.
- Large amount of water is entering the car deck resulting in a rapidly growing starboard heel angle up to about 35-40 degrees.
- The ramp may be fluctuating up and down due to the interaction between waves and the pitch motions.
- Water is flooding down to the lower decks through vents and centre casing.
- The officer on the bridge is decreasing the ship speed and starts a port turn.
- After turning the ship heel is still increasing and the Main Engines stop.
- The heel is increasing and the Auxiliary Engines trip and stop when the heel angle is more than 45 degrees.
- The ship is now drifting in wind, waves and current and when the heel is about 80-85 degrees the Emergency Generator shuts down.
- The ship capsizes.
- The ship sinks with bow up.
- The aft part of the ship is hitting the seabed first.

The foundering sequence as described is estimated to take about one hour.

The conclusions on the most likely sinking sequence established on the basis of evidence available rest primarily on three key inferences:

- The first heel resulted from water on deck flooding through forward doors, and not from flooding through any other breach of hull integrity.
- The ramp opened completely and closed due to gravity after heeling beyond 90 deg angle.

- The large side windows on the decks above the car deck withstood substantial pressures before breaking.

To bring conclusions on the loss mechanisms to near certainty, it would be highly recommended that the following further steps are taken:

- The whole hull of MV Estonia is inspected and documented in detail.
- The state of the ramp at the wreckage is inspected and documented in detail, and thereafter brought to surface for final confirmation of its state.
- At least three windows together with their frames are brought to surface and tested for breaking pressure.

Confirmation of the above key inferences would allow reaching a conclusion beyond reasonable doubt on the causes of the loss of MV Estonia.

15 REFERENCES

1. The Joint Accident Investigation Commission of Estonia, Finland and Sweden, 'Final report on the capsizing on 28 September 1994 in the Baltic Sea of the ro-ro passenger vessel MV ESTONIA'. Edita Ltd., Helsinki 1997.
2. Supplement to the Final report on the capsizing on 28 September 1994 in the Baltic Sea of the ro-ro passenger vessel MV ESTONIA.
3. "Estonia. Sjunkförloppsstudie. Rapport förstudie. 15 bilagor." Vam Frank Rosenius and Civ.ing. Staffan Sjöling, March 2003 (in Swedish).
4. "Bow arrangement collapse – Sequence of events", Jan-Ove Carlsson, MacGREGOR Technical Report, November 2007.
5. "DESSO- Design for survival onboard", Björn Allenström (editor), SSPA Research Report No, 132, ISBN 91-86532-45-6, ISSN 0282-5805, 2006

APPENDIX A - LIST OF PROJECT REPORTS

This is a complete list of project reports:

1. Vassalos, D, Jasionowski, A, Prigara, J, Guarin, L: “WP2.2 Definition of foundering scenarios, WP3.5 CFD Computations and validations, WP4.1 Comprehensive modelling of MV Estonia”, Safety at Sea Report No VIES01-RE-001-AJ, September 2006.
2. Rutgersson, O, Schreuder, M, Bergholtz, J: “WP2.1 Review of evidence and forming of loss hypothesis”, Department of Shipping and Marine Technology, Chalmers, Technical Report, October 2006.
3. Allenström, B, Thorsson, S: “Manoeuvring tests and bow ramp flooding tests” SSPA Report 4006 4100 – 1, March 2007.
4. Allenström, B: “Bow ramp flooding tests with complete car deck”, SSPA Report 4006 4100 – 2, May 2007.
5. Bergholtz, J, Rutgersson, O, Schreuder, M: “WP2.1 Review of evidence Report No. 2 Conceivable course of events”, Department of Shipping and Marine Technology, Chalmers, Technical Report, May 2008.
6. Blok, J J, Luisman, H: “Model experiments on MV Estonia: Flooding tests of superstructure deck No. 4”, MARIN Report No. 20374-1-RD, April 2008.
7. Carette, N F A J, van Daalen, E F G, Ypma, E L: “Computations on MV Estonia: FREDYN Simulations of flooding of superstructure deck No. 4”, MARIN Report No. 20374-2-RD, April 2008.
8. Tukker, J, Blok J J: “Model experiments on MV Estonia: PIV Measurements of flow velocity in flooding tests of superstructure deck No. 4”, MARIN Report No. 20374-3-RD, April 2008.
9. Blok, J J, van Daalen, E F G, Tukker, J, Ypma, E L: “Overall summary report of MARIN research”, MARIN Report No. 20374-4-RD, April 2008.
10. Schreuder, M: “WP4.1-4.3 Numerical simulations of foundering scenarios”, Department of Shipping and Marine Technology, Chalmers, Technical Report, April 2008.
11. Ottosson, P: ”SEAMAN simulations of course of events before foundering”, SSPA Report 4006 4100 – 3, April 2008.
12. Allenström, B: “Foundering tests”, SSPA Report 4006 4100 – 4, April 2008.
13. Strasser, C: “CFD Simulations on MV Estonia: Flooding simulations of superstructure deck No. 4”, Ship Stability Research Centre (SSRC), Universtity of Strathclyde, Report No VIES01-RE-003, May 2008.
14. Jasionowski, A: “PROTEUS3 Simulations of foundering scenarios”, Safety at Sea Report No VIES01-RE-002-AJ, May 2008.

15. Jasionowski, A: “Virtual demonstrator”, Safety at Sea Report No VIES01-RE-004-AJ, May 2008.
16. York, A: “Stability analysis MV Estonia”, Safety at Sea Report No VIES01-RE-005-AY, May 2008.
17. Jasionowski, A and Vassalos, D: “Technical Summary of the Investigation on The Sinking Sequence of MV Estonia”, Safety at Sea Report No VIES01-RE-006-AJ, May 2008.
18. SSPA Consortium: ”Final Report- Research Study on the sinking sequence of MV Estonia”, SSPA Research Report No. 134, ISBN 91-86532-47-2, ISSN 0282-5805, May 2008. *(This report)*

APPENDIX B – LIST OF INTERNATIONAL PANEL OF EXPERTS

The following international experts participated in the panel:

From shipping lines:
Jan Otto de Kat, A. P. Möller-Maersk A/S
Rolf Kjaer, Color Line
Harri Kulovaara, Royal Caribbean International & Celebrity Cruises

From ship yards and suppliers:
Jan-Ove Carlsson, MacGREGOR
Kai Levander, Aker Yards Finland
Alessandro Maccari and Giorgio Bacicchi, Fincantieri

From classification societies:
Pierre Besse and Jon McGregor, Bureau Veritas
John Carlton, Lloyd's Register

From governmental authorities:
Kees Metselaar, Dutch Maritime Administration
Andrew Scott, Maritime and Coastguard Agency MCA
Staffan Sjöling, Swedish Defense Materiel Administration FMV

From ship design and consulting companies:
Peter Andersson, MariTerm AB
Per Fagerlund, Globtech Marine AB
Werner Hummel, Marine Claims Partner (Germany) GmbH
Markku Kanerva, Deltamarin Contracting
Björn von Ubisch, UBITEC B.V.

APPENDIX C – CONTENT OF PROJECT DVDS

There are three DVDs included in the final reporting of the project:

- All 18 Project Reports (pdf format) listed in Appendix A.
- Model test: Foundering of MV Estonia (showing the most probable loss scenario, adjusted to full scale time) (wmv-file, 36 mins).
- Computer animation: Most Likely Sinking Sequence of MV Estonia (wmv-file, 11 mins).

These three DVDs contain the complete and final documentation of the project "Research Study on the Sinking Sequence of *MV Estonia*".