ANALYSIS OF THE SINKING SEQUENCE OF MV ESTONIA USING A COMBINED SIMULATION AND MODEL TEST APPROACH

Claes Källström, SSPA Sweden AB claes.kallstrom@sspa.se
Björn Allenström, SSPA Sweden AB bjorn.allenstrom@sspa.se
Peter Ottosson, SSPA Sweden AB peter.ottosson@sspa.se

ABSTRACT

On 28th September 1994 the Estonia-flagged ro-ro passenger ship *MV Estonia* sank rapidly between Estonia and Finland. The accident is considered to be the worst disaster at sea in post-war Europe. A research study on the sinking sequence of *MV Estonia* was carried out between 2006 and 2008. This paper summarizes the research study with focus on the use of a combined simulation and model test approach for analysis of the sinking sequence. The objective of the paper is to describe some of the tools used and to present results from both model tests and simulations of the sinking sequence.

Keywords: *ro-ro passenger ship, accident, sinking, foundering, scale model test, simulation*

1. INTRODUCTION

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, stern first, and disappeared from the radar screens of ships in the area at about 0150 hrs, Estonian time. 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 report “The Joint Accident Investigation Commission of Estonia, Finland and Sweden” (JAIC, 1997). This has also resulted in extensive discussion and speculation around the world.

In March 2006 the SSPA Consortium (SSPA Sweden, Safety at Sea/SSRC, Chalmers University of Technology and MARIN) was awarded a grant to investigate the sinking sequence and explain the underlying causes of the loss of *MV Estonia*. Recommended improvements regarding the future maritime safety of passenger ships were also provided at the end of the project. The project is summarized in the report: SSPA Consortium (2008). The review of evidence was an essential part, see Bergholtz, Rutgersson and Schreuder (2008), which is not considered in this paper. Another research study of the sinking of *MV Estonia* is reported in Valanto (2008).

In this paper the research approach adopted in the SSPA study will be presented and discussed in detail. *All units are given as full scale units.*

2. THE SINKING PROCESS

The sinking sequence of *MV Estonia* can be divided into following principal phases (SSPA

Consortium, 2008, and Jasionowski and Vassalos, 2008):

Phase 1: Initial heeling, approximately 0-40 deg, starboard side down.

1a. Initial inflow of water to car deck and initial heeling after partly opening up of bow visor and bow ramp due to heavy wave loads.

1b. Substantial inflow of water to car deck and fast increase of heel angle due to complete detachment of the bow visor and opening of the bow ramp.

1c. Decreased speed and port turn by order from officer on bridge.

Phase 2: Floating on starboard side, approximate heel angle 40-90 deg.

Side windows on decks above car deck become subjected to hydrodynamic loads and some windows break and water starts accumulating. Considerable inflow of water into the aft lower decks through side vents, and also considerable flooding of car deck resulting in water down flooding through the centre casing.

Phase 3: Capsizing, approximate heel angle 90-180 deg.

The capsizing phase starts when the heeling moment from the water inflow overcomes the ship's restoring moment.

Phase 4: Sinking by stern.

The aft trim develops further and the ship looses its buoyancy and sinks.

The sinking of *MV Estonia* as described above is a complex sequence of dynamical processes with substantial interactions. In order to describe, analyze and understand the entire sinking sequence several computer simulation tools as well as scale model tests were used. This is described in following Sections.

3. RESEARCH APPROACH

The research approach to analyze the sinking process was to combine hydrodynamic knowledge, scale model tests and computer simulations using advanced mathematical models.

The following steps were carried out:

1. To perform fundamental and systematic model experiments in order to derive data for improving and verifying numerical simulation models.
2. To build comprehensive mathematical 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.
3. To substantiate the sinking sequence by means of computer simulations-animations and physical model experiments.

4. SYSTEMATIC MODEL EXPERIMENTS

4.1 Fundamental Tests of an Accommodation Deck

Detailed model experiments to analyze the flooding into and through an accommodation deck were carried out. The deck above the car deck of *MV Estonia* was chosen for this study, see SSPA Consortium (2008), Blok and Luisman (2008), and Tukker and Blok (2008).

