Research Study on the Sinking Sequence of MV Estonia

WP2.2 Definition of foundering scenarios
WP3.5 CFD Computations and validations
WP4.1 Comprehensive modelling of MV Estonia

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Title:	*Research Study on the Sinking Sequence of MV Estonia*

Summary:

This report is a draft of combined deliverables D2.2 and D4.1 of this project, as well as a summary of progress of work undertaken in WP3.5 on CFD computations.

The revision process has proved far more laborious and time consuming than anticipated, resulting to a large extent from lack of readily available data or any relevant information. Therefore, while preliminary foundering scenarios have been put forward, a far more comprehensive review is needed and is ongoing, supported by the first set of numerical simulations.

The anticipated process of comprehensive modelling, the objective of WP4.1, is considered complete.

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1 Introduction

On the night of 27/28 September 1994, the large passenger Ro-Ro ferry MV Estonia sank in the Baltic Sea, while on route between Tallinn, Estonia, and Stockholm, Sweden with great loss of life. Instantly, a panel of investigators from Estonia, Sweden and Finland, was set up and the accident was studied in some detail. Primarily, inadequate design of the locking devices of the forward bow ramp was blamed for the tragedy.

Recognising that some aspects of the loss require further study, the Swedish Government has assigned VINNOVA (The Swedish Governmental Agency for Innovation Systems) in its capacity as the responsible agent for the national Sea Safety Programme to commission a research project with the aim of studying the sinking sequence of the MV Estonia. The results will be used for improvements of safety of today's- as well as future-passenger ships.

This report summarises progress achieved to date in efforts undertaken by Safety At Sea Ltd in the project commissioned to the SSPA Consortium (1st March, 2006 to 17th March, 2008), www.safety-at-sea.co.uk/mvestonia.

2 The premise

The premise of this study starts with the question: to which extent does the official JAIC report [1], explain the circumstances of capsizing and sinking of MV Estonia?

The JAIC report utilised state-of-the art techniques available at the time of the tragedy to study the mechanisms underlying the sequence of capsizing and sinking of the MV Estonia as described by witnesses. The prime techniques in question pertain to static stability calculations with computer package NAPA.

The sequence of the loss, established by JAIC from witness statements, can be summarised as:

Phase 1 Loss of the bow visor and flooding of the car deck, time before 01:22 hrs; heel up to 40deg
Phase 2 Gradual loss of stability, time between 01:22 hrs and c.a. 01:30 hrs; heel 40-80deg
Phase 3 Floating on side and sinking, time c.a. 01:30 and 01:50 hrs; heel beyond 80deg

Although the approach adopted was advanced at the time, no information on the evolution of the loss in the **time-domain** could be obtained other than by expert judgement supported by "spot-checking" with the mentioned static stability calculations. For this reason the proposed explanation of the mechanism put forward was incomplete, namely:

(a) It was concluded that the plausible mechanism for extensive heeling angles was large flooding of the car deck spaces; however
(b) No explanation of the mechanism for the vessel floating on her side (heel in excess of ~40deg without capsizing) was offered; and
(c) No plausible explanation of the mechanism for the vessel sinking (i.e., flooding of at least 7,700 tonnes into the spaces below the car deck) was offered. The only proposed flooding of spaces below the car deck was through the centre casings from the upper decks at high heel angles.

Hence this study is by no means conclusive.

Furthermore, a series of alternative studies have been presented, as follows.

Anders Bjorkman and German Group of Experts

Neither of the studies mentioned offered full and consistent explanation of the loss, as discussed in article [4] shown here as Appendix 3.

Pilot study

Finally, the Pilot Study by Staffan Sjoling and Frank Rosenius was the most recent attempt to explain the mechanisms underlying the vessel's loss.

This study has brought to light new information, namely that according to construction drawings there are 6 ventilation ducts wing ward on the starboard and port sides, which can lead water from the car deck space into the engine room spaces, with the flooding initiating at a heel angle of some 40deg. Thus, this newly proposed mechanism could possibly explain element (c) of the loss as outline above, i.e., flooding of the spaces below the car deck and the resultant sinking of the vessel.

However, as regards element (b) of the loss i.e., stability at large angles (>40deg) of heel, this study has not offered a satisfactory explanation and hence it is also considered inconclusive. On one hand it seems to concur with findings of the earlier study [4], namely that the mechanism for the vessel's stability (at heel >40deg) derives from the temporary buoyant superstructure, suggested by consideration of its flooding in various stages. However, this assumption has no justification. Flooding through the assumed 10 windows on each of the decks, when completely broken, results in flooding rates of some 2400 m^3/min (40 m^3/s) to each deck. Thus, it would take some 3 minutes to flood the 8000m^3 of space in either of the decks, which can be regarded as the rate of vessel's capsize.

On the other hand, it seems, the authors of the pilot study **imposed** another assumption in their calculations, namely that the rate of vessel capsize derived from the rate of flooding the car deck; in other words that the car deck provides the means of stability at large (>40deg) angles of heel. The main effect of this assumption on the conclusions concerning the sequence of the loss is that the time it takes reaches some **33 minutes**, which tallies well with JAIC report as emphasised by the authors. However, from basic static stability calculations it can be seen that if the superstructure is disregarded as the contributor to the vessel stability the vessel will capsize immediately if more than approximately 2,000 tonnes of water enters the car deck even if there was no more flooding into the car deck, regardless of flooding in the lower spaces[1].

These points are discussed for better clarity in the table below:

Pilot Study	Comment
It was assumed that the car deck floods with a rate of at least 300 t/min. Based on this it was estimated that the time to flood the car deck fully (up to 10,000t) and for the whole scenario of capsizing to evolve is **33min**. This time estimate is used to demonstrate good correspondence with the JAIC time estimates of the vessel loss.	This ignores a few facts, namely: (i) a ship's ability to float with heel in excess of some 40deg (2,000t of water on the car deck) depends **solely** on the upper decks[2], which means that (ii) a ship's capsizing rate depends on flooding rates of these upper decks, see Figure 1; so (iii) if these decks were flooding at a rate of, say, 39.9m/s each (pilot study), the vessel would heel from 40deg to 180deg, i.e., capsize, within less than 3.3minutes! (iv) the flooding rates into the car deck would increase from an average of 300-600t/min (accumulation of 2,000t on car deck, 40deg heel) to some 3,000-8,000t/min once the ship heels beyond 40-45deg, due to large inflow through the ramp of some 30m^2 inflow area[3], thus (v) the ship would never have floated on her side, she would have capsized progressively within 2-3 minutes! So, this study does not explain at all how she did not capsize within 2-3 minutes in their calculations. The study simply assumed that she did not capsize and based on this it proposed the stages of flooding of the upper spaces to show that if the assumptions were right, the vessel would not capsize. But how can one verify that these assumptions are right?

[1] At least for various assumptions of flooding into the lower spaces this proved to be the case. However, this flooding will have an effect on the evolution of the capsizing and sinking and must, therefore, be accounted for in future studies with better precision

[2] If only 2,000 tonnes of water could accumulate on the car deck, after which development any opening allowing this water in was closed, the ship would still capsize unless there was support from the superstructure

[3] Again, it is irrelevant if the flooding rates into the car deck vary at all, once there was more than 2,000 t of water on deck. The vessel will capsize, at a rate dictated by the rate of flooding of the upper deck spaces

In conclusion, this pilot study proposed new mechanism for flooding of spaces below the car deck, BUT it failed to demonstrate the ability of the vessel to stabilise at heel angles of more than 40deg for more than 2-3 minutes[4].

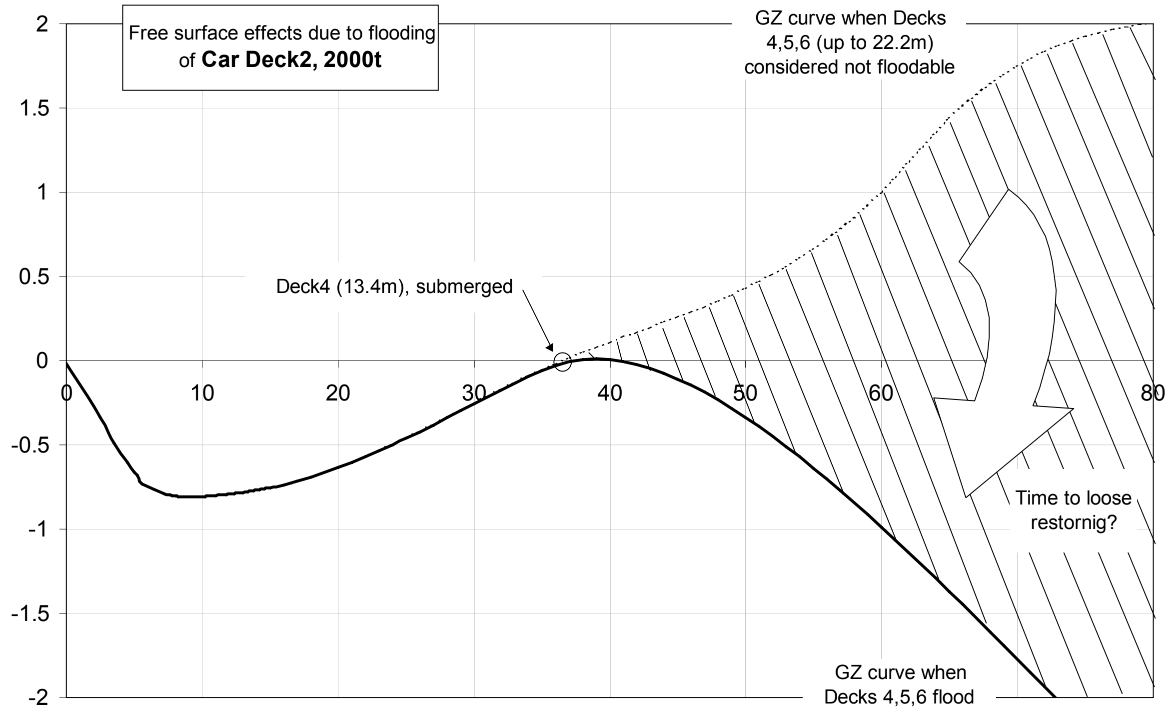

Figure 1: The process of flooding Decks 4, 5 and 6 takes place within a finite amount of time, estimated 13-28minutes if the JAIC statements were used as a reference base.

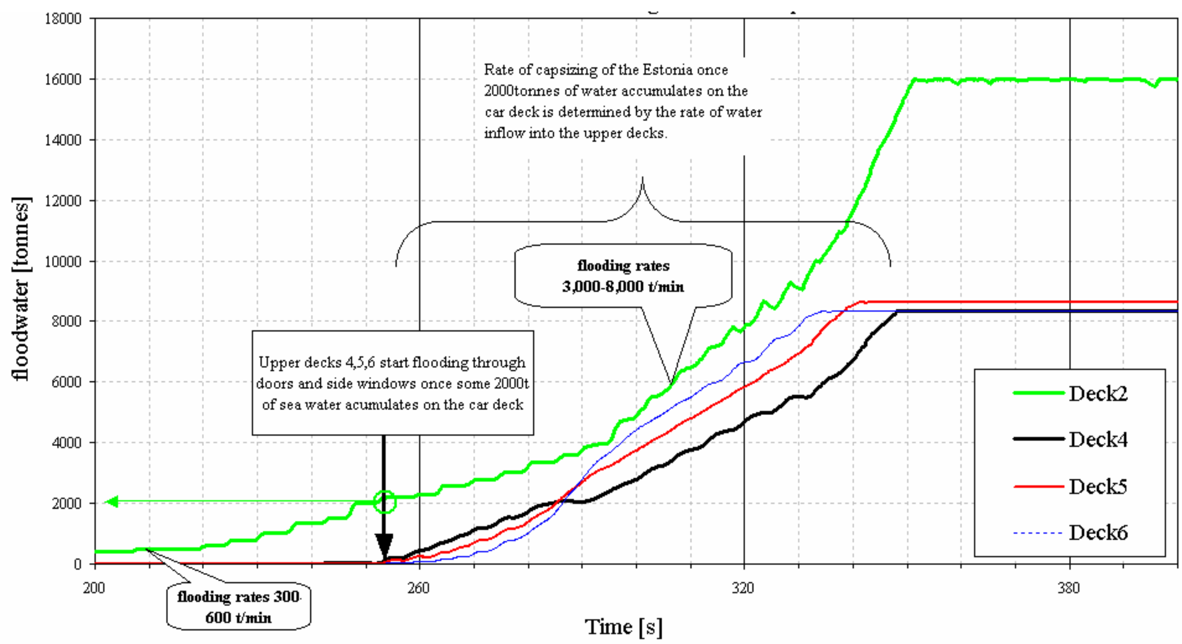

Figure 2 Estonia, Run136 (Figure 14 of [4]). Simulated typical flooding into Decks 2 (Car Deck) and Decks 4, 5 and 6 based on the JAIC scenario description. 15 windows assumed broken on each of upper decks with a total area of 20 m^2 for each deck. Car deck flooded through forward ramp.

[4] According to the statements by survivors the vessel stabilised at some 90deg heel for an extended period of time, presumably for some 30 minutes, allowing them to remain on the side of the vessel

To achieve an answer that will be accepted as objective appraisal of the facts and a result of scientific reasoning, the study must be based on state-of-the-art analytical/computational tools of time-domain simulators of ship survivability. PROTEUS3 from Safety At Sea Ltd (Commercial arm of the Ship Stability Research Centre (SSRC), Universities of Glasgow and Strathclyde) is one of the software suites that are employed in this project, as shown below and in Appendix 1.

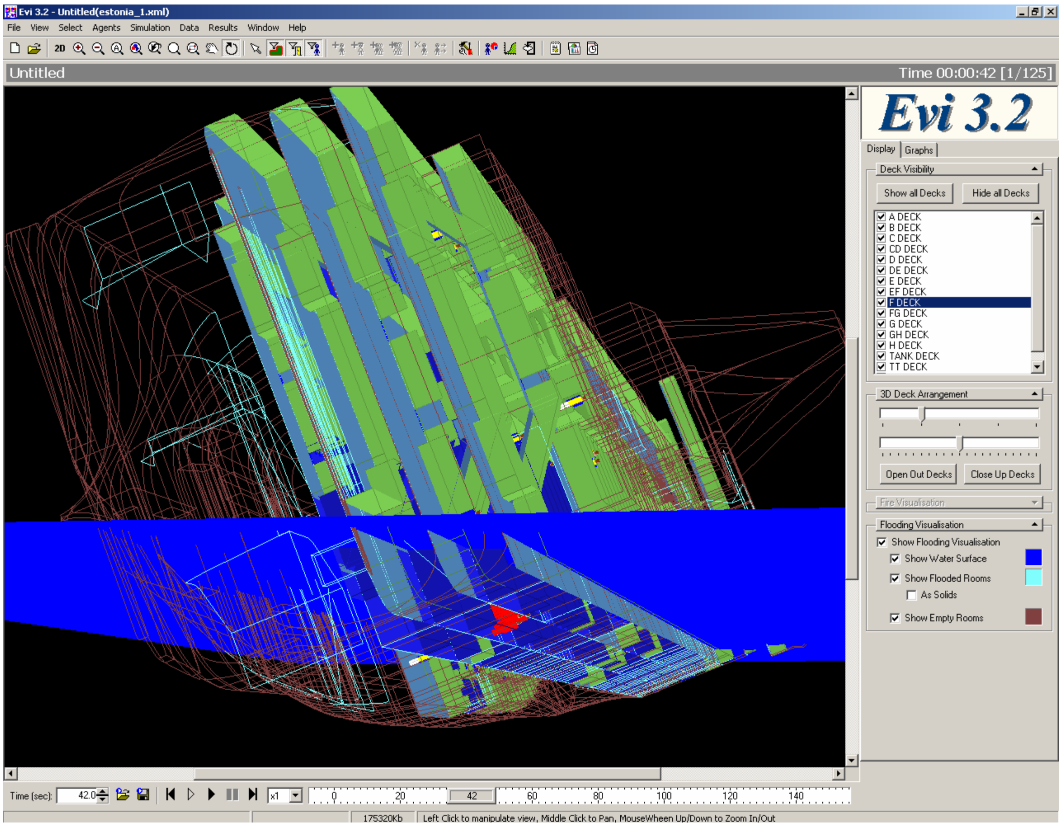

Figure 3 Combined flooding and evacuation models of MV Estonia - PROTEUS3 and Evi 3.2

The input initial conditions pertain to internal subdivision throughout the ship, including Decks 4 to 9, capacity to oppose flooding deriving from strength of external windows, internal doors, walls, etc, extent of opening of the forward and possibly aft ramps, possible external hull openings below the waterline, watertight doors operation, venting ducts, cargo shifting, speed, heading, ballasting during the casualty, a range of environmental conditions, wind effects. All of these parameters are of prime importance in studies of behaviour of the vessel in a limiting state, and each of them can have a potentially detrimental or fatal impact.

The choice of these conditions is setting up a loss scenario must satisfy the following facts of the accident:

- Flooding of some 7,700 tonnes of water below the car deck (sinking)
- Flooding of at least 2,000 tonnes of water onto the car deck (heeling)
- Slow stability deterioration 13 - 28 +/- minutes) (survivors)

In addition, it is known that 134 people survived the accident. Therefore their escape from the foundering vessel must be demonstrated to match the proposed loss scenario. Such demonstration can be achieved through combined modelling of flooding and evacuation processes, as briefly mentioned in Figure 3.

3 Foundering scenarios

Deriving from the above introduction of physics and facts pertinent to the loss, it is proposed to consider further the following set of phenomena and parameters for the investigation:

The process of flooding into the car deck
- Through the bow ramp, opened fully/partially, (at least 3 variations)
- Through side doors, fw/mid/aft (at least 3 variations)
- Through any hull breach at car deck level (not more than 10 variations)
- Through central casings “from below” (estimated 5 variations)

The process of flooding into the spaces below the car deck
- Forward of frame 80e, through collision with submarine or container / stabilising fins failure / mine /other, (estimated 5 variations)
- Aft of frame 80e, - // -
- Any of 21 watertight doors ON / OFF / MIX, (estimated 5 variants)
- 6 vents inlets / failures (3 variants)

The process of slow stability deterioration
- Effect of water below (variants considered above)
- Effect of the Car Deck (variants considered above)
- Effect of upper decks spaces
    - Windows strength (3 variants)
    - Doors strength (2 variants)
    - Modelling uncertainty (flooding coeff., 2 variants)
- Effect of emergency actions such as re-ballasting (2 variants)

In addition, the following uncertainty of basis data shall be considered:

Geographic position (2 variants)
- As established by JAIC
- Other suggested

Environmental conditions (3 variants)
- Hs at established location
- Hs at any other location

Loading conditions
- KG / draught (5 variants)
- Ballasting – heeling angle of 1deg starboard (3 variants)

Speed (3 variants)

Considering each of these variations would imply analyses of some 10^8 scenarios. Obviously, this is physically impossible. Therefore, the choice of case studies for explaining the loss mechanisms must follow from a careful reasoning process based on expert judgement.

Namely, it is proposed to undertake a few sessions involving acknowledged experts to discuss and rank a set of proposed scenarios in each session, with substitutive test studies based on numerical simulations after each session. The following set of scenarios is proposed to start this iterative process.

Proposed loss scenarios

No	Scenario	Highly Unlikely	Unlikely	Uncertain	Likely	Highly Likely
1	Bow **visor falls off**, car deck floods at 300t/min, heel to 40deg with 2,000t, water accumulates in the car deck, upper structure provide enough support for 10-30min, water reaches some 10,000 tonnes on car deck and starts flooding below through central casings aft, severe trim, sinking with the bow up					
2	Bow visor falls off, car deck floods at 300t/min, heel to 40deg with 2,000t, **vents break** under pressure, let the water to drain down at a rate of 100-300t/min, heeling develops further, upper structure provides buoyancy for ~10-15min during which time, spaces aft flood with some ~3,000-4,000tonnes, severe trim aft, heel ~180deg, (a number of passengers on the bottom walking), final sinking with bulbous bow up					
3	Stab fins break off or hull damage occurs through other means, water floods R813, R711, R1014, etc, vessel heels ~15deg, **visor falls off**, water accumulates on the car deck at 300t/min, heel increases to 35deg +, water propagates under car deck to aft spaces, ~3,000-4,000 tonnes, severe trim aft, upper spaces provide buoyancy, ~180deg and sinking with bulbous bow up					
4	Stab fins break off or hull damage occurs through other means, water floods R813, R711, R1014, etc, vessel heels ~15deg, water reaches car deck **from below**, heel increases to 35deg +, water propagates to aft spaces, ~3,000-4,000 tonnes accumulate, severe trim aft, upper spaces provide buoyancy, ~180deg and sinking with bulbous bow up					
5	Collision with container / mine / submarine, hull breach in space R711 / R813; then proceed as scenario 3 or 4					
6	Sabotage explosion at the ship's side, breach to starboard side shell plating at near car deck level forward, water ingress, heel to ~15deg, visor falls off, then proceed as scenario 3 or 4					

This table shall be filled in confidence by each expert taking part in the session.

4 Literature

[1] JAIC, 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"*, December 1997

[2] JAIC, *'Supplement to Final Report on the capsizing on 28 September 1994 in the Baltic Sea of the Ro-Ro Passenger Vessel MV Estonia, Part II'*, Preliminary Version, December 1997

[3] German Group of Experts, *"Investigation report on the capsizing on 28 September 1994 in the Baltic Sea of the Ro-Ro Passenger Vessel"*, 1999, http://www.estonia.xprimo.de/estonia/index.html

[4] Jasionowski Andrzej, Vassalos Dracos, *"Shedding Light Into The Loss Of MV Estonia*", RINA conference "Learning From Marine Incidents II", London, UK, 13-14 March, 2002

Appendix 1 Comprehensive digital modelling of MV Estonia

The digital modelling of the MV Estonia has comprised building of a representation of all geometrical aspects of both the external as well as the internal architecture of the vessel, in a digital format suitable for a set of software packages to be used in support of the investigation. Safety At Sea Ltd utilises the following specialist software for this study:

Software	**Purpose**	**Status**
NAPA	static stability assessment	Complete
PROTEUS3	simulation of flooding propagation and dynamic ship response	Complete
EVI	simulation of the evacuation process	Complete
FLUENT	simulation of the flooding propagation with the averaged Navier-Stokes solver	50%
SIMEX	simulation of the manoeuvring process	10%

The representative models are demonstrated in a series of figures in this and the following appendix.

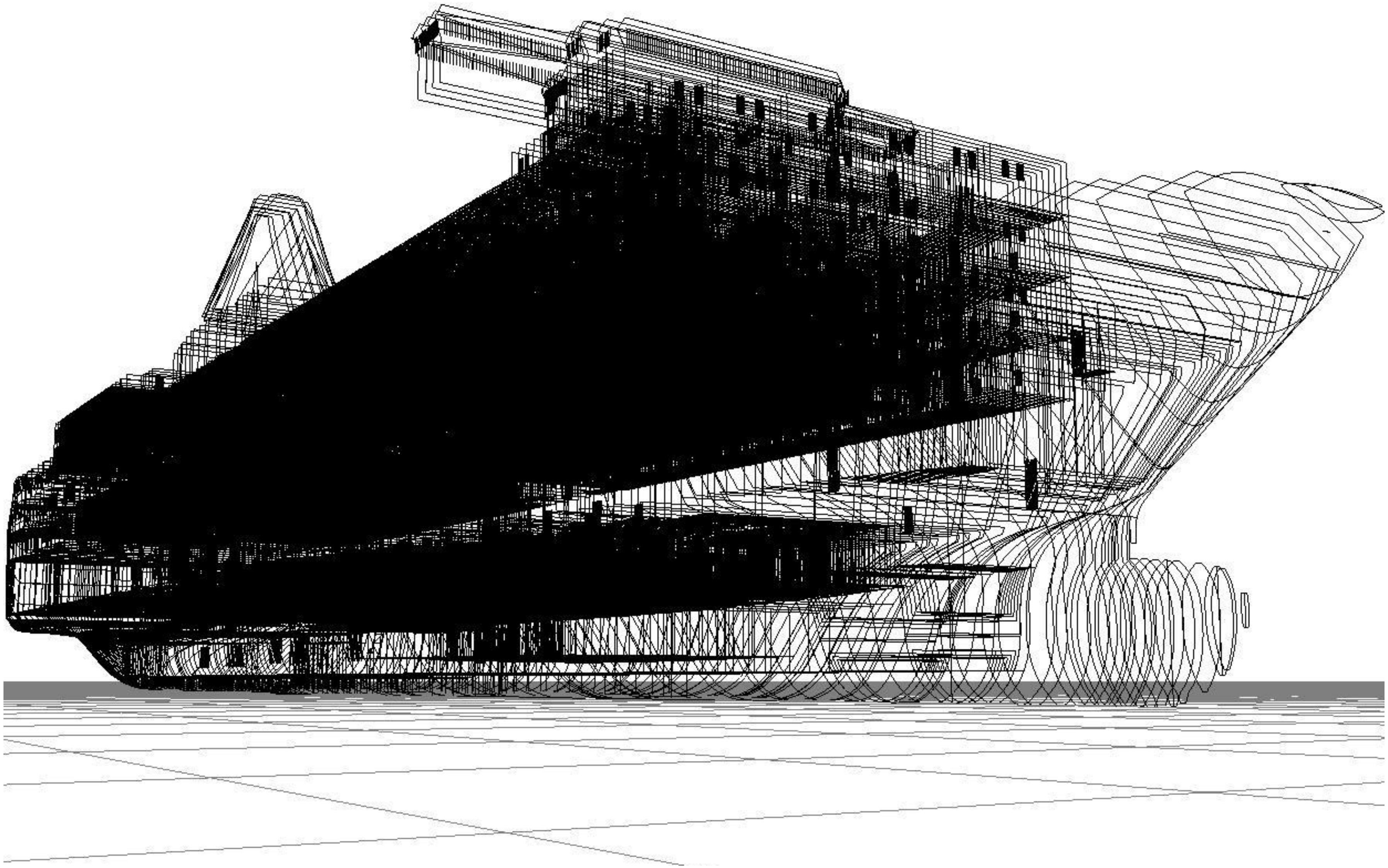

Figure 4 Digital model of MV Estonia, front view, PROTEUS3, www.safety-at-sea.co.uk

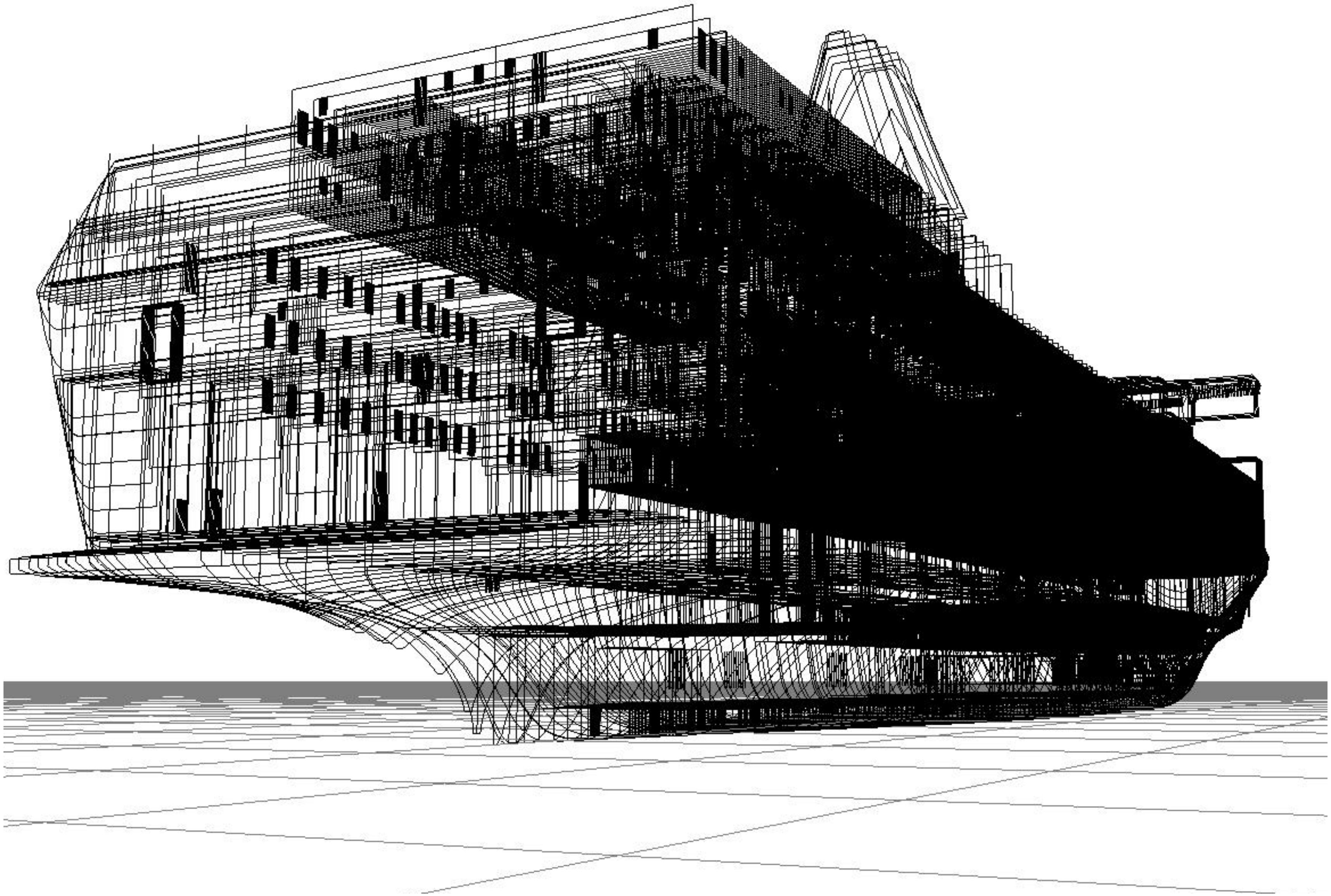

Figure 5 Digital model of MV Estonia, aft view, PROTEUS3, www.safety-at-sea.co.uk