The results of these experiments justify the following overall conclusions from Blok, van Daalen, Tukker and Ypma (2008):

- 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.

The data obtained in these model tests were used in the mathematical modelling described in Carette, van Daalen and Ypma (2008), Jasionowski (2008) and Schreuder (2008).

4.2 Model Tests of Flooding through Bow Opening

To analyze the foundering of *MV Estonia* it is of crucial importance to know the water flow into the car deck under different conditions. A set of model tests were carried out at the SSPA Towing Tank (260x10x5 m) and the Maritime Dynamics Laboratory (MDL, 88x39x3.5 m), see Allenström and Thorsson (2007).

All tests were performed in irregular waves using a JONSWAP wave spectrum with a significant wave height of 4.3 m and a peak period of 8.3 s. The tests in the Towing Tank were carried out with a towed model and the tests in MDL were free-sailing. Comparable experiments from the Towing Tank and MDL were analyzed and no significant difference was found. It was noticed in the Towing Tank tests that the bow ramp frequently closed for short moments. It is not impossible that this also could happen in full scale. It should be pointed out that size and weight of the bow ramp was correctly scaled, but the friction in the hinges was difficult to scale in a correct way. In order to obtain comparable data it was decided to use a magnet to keep the bow ramp open during the completely open bow ramp tests in MDL.

The purpose was to investigate the initial water flow into the car deck under different initial conditions. For that reason the water that entered the car deck was momentarily pumped out from the car deck and into a container, see Allenström and Thorsson (2007), so the model´s orientation due to water on the car deck was not changed. The initial condition was varied with respect to ship´s speed, wave direction, trim and heel. This testing technique allows for long data recordings, where accurate mean values of the water inflow easily can be calculated, also in the assumed irregular wave condition.

Results of tests with completely open bow ramp and no bow visor in different ship speeds and wave directions are shown in Figure 1. The approximate square dependence on ship speed is evident and the wave direction 150 deg (starboard bow sea) gives significant higher inflow than 180 deg (head sea). This is explained by the more severe roll and pitch motions of the ship in bow sea conditions compared to head sea.

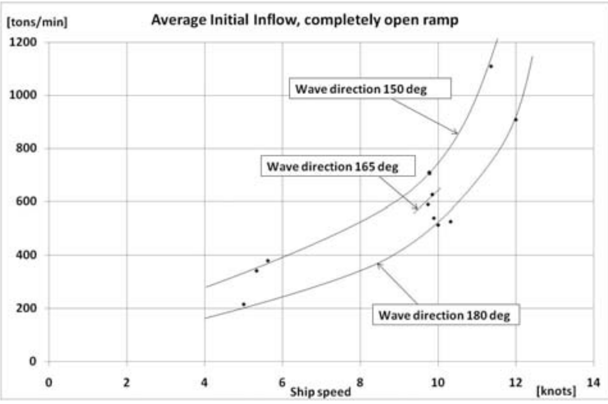

Figure 1. Measured average initial inflow to the car deck when the bow ramp is completely open and no bow visor. Wave direction 180 deg means head sea and 150 deg means starboard bow sea.

Figure 2 illustrates the significant increase of inflow when the static heel angle is 25 deg starboard down compared to zero heel.

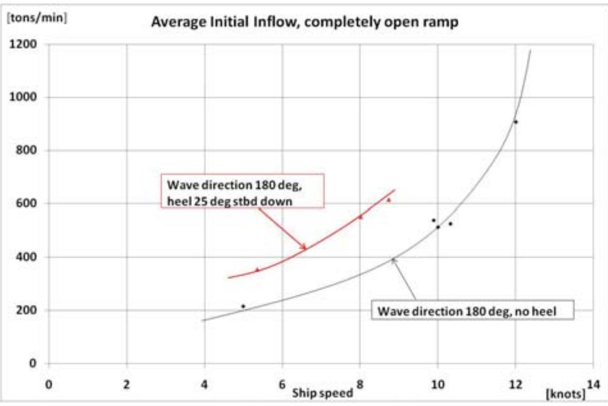

Figure 2. Measured average initial inflow to the car deck when the bow ramp is completely open and no bow visor. Wave direction 180 deg means head sea. The model was loaded for a static heel angle of 25 deg starboard down.

Figure 3 shows three measurement points with trim 1 m bow up and 1 m bow down compared to no trim. As expected a trim bow up increases the water inflow to car deck.

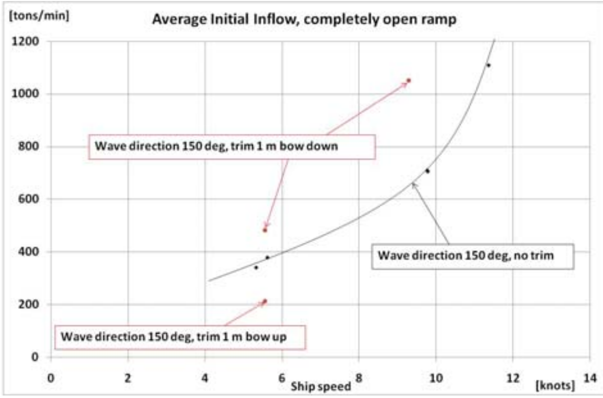

Figure 3. Measured average initial inflow to the car deck when the bow ramp is completely open and no bow visor. Wave direction 150 deg means starboard bow sea. The model was loaded for a static trim of 1 m bow up resp. 1 m bow down.

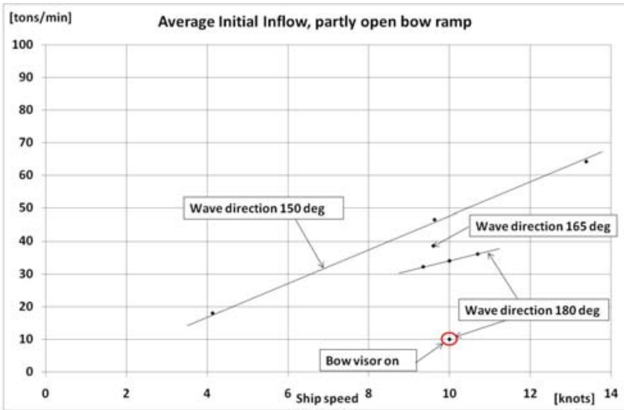

Figure 4. Measured average initial inflow to the car deck with partly open bow ramp (1 or 2 m opening). Wave direction 180 deg means head sea and 150 deg means starboard bow sea. The run marked “Bow visor on” means that the bow visor was completely fixed in front of the bow ramp.

Figure 4 summarizes the tests with partly open bow ramp, where the opening is 1 m or 2 m. It was concluded that 1 m or 2 m opening did not give any significant difference. One test with the bow visor completely fixed in front of the partly open bow ramp was carried out in head sea, see Figure 4. This test should not be regarded as significative, because during the foundering of *MV Estonia* the lower part of the bow visor, before complete detachment, was probably moving up and down. It was concluded in SSPA Consortium (2008) that during this phase of the foundering the water inflow to car deck can vary between a few tons per minute up to the order of 100 tons/minute. It was also estimated by extrapolation of the curves in Figure 1 that as much as 1500-1800 tons/minute can flow into the car deck depending on wave direction, if the ship speed is about 14 knots and the ramp is completely open and no bow visor. With an additional static heel angle of 25 degrees starboard down as much as 2000-2500 tons/min could enter the car deck initially (extrapolation of the curve in Figure 2).

The results from the model tests of flooding through bow opening were used in SEAMAN simulations (Section 5 and Ottosson, 2008), PROTEUS3 simulations (Jasionowski, 2008, and Jasionowski and Vassalos, 2008), and SIMCAP simulations (Schreuder, 2008).