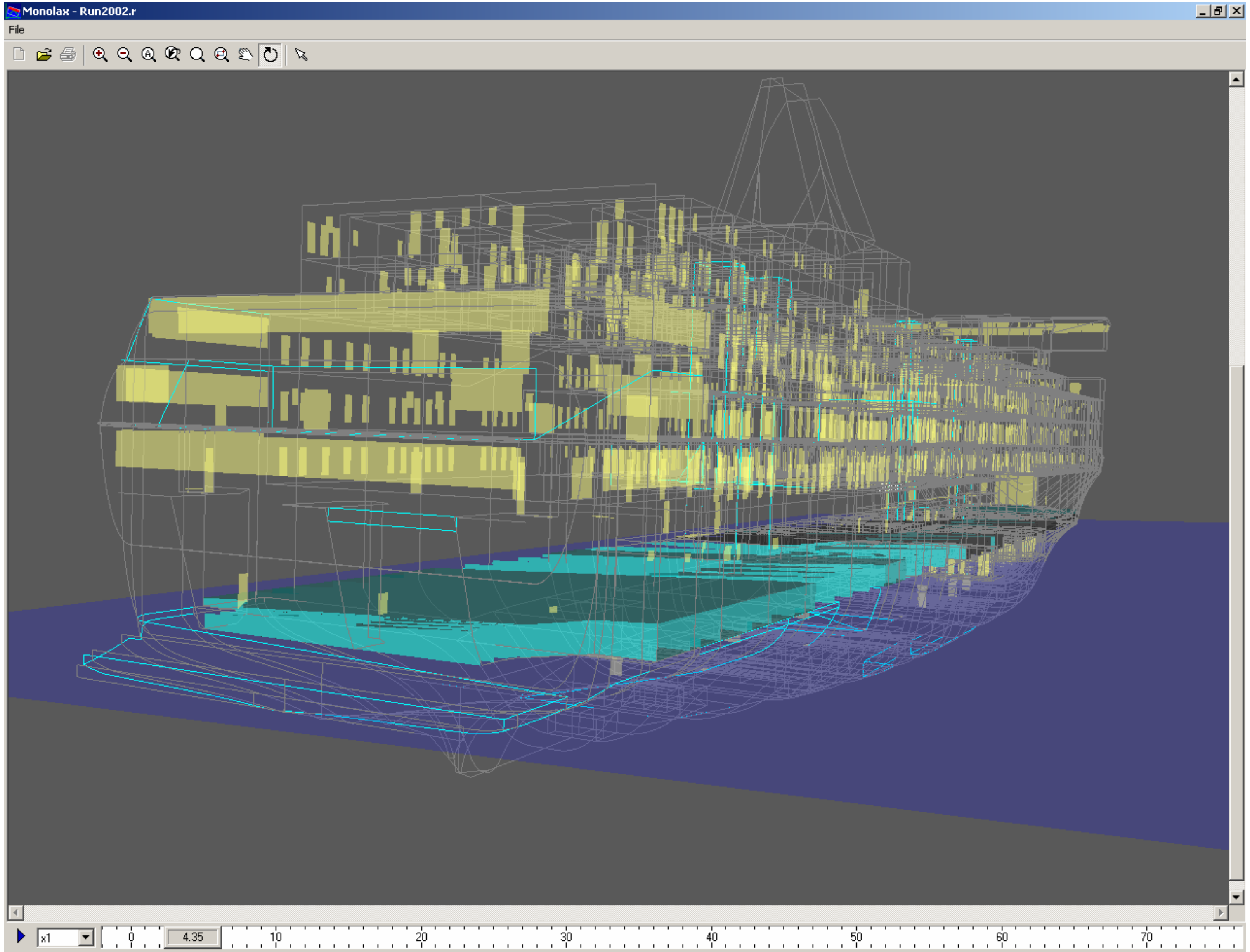

Figure 6 Flooding post-processing, virtual model of MV Estonia, aft view, MONOLAX, www.safety-at-sea.co.uk

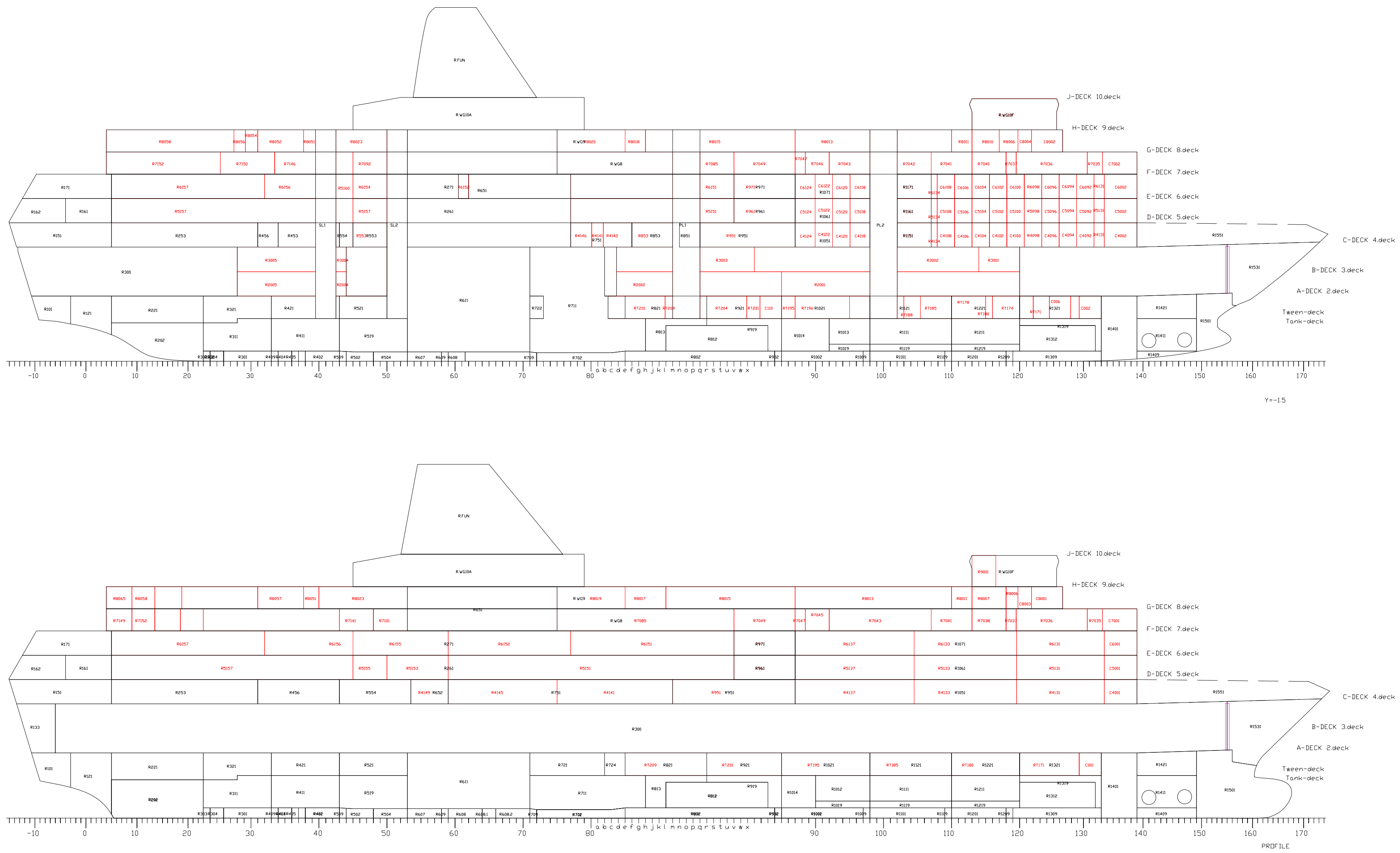

Figure 7 Digital model of MV Estonia, space and openings codes

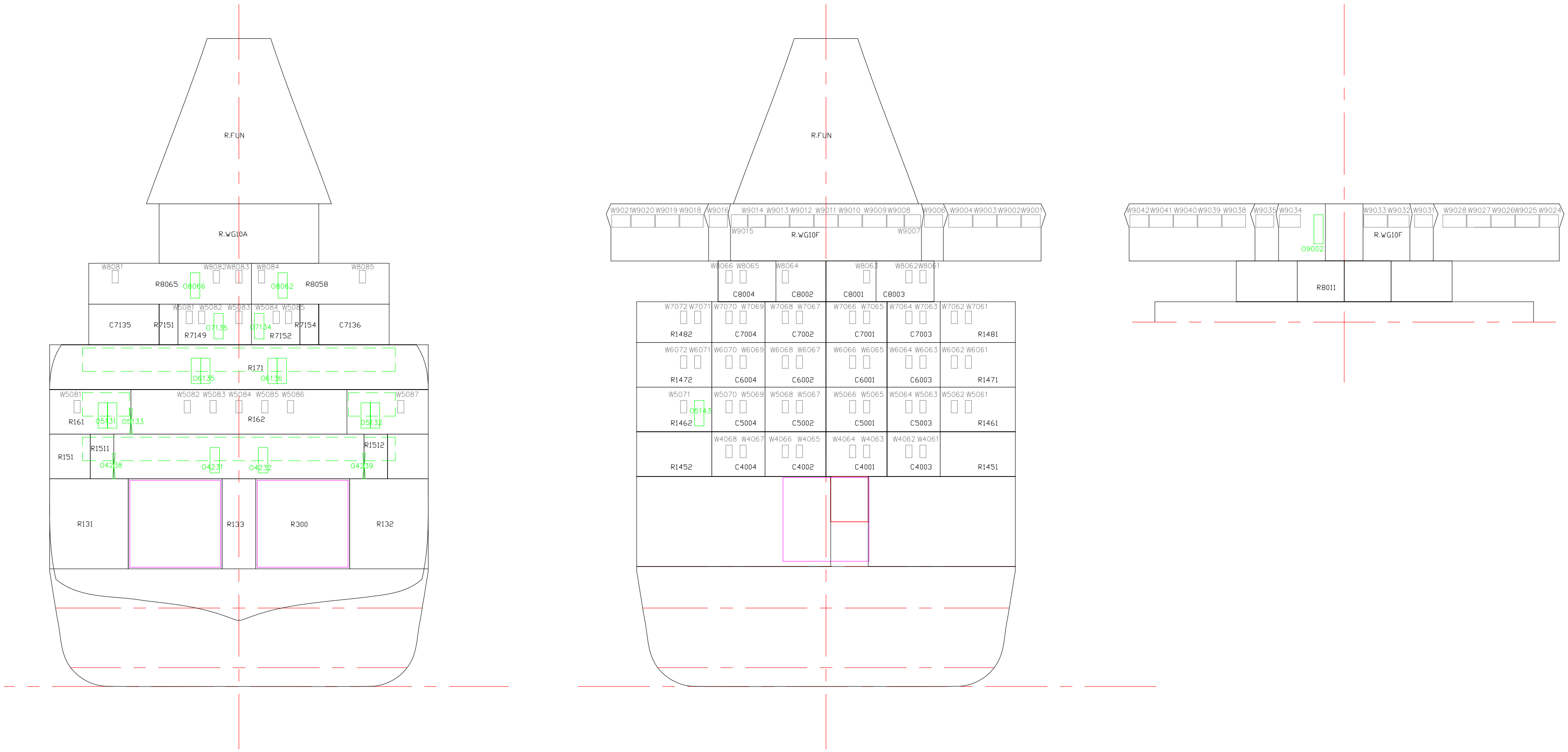

Figure 8 Digital model of MV Estonia, space and openings codes

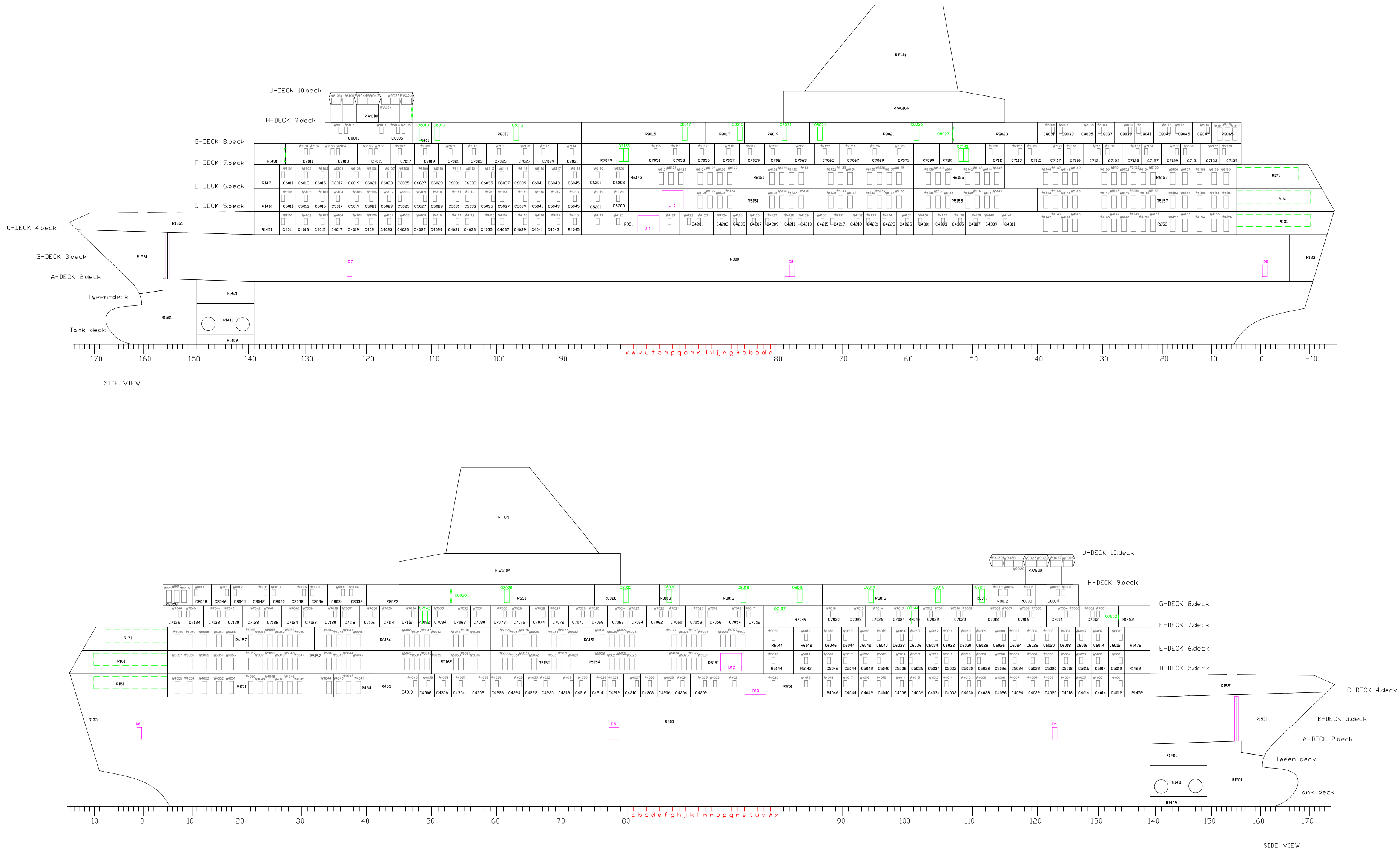

Figure 9 Digital model of MV Estonia, space and openings codes

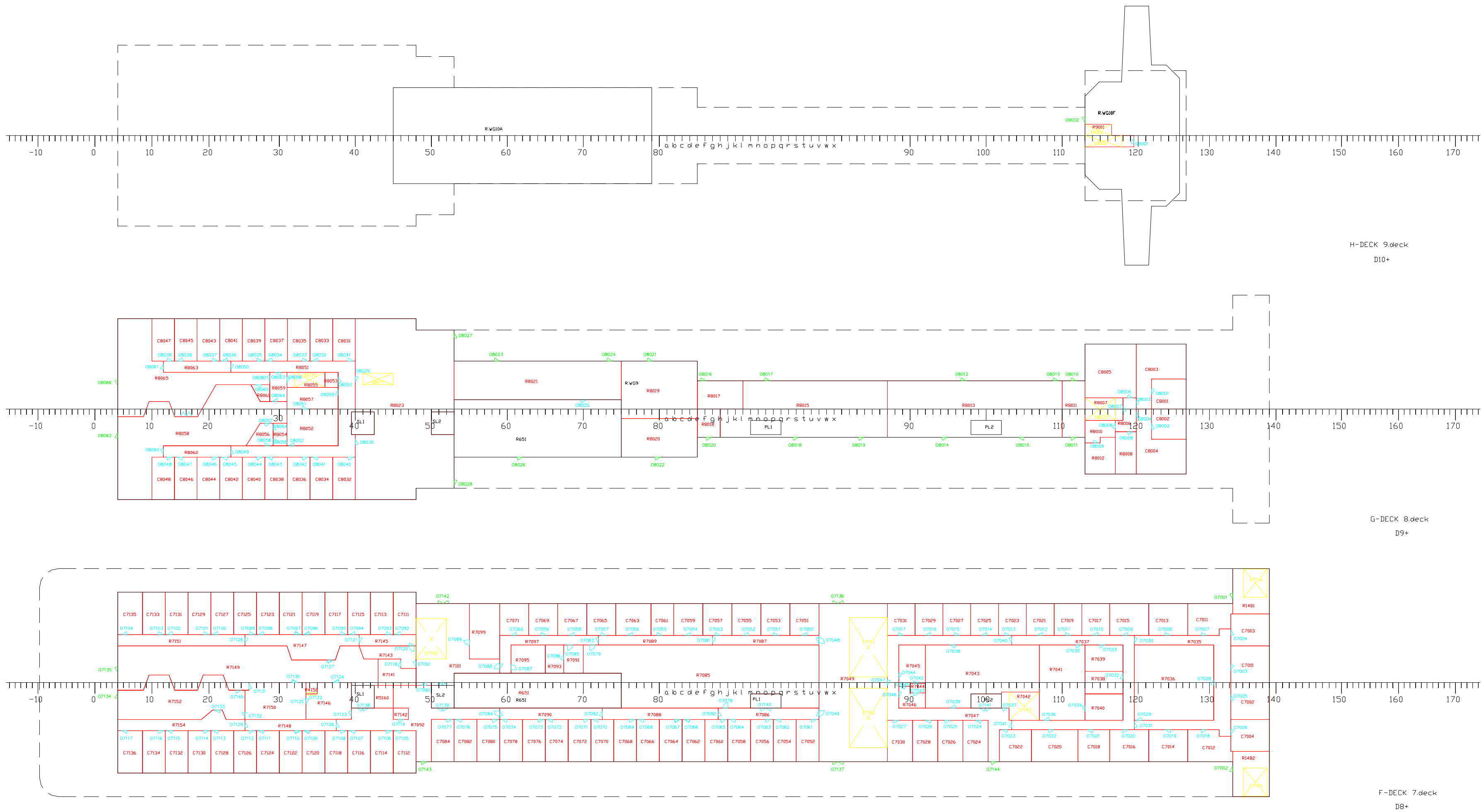

Figure 10 Digital model of MV Estonia, space and openings codes

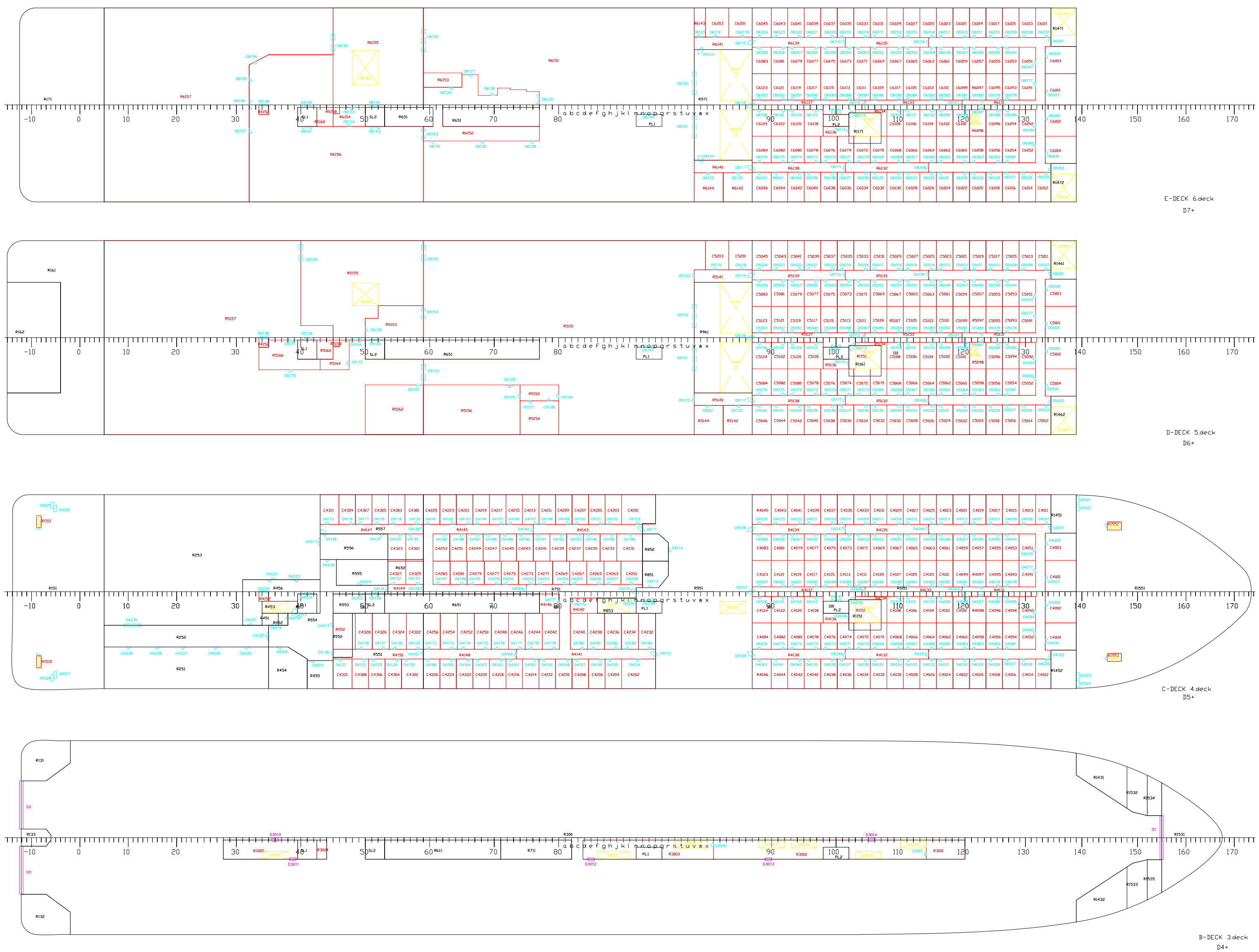

Figure 11 Digital model of MV Estonia, space and openings codes

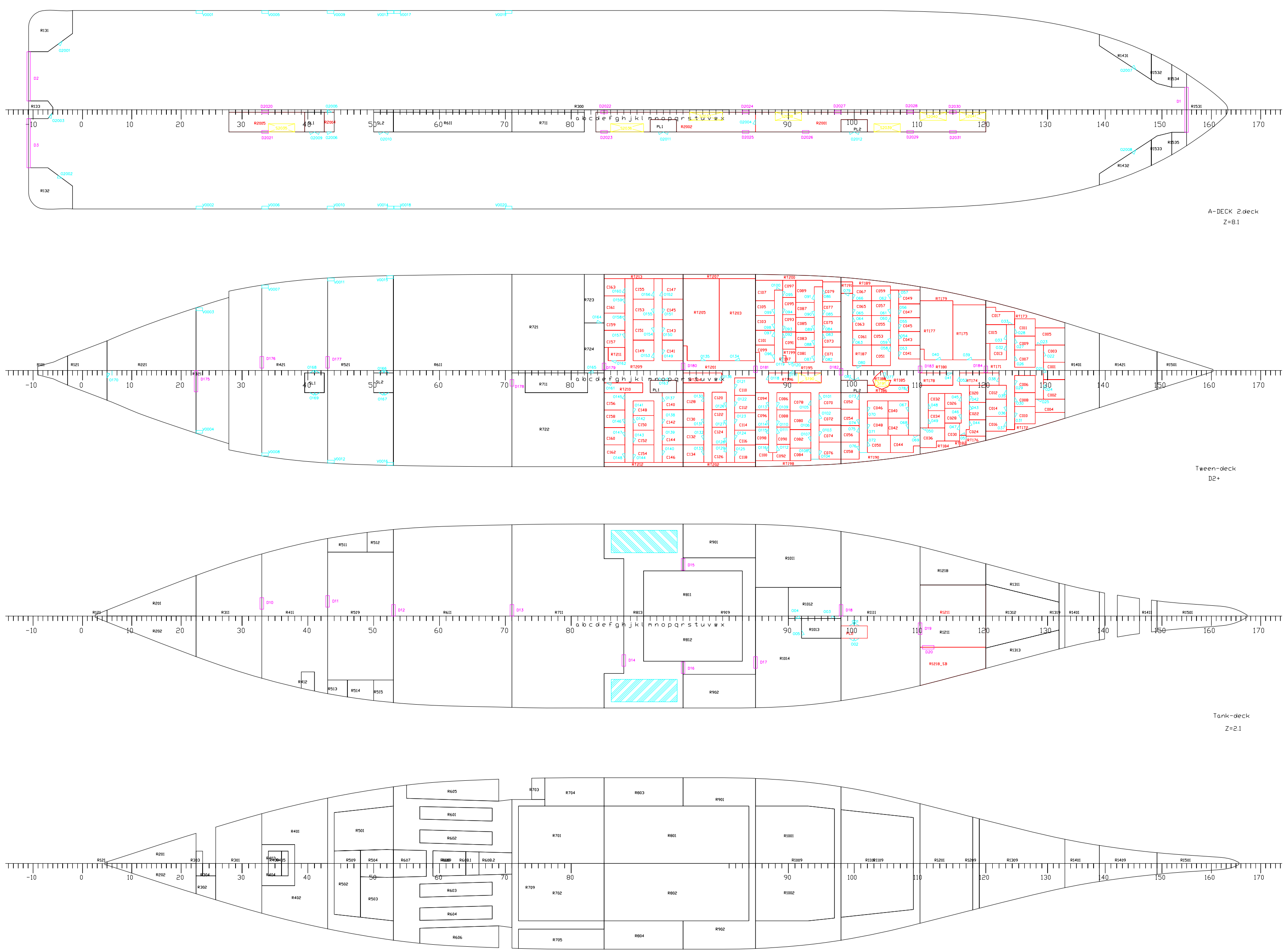

Figure 12 Digital model of MV Estonia, space and openings codes

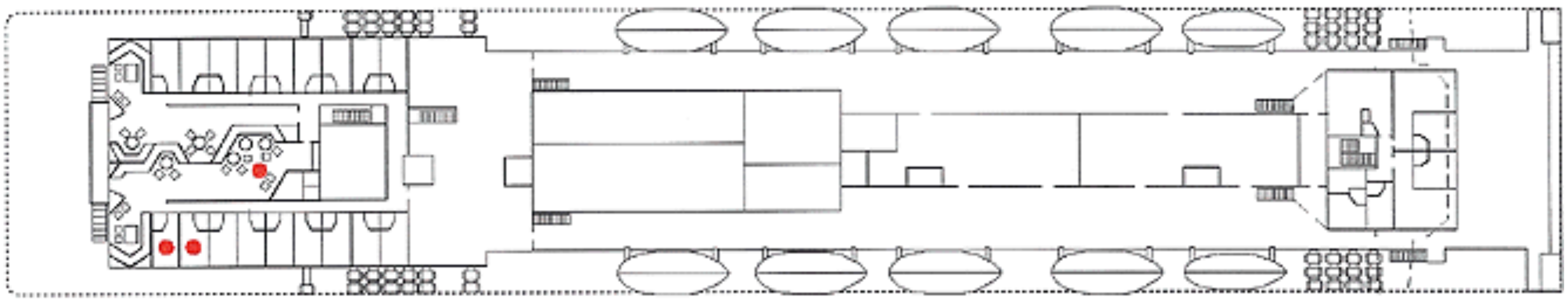

Figure 13 Plan showing deck 8, red dots mark all known locations of **3** survivors at the onset of the accident, [1]

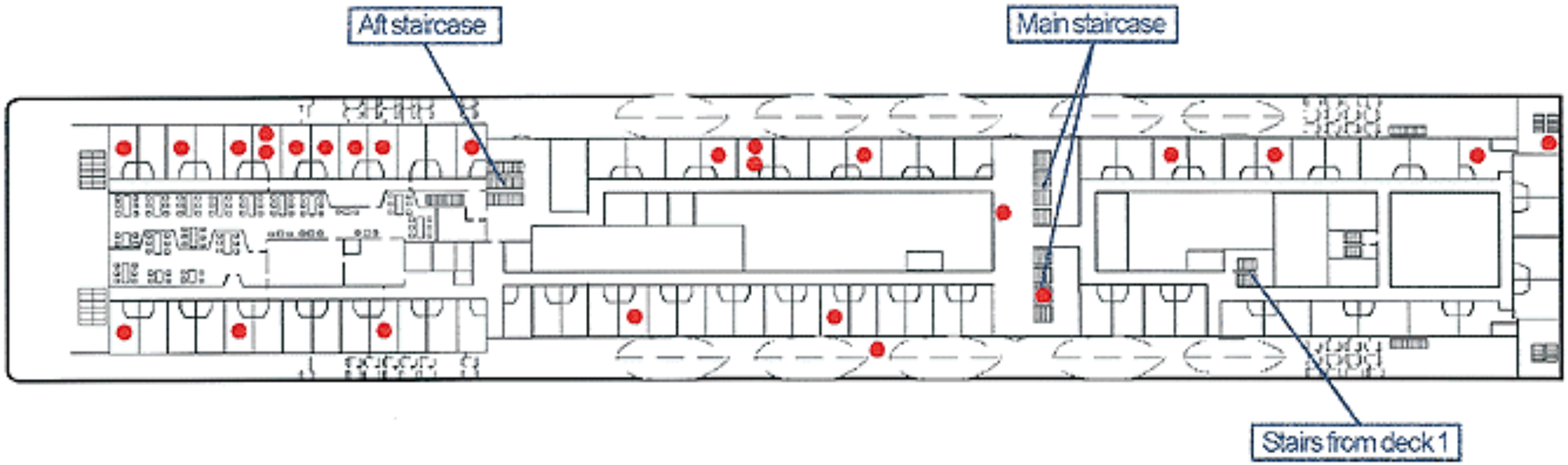

Figure 14 Plan showing deck 7, escape routes led to 18 rescue station located on this deck, red dots mark all known locations of **26** survivors at the onset of the accident, [1]