In Allenström (2007) some preliminary model tests to analyze the initial dynamic performance of *MV Estonia* when the car deck was flooded are described. These tests were stopped when a stable heel angle of about 46-47 degrees was achieved, since no adequate superstructure was mounted on the model in these tests. The result was that when the bow was opened up completely at 14.5 knots and at the same waves as described in the beginning of this Section, a heel angle of 15 degrees starboard down was obtained after about half a minute, 25 degrees heel after one minute and a stable condition at 46-47 degrees after 3-4 minutes.

4.3 Model Tests to Determine the Motion Responses and Manoeuvring Characteristics

Systematic model tests in SSPA's MDL were performed to determine the motion responses of *MV Estonia* in different irregular wave directions and at different static heel angles, see Allenström and Thorsson (2007). The water that entered into the car deck was momentarily pumped into a container as described in Section 4.2.

The JONSWAP wave spectrum with significant wave height of 4.3 m and peak wave period of 8.3 s was used again. Tests with intact bow (closed bow ramp and bow visor) as well as with completely open bow ramp (no bow visor) were carried out. In the report Allenström and Thorsson (2007) a number of turning circle tests and zig-zag tests in calm water and irregular waves are described. All measured data were used for the mathematical modelling of *MV Estonia* as described in SSPA Consortium (2008) and Ottosson (2008). See also Section 5 below, where the SEAMAN simulations are summarized.

The motion response tests are summarized in Figures 5-6, where significant values (single amplitude) of roll motions are plotted versus wave direction.

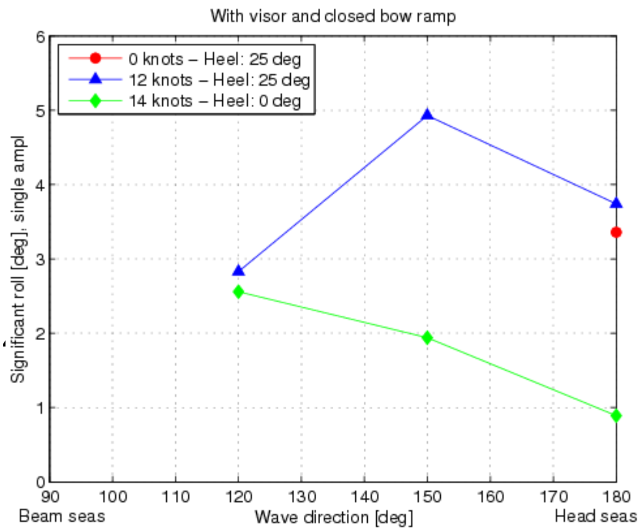

Figure 5. Roll response of *MV Estonia* (with closed bow ramp and bow visor) versus wave direction.

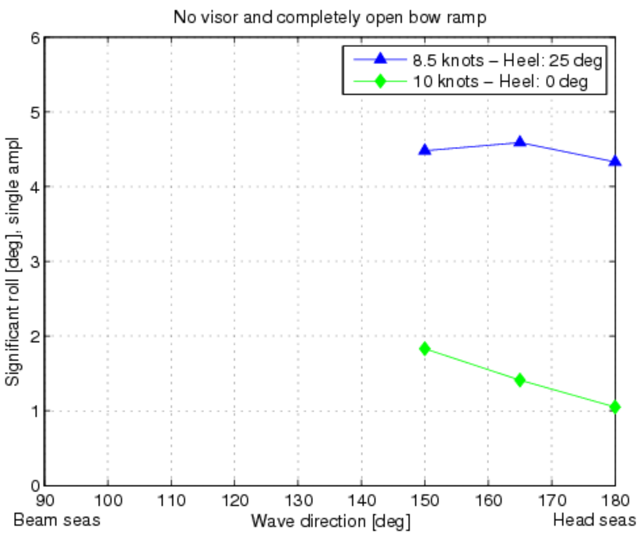

Figure 6. Roll response of *MV Estonia* (no bow visor and open bow ramp) versus wave direction.

5. COMPUTER SIMULATIONS

In order to analyze and understand the dynamical processes involved in a foundering sequence such as *MV Estonia´*s, computer simulations are of crucial importance. However, it is also of greatest importance that well documented and verified simulation programs are used and that the validity region is established. The systematic model experiments described in Section 4 were extremely valuable for these purposes.