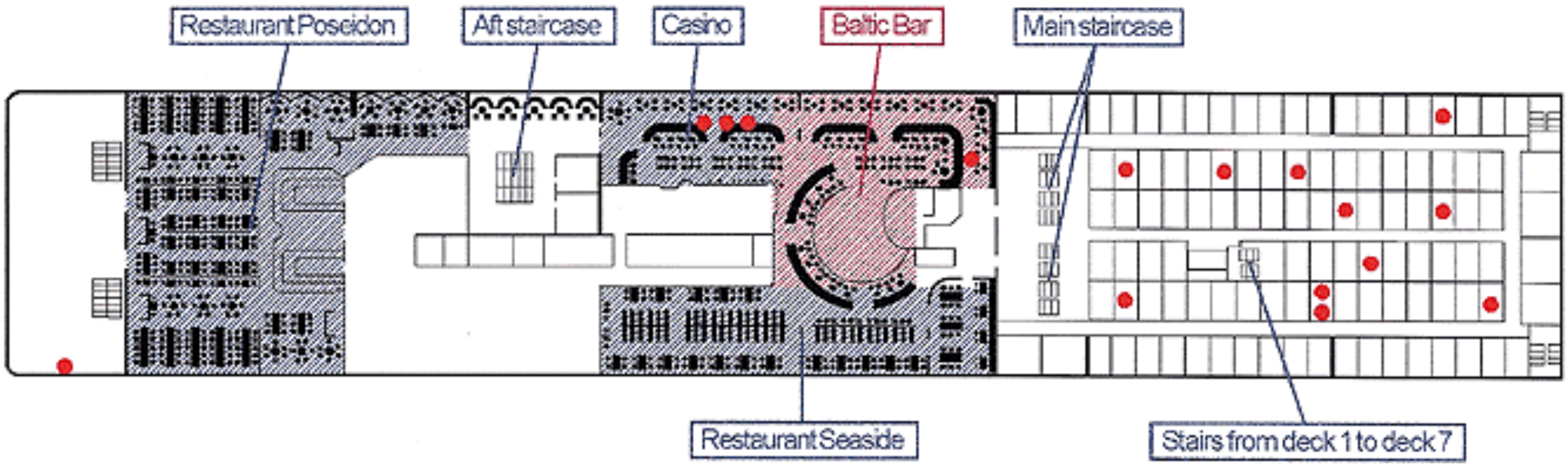

Figure 15 Plan showing deck 6, red dots mark all known locations of **16** survivors at the onset of the accident, [1]

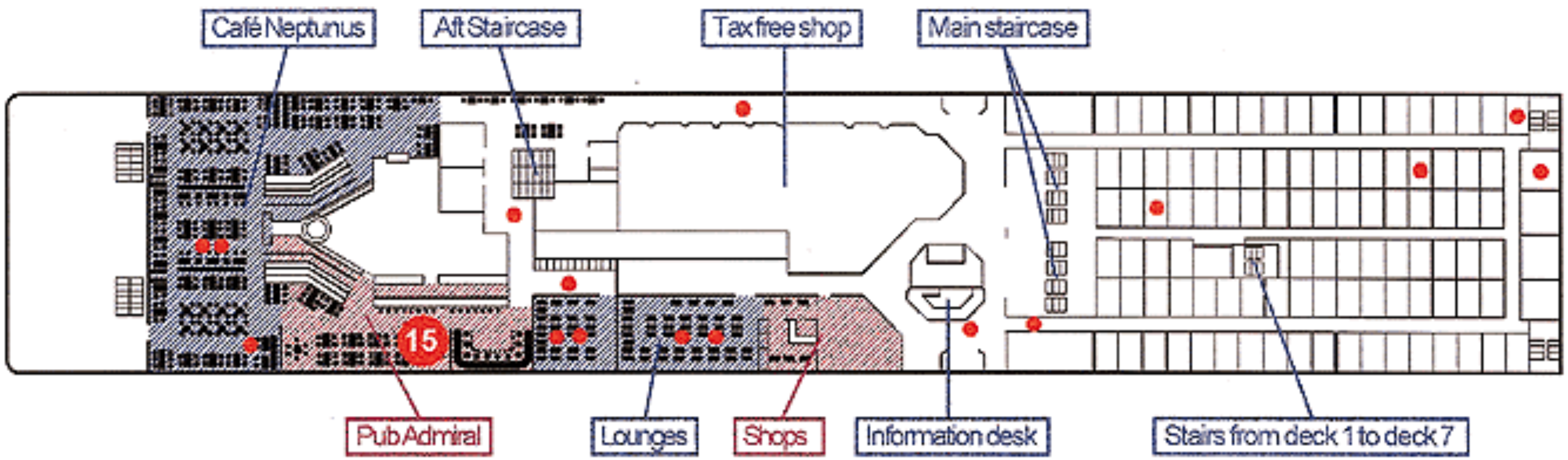

Figure 16 Plan showing deck 5, red dots mark all known locations of **31** survivors at the onset of the accident, digits in red dot refer to numbers of survivors from this area., [1]

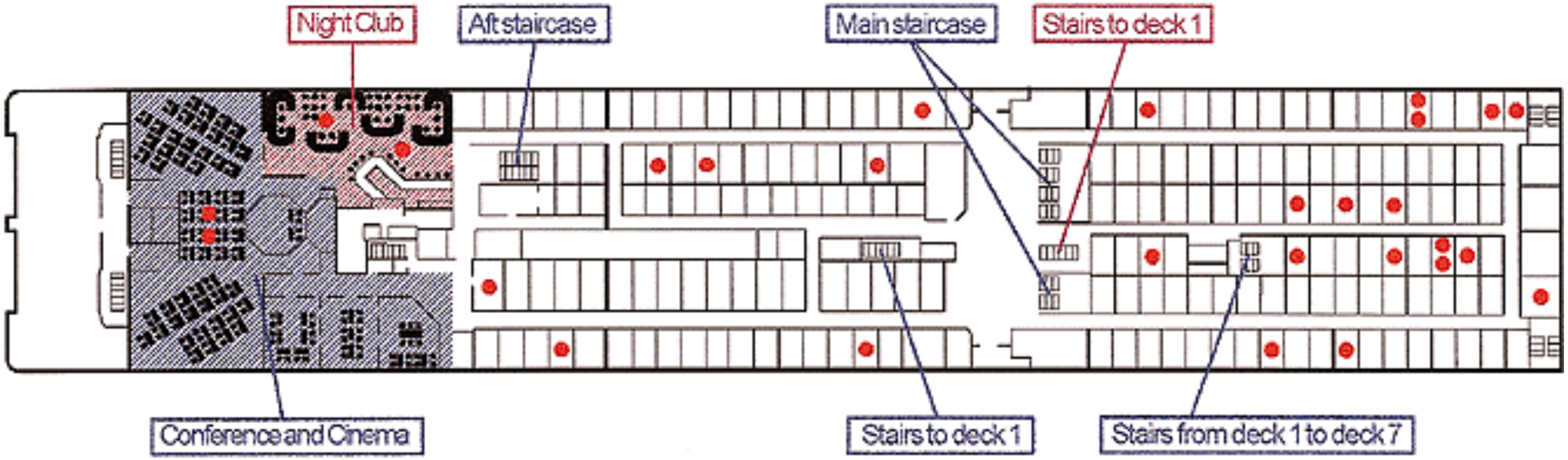

Figure 17 Plan showing deck 4, red dots mark all known locations of **28** survivors at the onset of the accident, [1]

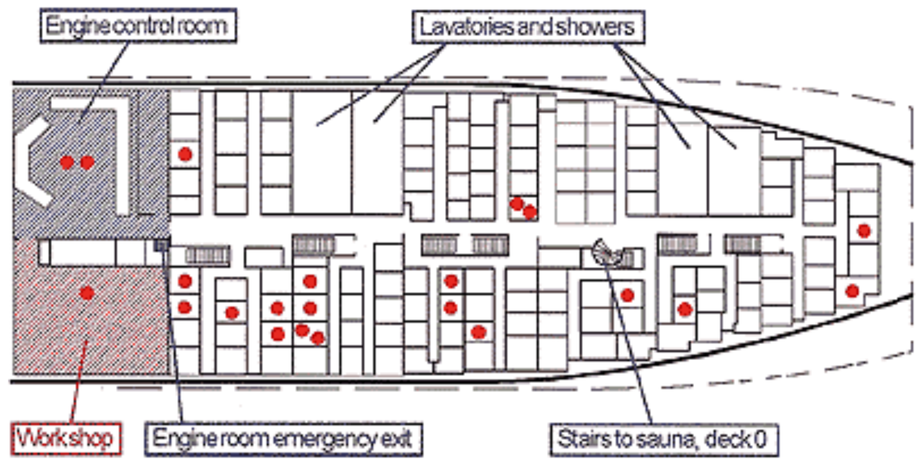

Figure 18 Plan showing deck 1, red dots mark all known locations of **22** survivors at the onset of the accident, [1]

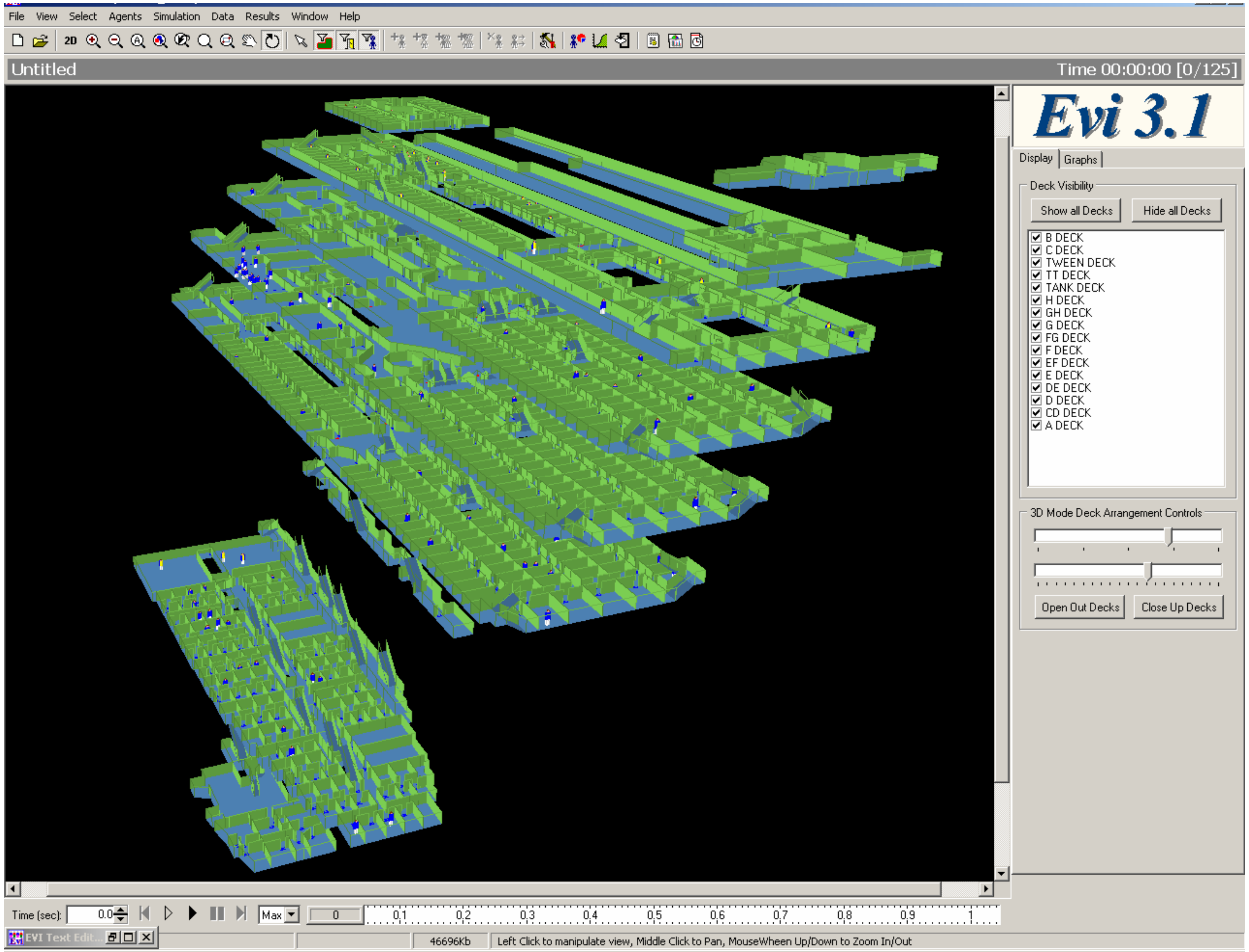

Figure 19 Evacuation model of MV Estonia, forward view, 126 survivors distributed as reported in [1], Evi 3.1, www.safety-at-sea.co.uk/evi

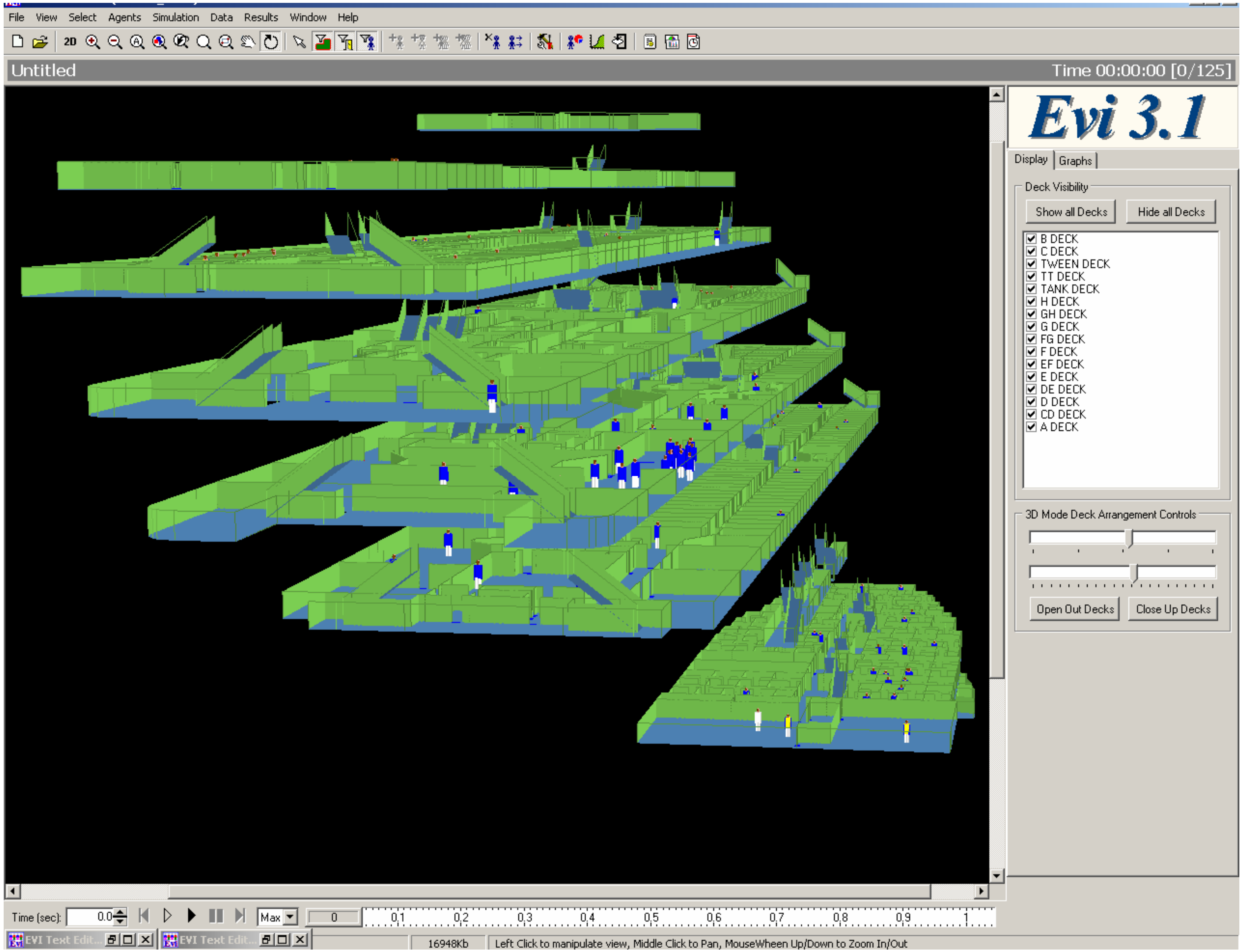

Figure 20 Evacuation model of MV Estonia, aft view, 126 survivors distributed as reported in [1], Evi 3.1, www.safety-at-sea.co.uk/evi

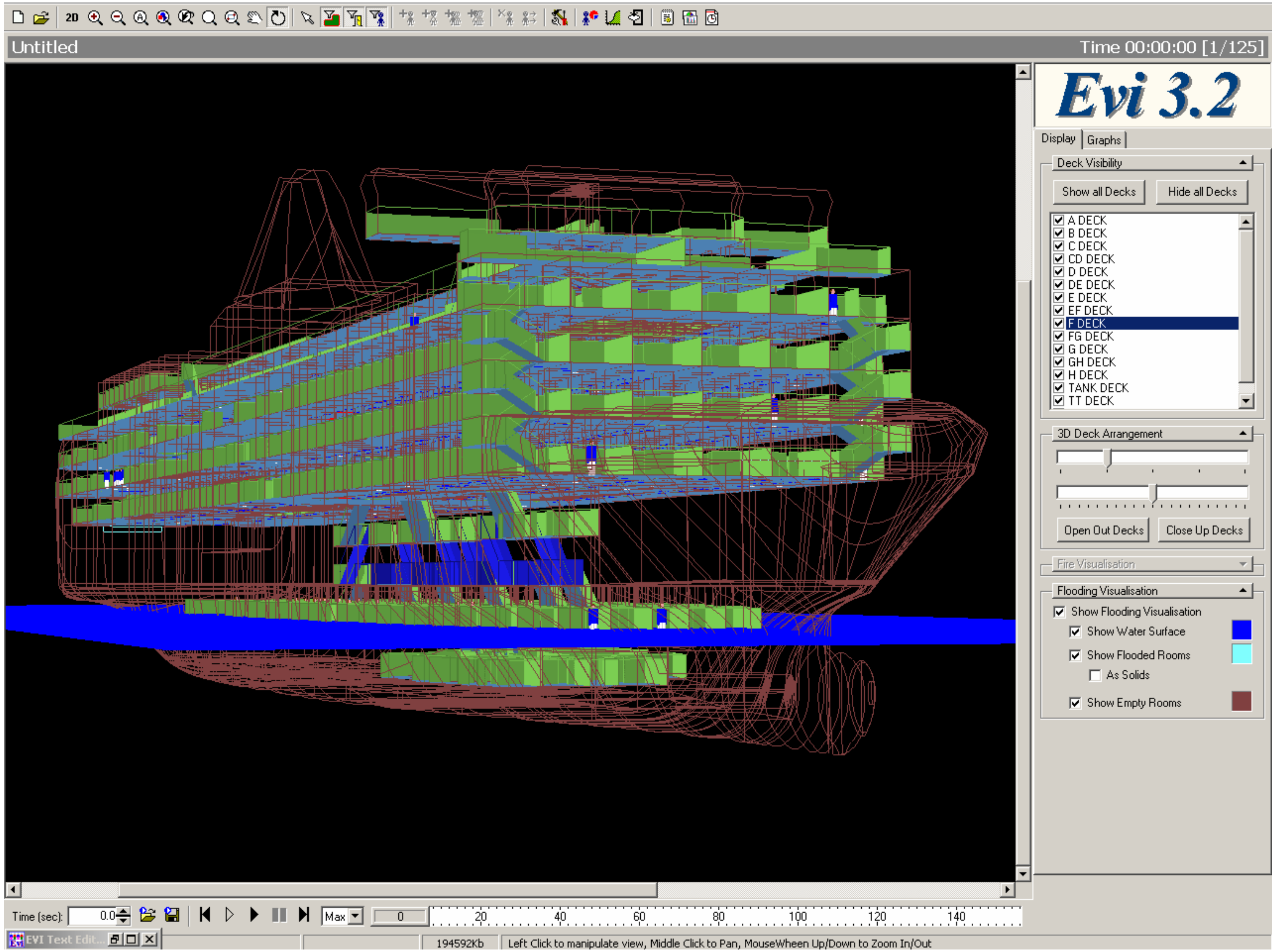

Figure 21 Combined evacuation and flooding model of MV Estonia, forward view, 126 survivors distributed as reported in [1], Evi 3.2 and PROTEUS3, www.safety-at-sea.co.uk/evi

Appendix 2 CFD computations

The task on CFD computations undertakes to specifically analyse the process of floodwater progression through the complexity of internal arrangement on the Deck 4 by means of state-of-the-art techniques in simulation of fluid dynamics based on the RANSE codes. Purposefully designed set of physical model scale experiments using 2D PIV measurements will be executed for validation. These analyses will be used to substantively verify, or if necessary to review, the simplifying assumptions adopted for time-domain simulations of progressive flooding processes and based on the otherwise established industry standard, the Bernoulli model.

The pertinence of such study to this investigation derives from the strict requirements for precision in efforts to reconstruct the reportedly witnessed rate of deterioration in vessel stability and floatability, and currently perceived to be contrary to the traditional stability comprehension. No such analyses have been found to be undertaken thus far.

The following 9 flooding cases will be investigated to gather more information about the water propagation and finally to set boundary conditions to get results as accurate as possible compared to the full scale scenario.

Table 1 CFD test cases

✓ … not started ✓ … started ✓ … finished	Static state of deck	Linear motion of deck in z-axis	Predefined 3D motion of deck
Deck 4 without watertight sections and cabins	✓	✓	✓
Deck 4 with watertight sections but without cabins	✓	✓	✓
Deck 4 with watertight sections and cabins	✓	✓	✓

The geometry shown in Figure 22 and Figure 23, is created with the commercial grid generator Gambit. The deck is created in a water/air domain which is 6 times larger than the deck itself in order to limit wave reflections with the domain boundary and to ensure to have a constant water level. To achieve this constant water level for the static approach the outer boundaries of the domain are set to pressure in- and outlets which allows to compensate the loss/gain of water volume in the domain due to the in-/egress of floodwater into the compartment. Furthermore the mesh is becoming coarser in the area of the domain boundaries to ensure that wave reflections can be damped. The deck itself consists of walls with several openings which can be opened or closed during the calculation in the time domain. For the model with the static state deck and the deck with watertight sections a structured hexagonal mesh is chosen contrariwise for the more complex deck an unstructured tetragonal mesh will be designed.

A volume of fluid (VOF model) approach will be used to be able to handle the free surface interface. The implicitly solved equations are pressure-based. The flow and the volume fraction equations are solved as follows:

Table 2 Solution control for flow and volume fraction equations

Solution control	**Mode**
Discretization	
Pressure	Presto
Momentum	1^{st} Order Upwind
Volume Fraction	Geo-Reconstruct
Pressure-Velocity Coupling	Simple

When the deck is completely filled with water calculations will stop. The result of the calculation includes forces and moments in x, y and z-direction as well as the mass flow rate through the openings. Based on this data the flooding time can be derived and can be compared to experimental data.

Further calculations could be made by considering permeable walls of cabins and breaking windows and doors caused by high pressure and velocity of the floodwater.

The computations are at present at calibration and testing phases.

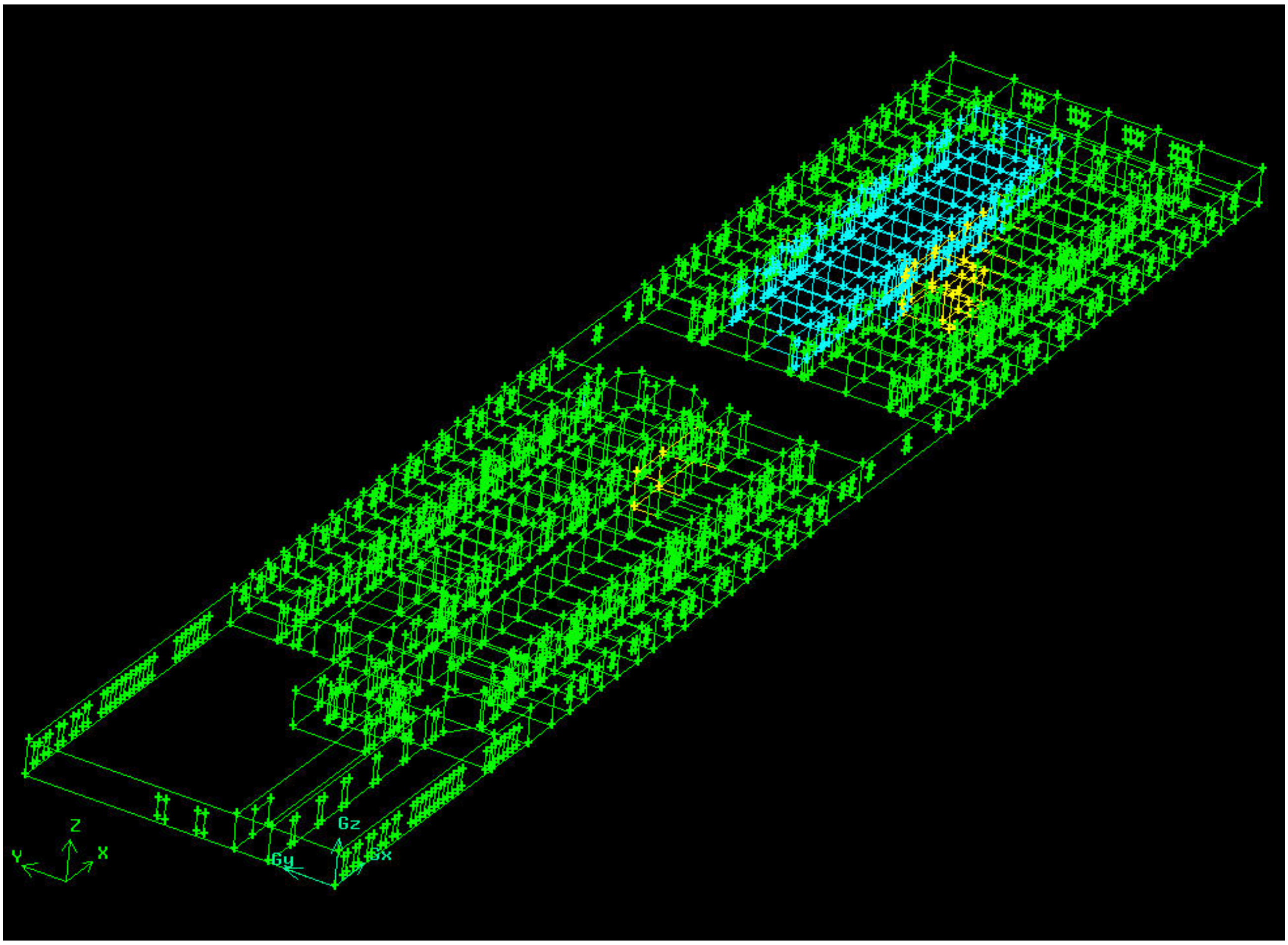

Figure 22 Deck 4 without all watertight sections and cabins, FLUENT model

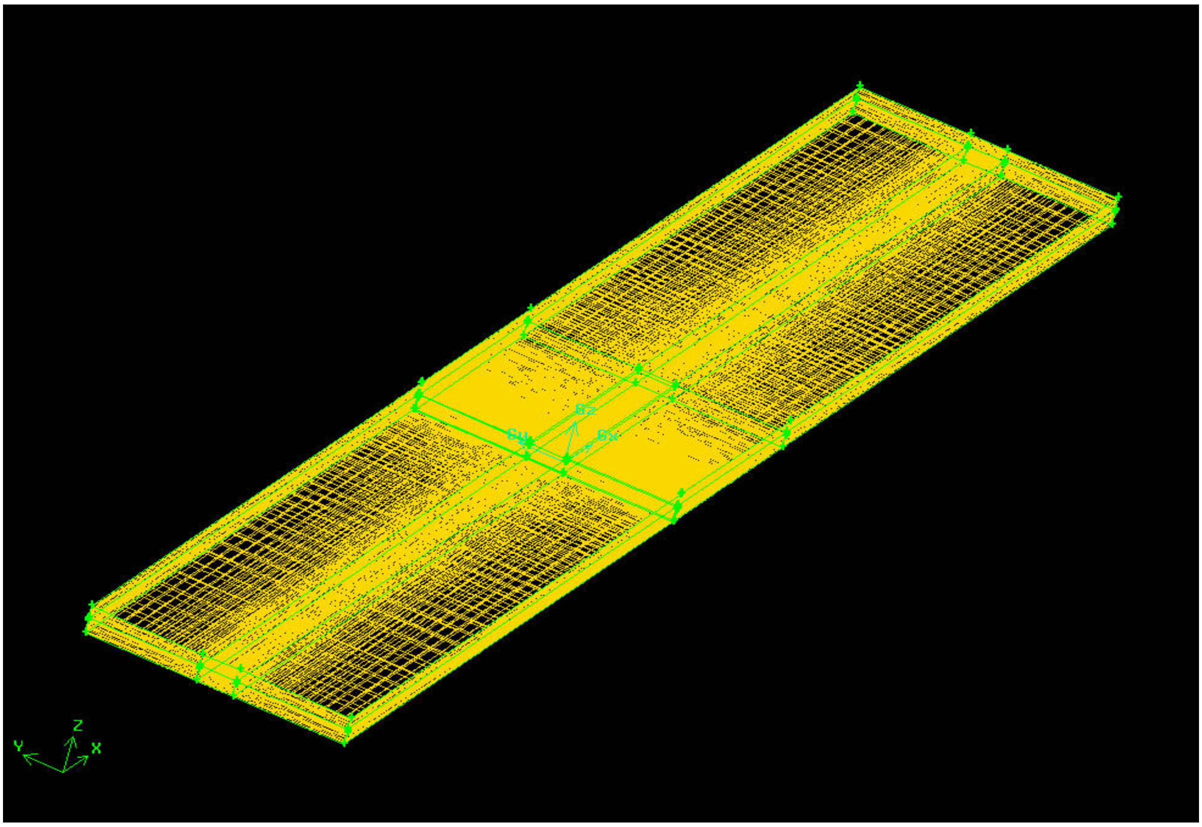

Figure 23 Deck 4 without all watertight sections and cabins in the water/air domain, FLUENT model

Appendix 3 SSRC study

Jasionowski Andrzej, Vassalos Dracos, *"Shedding Light Into The Loss Of MV Estonia*", RINA conference "Learning From Marine Incidents II", London, UK, 13-14 March, 2002

SHEDDING LIGHT INTO THE LOSS OF MV ESTONIA

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SUMMARY

This paper addresses aspects of the sinking process of the MV Estonia not explained consistently by any investigation published to date. Identified elements of contention, deficient explanations or misconceptions are submitted to analytical scrutiny based on fundamental physical concepts and advanced numerical techniques to assess damaged ship dynamics. The two principal questions addressed concern the "sinking" and "floating on the side" phenomena. It has been concluded that for sinking to materialise, extensive flooding had to take place, in particular in the spaces on and below the Car Deck. The indisputable role of the superstructure in providing momentary stability in the process of sinking has been demonstrated. The remaining question is the relative sequence of flooding of the spaces below or on the Car Deck. Although the analysis can be considered extensive, by no means can it be deemed exhaustive or conclusive and it falls far short than the effort warranted providing definitive answers on the cause and mode of this disaster.