5.1 Summary of Simulation Programs

In the research study of the sinking sequence of *MV Estonia* four different simulation programs were used in order to cover to entire sinking sequence (see SSPA Consortium, 2008, for an overview):

- SEAMAN (Ottosson, 2008)
- FREDYN (Carette, van Daalen and Ypma, 2008)
- PROTEUS3 (Jasionowski, 2008)
- SIMCAP (Schreuder, 2008)

In this paper the SEAMAN simulations are summarized in next Section.

5.2 SEAMAN Simulations of the First Phase of the Sinking

The SSPA SEAMAN simulation program has been developed and used for more than 20 years, see Ottosson and Byström (1991) and Ottosson (1994). SEAMAN is specially designed for investigation of manoeuvring and seakeeping performance in six degrees of freedom, including manoeuvring in irregular waves. The theoretical foundation was given already by Norrbin (1970). During recent years the SEAMAN program has also been updated with internal flow models covering also progressive flooding.

The model experiments described in Section 4 were used for verification and validation of SEAMAN, see Ottosson (2008), where also the mathematical model used for the *MV Estonia* study is described. The flow model in SEAMAN consists of:

1. In- and outflow through bow ramp opening
2. In- and outflow through stern ramp opening
3. Dynamics of water on car deck
4. In- and outflow to decks above car deck, including breaking of windows
5. In- and outflow to car deck and decks below car deck through an opening in the hull
6. Internal flow between car deck, decks above car deck and decks below car deck through centre casing and vents.

In the validation process it was established that SEAMAN is accurately simulating a foundering process up to a heel angle of 90 degrees, but the present version should not be used for larger heel angles. Therefore, the SEAMAN simulations were always stopped at this heel angle. By use of other programs listed in Section 5.1 also the capsizing and sinking phases were analyzed, see SSPA Consortium (2008) and Jasionowski and Vassalos (2008).

Figure 7 shows a heel angle comparison between SEAMAN and a typical foundering test.

Figure 7. shows a heel angle comparison between SEAMAN and a foundering test.

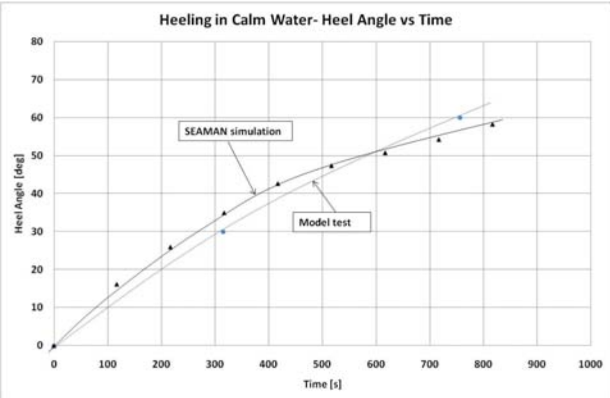

Figure 7 Water flooding into car deck. Comparison between model test and SEAMAN simulation.

A comprehensive 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 90 degrees. All details of these simulations are presented in Ottosson (2008) 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: Irregular waves (JONSWAP wave spectrum) with a significant wave height of 4.0 m with a peak period of 8.3 s, but a wave height of 4.3 m was also used for calibration against model tests. The waves were assumed to come from WSW.

The ship was, in the simulations, steered by an autopilot keeping the ship on course before the loss of the visor and also controlling the port turn. 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).

The simulation in Figure 8 shows a realization of the most probable scenario before capsizing. The simulation starts at T=0 with a partly open bow ramp. The simulation was stopped when the heel angle exceeded 90 deg, with a drifting direction towards the wreck.