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Professor Dracos Vassalos is the Head of Department of Naval Architecture and Marine Engineering. He is also the founder and Director of the Ship Stability Research Centre, a research centre of excellence comprising 50 researchers that deal with wide-ranging aspects of dynamics, stability, safety and design of ships and advanced marine vehicles. He has been involved in research, development and application on the stability and safety of ships and advanced marine vehicles for 24 years and has published and lectured widely in the area, compiling 5 patents, 3 books and over 250 technical publications as well as various prizes and awards. Professor Vassalos is the co-ordinator of the largest EU Thematic Network, "Design for Safety", involving 92 organisations from 16 European and Associated Nations, spanning the whole spectrum of the marine industry. He is also the Chairman of the ITTC Specialist Committee on Ship Stability, Chairman of the International Standing Committee of the STAB Conferences and International Round-Table-Discussion Workshops and member of the UK delegation to IMO for ship stability.

NOMENCLATURE AND CONVENTIONS

I'_s	Inertia matrix of ship ("s") w.r.t. G_s
I'_w	Inertia matrix of water ("w") w.r.t. G_s
$\vec{v}'_{Gs}, \vec{\omega}'$	Ship rectilinear and angular velocities
M_w	Mass of floodwater in a single compartment
$\vec{r}'_w$	Position vector of the centre of buoyancy of floodwater "w" in a body-fixed reference system with origin at *Gs*
$\vec{v}'_w$	Velocity vector of the above point
$\vec{M}'_{Gs}$	Resultant of all external moments acting on ship (three-component vector)
$\vec{g}'$	Gravity acceleration vector
$\frac{d}{dt}$	Local time derivative
ρ	Density of water (1.025 t/m^3)
∇	Ship underwater volume [m^3]
Δ	Ship displacement [kt]

All text in *italics* refers to quotations.

Any point coordinates given in this paper are expressed in a system Kxyz with origin K fixed at the intersection of base, centre and midship planes of the ship, with x axis pointing towards the bow, y axis to the port and z axis vertically upwards. Trim angle is positive by bow. Heel angle is positive to starboard side.

1 INTRODUCTION

852 human lives were lost when the passenger Ro-Ro ferry MV Estonia sank on the night of 27/28th of September 1994. Instantly, a panel of investigators from three countries, Estonia, Sweden and Finland, was set up and the accident was studied in some detail. The conclusions as to the causal factors as well as the established sequence of events leading to sinking of the vessel have been published 37 months later in the official report [1]. Primarily, inadequate design of the locking

devices of the forward bow ramp has been blamed for the tragedy.

The conduct of this investigation, however, has been challenged and criticised severely by a rather broad spectrum of individuals representing either parties affected directly by the conclusions or simply independent devotees to the profession. The main reason for the emerged dispute derives from lack of objectivity of the commission in examining and openly discussing alternative opinions on many aspects of the loss. To date, what should have been an impartial study, has grown to be a controversy.

Not accounting for all the risen conspiracy theories as being beyond any scientific argument, two alternative hypotheses on the loss remain under dispute. Firstly, according to the German Group of Experts (GGE) the main cause of the accident was the unacceptable general maintenance standard of visor and bow ramp. The second, put forward by Anders Björkman, implies breach of the hull integrity below the waterline as the main cause of the sinking.

Emergence of alternative opinions is a natural ingredient of any investigation of a disaster. Various technical backgrounds, expertise, investigative experience, or sheer emotional attitude unavoidably leads to different judgement, beliefs, assessments, and most importantly interpretations of evidence. Therefore, analysis techniques, methodology of gathering, classifying, validating and qualifying often-huge amounts of information and thus discriminating facts synthesized into suggested loss scenarios, procedures for testing these theories, and finally the format of communication of the findings, must be clearly set up and closely adhered to. Public dispute is part of this process or, indeed, is a prerequisite for the investigation to reach objective, understandable and acknowledgeable conclusions.

Recognising that the sequence of events leading to the tragic accident of MV Estonia established officially displays incompleteness and lack of clarity, authors of this article have undertaken to contribute to the ongoing discussion on the subject by addressing the most basic yet non-trivial aspect of the loss, the sinking of the vessel, by use of advanced techniques of first-principles modelling in examining pertinent aspects of the loss. Specifically, this limited study aims at providing some observations and clues concerning mechanics of the sinking that would prove valuable for any further studies that could (should) be undertaken to resolve any remaining disputes.

In pursuing this objective, a three-stage methodical reasoning has been adopted. Firstly, some elementary laws of physics pertinent to the sinking are explained and exemplified. Secondly, a number of quotes extracted from publicly available sources relevant to the sinking have been assembled, allowing distinguishing of contentious elements in need of further elaboration. Thirdly, all these are submitted to analytical testing and scrutiny. A number of conclusions have been drawn and recommendations concerning further studies proposed.

Before embarking on the details of the study it should be noted, that as fundamental as the sinking process in the loss of the MV Estonia is, it still constitutes a piece of the puzzle, incapable of explaining the tragedy without considering other facts.

2 FUNDAMENTAL PHYSICS ON FLOATABILITY

The process of sinking involves direct loss of a ship's fundamental characteristic, her floatability. Although the meaning of the latter term is most often taken for granted it is worth explaining this elementary property for better clarity of the discussion presented herein.

Floatability in classical *Archimedean* naval architecture is the ability of the vessel to support a given weight ***W***, by means of the hydrostatic pressure acting on the underwater surfaces, giving rise to the buoyancy force, ***B***. The buoyancy force can be calculated as a product of the volume of the submerged part of the ship, ∇ [m^3], the density of the fluid where it is submerged, ρ [kg/m^3] and the gravitational acceleration, g [m/s^2], $B = \rho \cdot g \cdot \nabla$. For convenience of hand calculus, the gravity acceleration in both ***W*** and ***B*** is often omitted and the mass ***M*** of the ship and that of the displaced water $\Delta = \rho \cdot \nabla$ are used to determine the floatability of a vessel.

Note that the sinking of the ship is not related to her stability characteristics, that is, the ability to return to a state of functional equilibrium (upright) when disturbed from it.

To enhance understanding of floatability, consider an example of a fully watertight barge of principal dimensions 137.42[m], 24.2[m] and 7.65[m] in length, beam and depth, respectively, and weight of 12,000 tonnes. For this weight to be sustained on the free surface of fluid of density ρ=1.025 [t/m^3], only 46% of the volume of the barge shall be submerged. Considering the upright-floating attitude, this would correspond to 3.52m in draught, as illustrated in Figure 1. Considering the above, the distance above the waterline will be 4.13m.

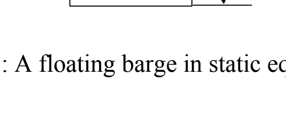


Figure 1: A floating barge in static equilibrium

Consider now this same barge with attached non-watertight superstructure extending up to 22.2m in depth, fully filled with water of total weight of 49,600 tonnes. The total weight of the barge with water inside is 61,600 tonnes, her volume is now 75,673 tonnes, and therefore the draught is 18.07m, as shown in Figure 2, that is, 4.13m of the depth of the barge remains above the waterline. In case where the stability of the barge is lost resulting to capsize, the depth above the waterline remains unchanged, also shown in Figure 2.

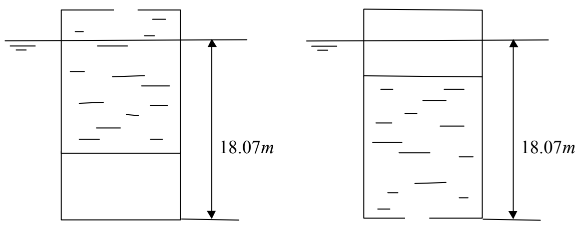
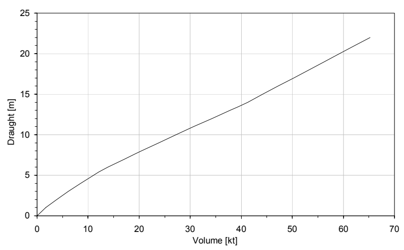


Figure 2: A barge with superstructure at upright floating and upside down attitudes

The conclusion deriving from the above exercise is that any volume within the ship hull has to be overcome by an equivalent or larger weight (e.g. related to floodwater) for the ship to begin sinking.



T[m]	Δ[kt]
5.39	12.12
7.65	19.26
13.4	39.30
22.2	65.87

Figure 3: Underwater volume of the MV Estonia hull as a function of draught.

As can be seen in Figure 3, for MV Estonia to sink, with a capacity up to the top of the sixth deck at 22.2m of approximately 65,870 tonnes, a weight of 53,670 tonnes has to be added to her approximately 12,200 tonnes. Without going into details of permeabilities and exact geometries of the floodable spaces, this volume can be composed by flooding the accommodation decks 4, 5 and 6 collectively having a total capacity of approximately 26,000 tonnes, the car deck space with a capacity of about 20,000 tonnes including central casings (see Table 1 to Table 4 for more accurate estimates of the actual volumes of floodable spaces) and approximately 7,700 tonnes below the car deck space. Only then would the vessel loose her floatability.

Note again that the loss of stability is in no way a prerequisite of sinking if there are alternative means of flooding the ship. The only effect of capsizing in the sinking process can be the contribution to faster flooding of the interior spaces, e.g. accommodation decks 4, 5 and 6.

It seems that it is primarily this subtle (albeit obvious) detail, not having been clearly elaborated in the JAIC report, that has given rise to severe criticism of the identified causal factors of the accident and the suggested sinking scenario.

By way of background further discussions of the mechanics of the sinking, providing a comprehensive account of the relevant technical debate found in public domain will be given next.

3 THE DISPUTED SCENARIO OF THE SINKING

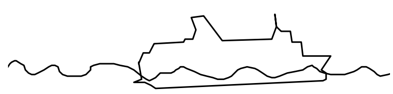
The studies, findings and conclusions derived during the course of the investigation into the sinking of the MV Estonia performed by the JAIC have been reported in [1] and a number of supplementary documents or other public discussion papers, [2] to [7]. A number of alternative opinions regarding the causal factors and the loss scenario or mechanism of sinking have been offered, notably that by Anders Bjorkman (AB), [8], [9], and the German Group of Experts (GGE), [10].

Details relevant to the sinking process have been extracted from these publications and reproduced here in a logical sequence. Utmost care has been taken to avoid bias or misinterpretations of the opinions taken out of the context of often-lengthy narrations, by concentrating only on the specific foundering-related information, estimates or conclusions. Therefore it is hoped that these excerpts are compiled in a scientifically objective manner.

Note that the division of the sinking process into three phases is an arbitrary choice of the authors aimed at better differentiation between distinctive events reported by the JAIC. Note also that the assisting sketches are not to scale and drawn only for illustration purposes.

3.1 SEQUENCE OF EVENTS ESTABLISHED BY THE JAIC

Phase 1	Loss of the visor and flooding of the car deck Some time before 1:22 hrs



Quote 1 - [1] p. 162: ***"Theoretical** studies were ordered by the Commission to clarify and simulate the **rapid** flooding, capsize and sinking of the Estonia. These studies include analysis of hydrostatic floating conditions* *and stability, wave induced motions in heeled conditions and water inflow rate on the car deck in the initial phase of the capsize."*

Quote 2 - [1] p. 163: "*During the first phase of the accident, the Estonia is assumed to have been sailing at a speed of about **14 knots** into bow-incoming waves with a significant wave height of about **4m**."*

Quote 3 - [1] p. 175: *"... the opinion of the Commission is that full service speed setting was maintained up to the time when the list developed."*

Quote 4 - [1] p. 161: *"It has been discovered both from sonar investigations of fragments on the seabed and from manoeuvring simulations that the Estonia made a port turn at an early stage of the accident."*

Quote 5 - [1] p. 223: *"...the visor at about 0115 hrs fell into the sea, pulling the ramp fully open. Large amounts of water entered the car deck"*

Quote 6 - [1] p. 163: *"The average water inflow at the instant when the ramp was torn fully open has been calculated to be in the range of 300-600 t/min. ... This means that within just one or a few minutes a heel angle of about 20 deg could possibly have developed. ... When the ship heels over, the freeboard to the ramp opening decreases and the inflow accelerates ... the inflow rate is generally **2-3 times larger** than the initial upright condition when 1,800t has entered the car deck and the heel is around 35 deg."*

Quote 7 - [6] p. 4.5 Figure 4.2&4.3: The mean water inflow onto the car deck through the fully opened ramp in bow seas (150-180deg) in speeds of 10-15kn is of the order of 140-280 ton/min.

Quote 8 - [6] p. 4.5: A comparison of the predicted inflow rates by two different approaches, the time domain simulations (TDS) of [5] and the frequency domain statistical (FDS) study of [6] is given. In conclusion the two-fold higher predictions of the flooding rates when based on the TDS have been mainly attributed to different wave profile (long-crested vs. short crested) and different freeboard (2.4m vs. 2.97m) used.