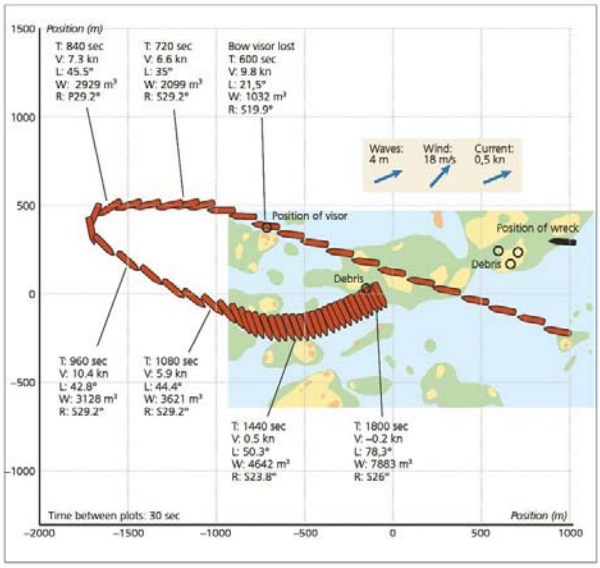

Figure 8. Realization of the most probable scenario before capsizing by use of SEAMAN. The simulation was stopped when the heel angle exceeded 90 deg, with a drifting direction towards the wreck. “Debris” indicates possible lost material from *MV Estonia*. A sonar plot is added in the background, courtesy by Dr. Nuorteva. T means time from simulation start, V ship speed, L list or heel angle, W total water volume inside ship, and R means rudder angle towards starboard (S) or port (P).

The following conclusions were 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 were tested and it was 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 has been lost 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.
- When the list has reached 60-70 deg, the list increases more rapidly until 90 deg, when the simulation is stopped.

6. REALIZATION OF THE FOUNDERING BY MODEL EXPERIMENTS

The complete foundering sequence of *MV Estonia* was also realized by model experiments in the SSPA MDL be use of a scale model (scale 1:40, see Figure 9-11).

Figure 9. The scale model of *MV Estonia*. In the background SSPA's Maritime Dynamics Laboratory (MDL) is shown.

Figure 10. Model test in MDL. When the bow visor was lost and the ramp was open, a large amount of water was entering the car deck resulting in a rapidly growing starboard list.

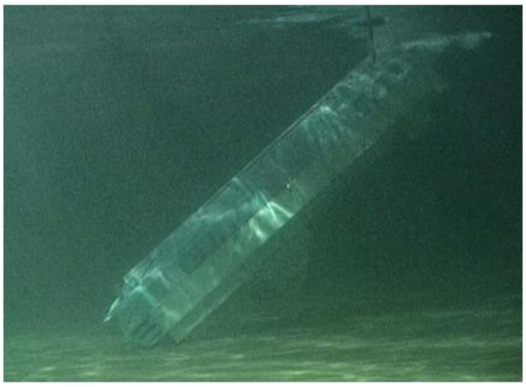

Figure 11. Model test in MDL. After capsizing the ship sank with stern first.

A number of model tests of the foundering were carried out and the results turned out to be quite robust. In Figure 12 the heel angle versus time is shown, where all test results are combined into one curve.

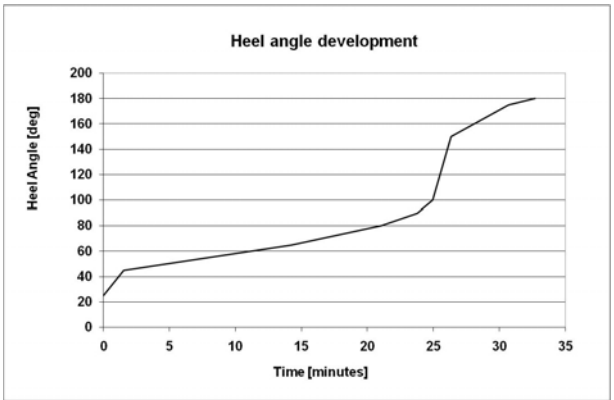

Figure 12. The heel angle development. As soon as the model reached a heel angle of about 40 degrees water started to fill the aft rooms on tank deck through the ventilation shafts. At the same time water flooded the deck above car deck. This explains the relatively slow increase in heel angle until the model reaches 90-100 degrees. From this point the heel increases rapidly up to about 150 degrees.

7. CONCLUSIONS

The combined simulation and model test approach adopted in the research study on the sinking sequence of *MV Estonia* turned out to be a very efficient technique. Realizations of the most probable foundering scenario by use of model tests as well as simulations were robust and consistent. It was possible to analyze efficiently in detail the different phases of the sinking sequence, but also the overall performance during the total foundering.

8. ACKNOWLEDGEMENTS

VINNOVA (The Swedish Governmental Agency for Innovation Systems) is acknowledged for the financial support of the Research study on the sinking sequence of *MV Estonia* (VINNOVA Registration Number 2005-02852). The SSPA simulation and model test work was also supported by *Fru Martina Lundgrens fond för sjöfartsteknisk forskning* (ML 87 and ML88) and *Hugo Hammars fond för sjöfartsteknisk forskning* (HHS176, HHS182, HH188), both gratefully acknowledged.

Lastly the authors wish to express their deepest sympathy to the relatives and friends of those who perished in the accident.

9. REFERENCES

Allenström, B., 2007, “Bow ramp flooding tests with complete car deck”, SSPA Report 4006 4100 – 2.

Allenström, B., 2008, “Foundering tests”, SSPA Report 4006 4100 – 4.

Allenström, B., Thorsson, S., 2007, “Manoeuvring tests and bow ramp flooding tests”, SSPA Report 4006 4100 – 1.

Bergholtz, J., Rutgersson, O., Schreuder, M., 2008, “WP2.1 Review of evidence Report No. 2 Conceivable course of events”, Department of Shipping and Marine Technology, Chalmers, Technical Report.

Blok, J. J., van Daalen, E. F. G., Tukker, J., Ypma, E. L., 2008, “Overall summary report of MARIN research", MARIN Report No. 20374-4-RD.

Blok, J. J., Luisman, H., 2008, "Model experiments on MV Estonia: Flooding tests of superstructure deck No. 4", MARIN Report No. 20374-1-RD.

Carette, N. F. A. J., van Daalen, E. F. G., Ypma, E. L., 2008, "Computations on MV Estonia: FREDYN Simulations of flooding of superstructure deck No. 4", MARIN Report No. 20374-2-RD.

JAIC, 1997, "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.

Jasionowski, A., 2008, "PROTEUS3 Simulations of foundering scenarios", Safety at Sea Report No VIES01-RE-002-AJ.

Jasionowski, A., Vassalos, D., 2008, "Technical Summary of the Investigation on The Sinking Sequence of MV Estonia", Safety at Sea Report No VIES01-RE-006-AJ.

Norrbin, N. H., 1970, "Theory and observations on the use of a mathematical model for ship manoeuvring in deep and confined waters", Proc. 8th Symposium on Naval Hydrodynamics, Pasadena, California, USA.

Ottosson, P., 1994, "Mathematical Models in PORTSIM". Paper presented at "Manoeuvring and Control of Marine Craft, MCMC'94", Southampton, UK.

Ottosson, P., 2008, "SEAMAN simulations of course of events before foundering", SSPA Report 4006 4100 – 3.

Ottosson, P., Byström, L., 1991, "Simulation of the Dynamics of a Ship Maneuvering in Waves", SNAME Transactions, Vol. 99, pp 281-298.

Schreuder, M., 2008, "WP4.1-4.3 Numerical simulations of foundering scenarios", Department of Shipping and Marine Technology, Chalmers, Technical Report.

SSPA Consortium, 2008, "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.

Tukker, J., Blok J. J., 2008, "Model experiments on MV Estonia: PIV Measurements of flow velocity in flooding tests of superstructure deck No. 4", MARIN Report No. 20374-3-RD.

Valanto, P., 2008, "Research Study on the Sinking Sequence and Evacuation of the *MV Estonia* – Final Report", HSVA Report No. 1663.

The reports from the "Research Study on the Sinking Sequence of *MV Estonia*" are available at www.sspa.se or www.safety-at-sea.co.uk/mvestonia/ where also video recordings from the model tests and a computer animation of the sinking sequence can be downloaded.