Quote 9 - [1] p. 163: "*The simulations indicate that the time from the first inflow through the ramp opening until progressive flooding of accommodation deck 4 started was about 5-15min. However, the time estimates depend greatly on what action is assumed to have been taken during the first critical minutes."*

Quote 10 - [1] p. 175: *"During the port turn water continued to enter the car deck and the list increased to 20-30deg where the vessel for some minutes stabilised as the water inflow decreased."*

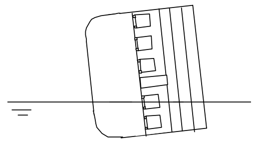
Quote 11 - [3] p.8: *"The final situation before the ship sank was probably quite static without significant roll motion because the ship did not turn up-side down though it had not much dynamic stability left. The relatively small water amount of 1000 tons on the car deck caused the static heel angle of about 20 degrees."*

Quote 12 - [1] p22: *"A first Mayday call from the ESTONIA was received at 0122 hrs. ... At about this time all four main engines had stopped. ... The ship was now drifting, lying across the seas. The list to starboard increased and water had started to **enter the accommodation decks**."*

Quote 13 - [7] p.17: *"Flooded stability calculations show that the list could not have been induced by water penetrating into compartments under the car deck. ... The evidence is overwhelming and most convincing, that the list was due to water on deck, as concluded by the JAIC"*

Quote 14 - [1] p. 175: *"After the main engines stopped, the Estonia drifted with a list of about 40 degrees and the starboard side towards the waves. Water continued to enter the car deck through the bow but at significantly lower rates."*

Phase 2	Gradual loss of the stability Time between 01:22 hrs and c.a. 01:30 hrs



Quote 15 - [1] p. 175: *"Waves were pounding against the windows on deck 4. Window panels and aft doors broke, allowing flooding of the accommodation to start."*

Quote 16 -[1] p. 181: *"Because of the list, waves reached up to the accommodation decks, breaking doors and windows. The interior started to flood and the stability reserve disappeared."*

Quote 17 -[1] p.182: *"The first potential openings to be submerged were the aft windows on deck 4. In calm water this would have happened when about 2,000 tones of water had entered the car deck and caused a heel angle of about 40deg. Waves with considerable impact energy would have pounded against these windows earlier. It is unlikely that the windows, although of heavy construction, withstood such impact forces. **The first window broke probably a little after the main engines had stopped** and when the vessel was drifting with her starboard side to the waves. Quickly submerged were also the aft doors on deck 5."*

Quote 18 -[1] p.182: "*When some of the large windows on decks 4 and 5 broke, these decks became subject to progressive flooding and **no buoyancy or stability***

contribution was available from this part of the superstructure. *List and trim to stern increased and the flow through the openings accelerated.*

Quote 19 -[1] p.182: *As soon as the accommodation spaces started flooding, the flooding could not stop before the vessel* ***sank****, or the condition could no longer remain stable as there were connections between different decks via staircases and other openings.* ***The watertight compartments below the car deck were thus flooded from above****."*

Quote 20 - [1] p.183: *"If the windows and doors had remained unbroken the vessel may have remained in a stable heel condition for some time. It is, however, less likely that any reasonable strength of the large windows would have been adequate to withstand the wave impact forces."*

Quote 21 - [1] p.183: *"It can be concluded that ... the vessel had no possibilities to withstand progressive flooding through the superstructure openings once the heel angle approached 40deg. When windows on the accommodation decks were broken by wave forces, subsequent sinking was inevitable."*

Quote 22 - [1] p.223: *"... At about 0125 the list was more than 40deg. By then windows and a door had broken in the aft part on the starboard side, allowing progressive flooding of the accommodation."*

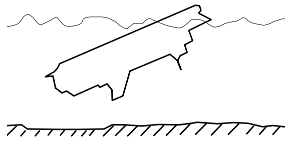
Quote 23 - [3] p.8: "*The progressive flooding started earlier probably on the* 4^{th} *deck through the windows broken by the water pressure."*

Quote 24 - [6] p. 1.1: *"The capsize is fulfilled only when water starts entering other areas of the ship. According to the hydrostatic calculations, this condition appears when 1500-2000 tons has entered the A-deck ((car deck) and the heel angle is in the range of 35-40deg. Apparently there have also been some water leaking down through the centre casing doors before the flooding of upper decks. However this is believed to have had no significant effect on the stability or heeling of the vessel."*

Quote 25 - [7] p.14: *"The flooding of the accommodation decks started from aft since there were large openings, windows and doors, which reached the waterline as the list increased. The stern part of the accommodation decks was also mainly open restaurant and cafeteria space, where the flooding could proceed quickly, while it must have taken considerably longer for the water to flood and for the air to escape from the forward passenger compartments."*

Quote 26 - [1] p22: *"... Flooding of the accommodation continued with considerable speed and the starboard side of the ship was submerged at about 0130 hrs."*

Phase 3 Floating on the side and sinking
Time between c.a. 01:30 and 01:50 hrs



Quote 27 - [1] p. 175: *"As the flooding progressed, the list and the trim by the stern increased and the vessel started to sink. At a list of about 80deg the bridge was partly flooded. This happened shortly after 0130 hrs as indicated by a clock in the chartroom whose hands had stopped at 2335hrs UTC."*

Quote 28 - [6] p. 2.3: *"When water starts entering the C-deck (i.e. the passenger deck above car decks), the ship is predestined to sink."*

Quote 29 - [1] p. 223: *"...As the list increased the Estonia started to sink stern first. At about 0135 hrs the list was about 80deg."*

Quote 30 - [1] p22:*"During the final stage of flooding the list was more than 90degrees."*

Quote 31 - [7] p.14: *"When Estonia had a list of nearly 90deg, survivors moved on the vessel's side and at least one slid to the water towards the upper decks, i.e., the ship had a list significantly more than 90deg. Several survivors noted that the stern was sinking faster than the bow."*

Quote 32 - [1] p. 225: *"The Estonia capsized due to large amounts of water entering the car deck, loss of stability and subsequent flooding of the accommodation decks. ... windows and doors broke, which led to progressive flooding and sinking."*

Quote 33 - [7] p.14: *"During the final stage of the sinking, some survivors noted that the bow turned upwards and the bulb was pointing towards the sky"*

Quote 34 - [7] p.14: *"If the passenger compartments below the car deck had been the first to flood, the ship would have sunk bow first."*

Quote 35 - [1] p22: *"The ship sank rapidly, stern first, and disappeared from the radar screens of ships in the area at about 0150 hrs."*

Quote 36 - [1] p. 175: *"... The sinking continued stern first, and the vessel disappeared from the surface of the sea at about 0150 hrs."*

Quote 37 - [1] p.223: *"The vessel disappeared from the surface at about 0150 hrs."*

3.2 ALTERNATIVE STUDIES

3.2.1 Anders Bjorkman

Quote 38 - [8] p. 5: *"The main fact is that ro-ro passenger ship of Estonia type cannot sink due to water on the car deck. ... The fact is that Estonia with water on car deck should have capsized due to negative righting arm (GZ) and lack of residual stability before sinking and should have floated upside down on the surface. As she did not do that, it should be clear that there was no water on the car deck."*

Quote 39 - [8] p. 5: *"Estonia had 18000 m^3 of air below the watertight car deck. Water on the car deck of Estonia could not flow down to the compartments below ..."*

Quote 40 - [8] p. 20: *" ... the vessel could not float with 90deg list!"*

Quote 41 - [8] p. 34: *"With water on the car deck the vessel should have tipped and floated up side down ..."*

Quote 42 - [8] p. 72: *"...at 50-60deg list the vessel is never stable with water on the car deck – she will always turn upside down."*

Quote 43 - [8] p. 76: *"... a lot of water entered accommodation decks nos. 4,5,6, when the ship listed >30deg and windows were broken, and at 34deg list the ship should have turned upside down."*

Quote 44 - [8] p. 53: *"... conclusion is that there was no water in the garage."*

Quote 45 - [8] p. 103: *"As Estonia did not turn upside down, there could not have been any water on the car deck"*

Quote 46 - [8] p. 54: *"That the ship finally sank (0155) and did not, e.g. tip over up side down, was due to the fact that there was a hole below the waterline ... and plenty of water (weight) below the car deck, which stabilised the ship."*

Quote 47 - [8] p. 54: *"... because the watertight doors were open in the bulkheads, the water spread and Estonia first listed and then sank"*

Quote 48 - [8] p. 54: *"The more water enters the car deck, the more Estonia lists, and at a certain angle of heel with certain amount of water on car deck she tips upside down ... The reason for this is that the righting arm, GZ, becomes 0 at abt. 34deg heel and the vessel then is unstable. The vessel cannot float with list 90deg ... the vessel is on its way of turning turtle with the whole superstructure flooded."*

Quote 49 - [8] p. 38&40: *"(Compartments on deck no.0 were full of water and spilled out on deck no.1 ... Angle of list was now about 30deg ...) .Water started to flood deck no.4 starboard side – the windows ... started to break as they came below", "The starboard main engines shut down ... Some water may have entered into the garage at the forward ramp at this time as the inner ramp opened a little at the top."*

Quote 50 - [8] p.41: *"0135 Clock stopped on bridge. (Angle of list was probably >70deg ... Garage started to flood from deck no.1 level. 6m bow trim)"*

Quote 51 - [8] p. 52, Fig 2.16.2E: *"45deg list. Water spreads on deck 1 through open watertight doors and fills spaces on deck 0. Water on decks 4 and 5".*

Quote 52 - [8] p. 54: *"All air in the ship below the car deck and forward of the engine room escaped through the ventilation system while the angle of heel was less than 90deg and the buoyancy was reduced to <12,000 tonnes. The engine room was still dry, but its buoyancy was maybe 5,000 tonnes, so Estonia could not float on that. Thus she sank, probably with the bow first"*

Quote 53 - [8] p. 20: *"...surviving passengers state ..., that there was a temporary loss of stability, when the vessel suddenly first listed 50deg to starboard, and then stability clearly was regained at 15deg to starboard .... Thereafter, the vessel was only very slowly heeling over, until it was on the side."*

Quote 54 - [8] p. 53: "*If three compartments* (on Deck 1) *are flooded, >2,200tonnes, the initial stability becomes negative and the ship may suddenly list 50deg. But because it is only 2,200 tonnes of water in the ship, it becomes stable again, when it has listed a certain angle, (c.a. 18deg), because the free water surfaces are reduced by the heeling, when the water is pushed up against the watertight deck."*

Quote 55 - [8] p. 57: *"... thus the ramp was never opened up. Of course, had the ramp opened up and water had entered the car deck, Estonia would have tipped upside down."*

Quote 56 - [8] p. 116: *"A hole in the starboard side below waterline could explain the sinking. Water floods the damaged compartment, water spreads to adjacent compartments through open watertight doors and in an intermediate stage of flooding the initial stability (GM) is zero and the vessel lists 50deg, where the righting arm is positive and brings the ship back to 15deg list as observed aboard ..."*

Quote 57 - [8] p. 41: *" It is ... probable that the vessel sank with the bow first as forward spaces on deck nos. 0 and 1 were flooded ..."*

Quote 58 - [9] p.4: *"A massive leak into one compartment aft below the waterline explains the fast sinking. ... a leak aft would quickly flood three or more compartments. The result would be sudden loss of stability, as observed aboard at 0102hrs, up righting, more listing while sinking on the stern, which actually happened. ... the Estonia simply sank due to a leak aft."*

Quote 59 - [9] p.9: *" ... the inflow of water through a hole below the waterline was say about 150 tons/min and spread through open watertight doors to several watertight compartments below the car deck. After 30-40 minutes all buoyancy aft below the car deck was lost, the superstructure was immediately flooded so that the ship sank stern first. The car deck was still intact and contained buoyancy, but it was not sufficient to keep the ship afloat."*

3.2.2 German Group of Experts

Quote 60 - [10] Chapter 31: *"Due to the missing and/or defect rubber packings on the forepeak deck ... the inside of the visor quickly filled with water to the outer level. ... Simultaneously water penetrated to the car deck at the port lower side of the bow ramp in spite of the "sealing material" stuffed into the big gap by the crew."*

Quote 61 - [10] Chapter 31: *"... Due to the high water column inside the visor ... the water quantities ... streaming onto the car deck were increasing and accumulating at starboard to which side the vessel was continuously heeling since departure ... To avoid the worst the crew seems to have opened the starboard stern ramp slightly ... to maintain the gap through which water was flowing from the car deck."*

Quote 62 - [10] Chapter 31: *"... Water entered the car deck in increasing quantities"*

Quote 63 - [10] Chapter 31: *"2. The slow port turning increased rapidly while the vessel heeled wide over to starboard c.a. 45-50deg, and came back to c.a. 10deg STB heel after the turning had stopped. The wind and waves now came from starboard abeam. 3. The heeling to STB increased stepwise with roll movements."*

Quote 64 - [10] Chapter 31: *"1. The Vessel sank stern first. 2. The bow was still above water when the stern was already on the sea bottom."*

3.3 GENERAL DEDUCTIONS AND COMMENTS

As can be seen the issue of sinking of the MV Estonia remains contentious. The ultimate resolution to these disagreements can be achieved by thorough re-examination of the wreckage, further analytical studies and open public debate. Although there does not seem to be much of a will to survey the ship, the latter two elements of forensic studies can be continued if contributed to by various independent parties. To this effect the following comments have been derived in this paper regarding the opinions presented above.

In view of the rather conspicuous evidence a common consensus between any of the opinions is that the MV Estonia <u>sank</u>. Note here again that for this to take place approximately 54,670 tonnes of seawater have to enter her hull, see §2. The main cause of the dispute relates to the mechanism of the sinking or specifically the rate and sequence of flooding of the ship space, i.e., spaces below the car deck, the car deck itself and accommodation spaces on the upper Decks 4, 5 and 6.

As will be shown later, this sequence of flooding, however, has not been explained consistently by any of the experts or expert groups to date. Subsequently, according to the authors of this paper, two distinguishable phenomena of the loss have been grossly misinterpreted and remain still unresolved. Namely, no congruous explanation has been offered on (a) the reported by witnesses semi-stable floating attitude with heel angle in the range of about 50 and more degrees, and (b) the sinking itself, or more specifically the extent of flooding needed for the vessel to sink.

For instance, focusing on Phase 2 and 3 of the JAIC scenario, §3.1, it can be seen that the sinking took place between 0122hrs, Quote 12, starting with a heel angle of about 35-40deg, and 0150hrs, when the vessel sank stern first with bow up, Quote 33 and Quote 37. Sometime within these <u>28 minutes</u>, a heel angle of some 90deg developed, Quote 27, Quote 30, Quote 31. Although it has not been implied directly by JAIC, it shall not be excluded that this heel angle did not reach actually near-180deg, see for instance Quote 33. The main reason for the heel in excess of 40-50deg has been attributed to the heeling moment due to <u>water on deck</u>, Quote 13. However, the very relevant issue of the restoring moment capable of counterbalancing the heeling moment, thus effectively enabling the vessel to remain stable with such heel (not capsize within few seconds) over a period of some 13-28 minutes, see Quote 27 again, <u>has not been explained</u>. Any support from the superstructure has been categorically discounted, see Quote 15 to Quote 22, and in particular Quote 18, although some thought has been given on the possible implications of the windows strength on stability, Quote 20. The loss of floatability has been described as a result of flooding of car deck, upper accommodation decks and spaces below the car deck. However, the description of the flooding of the latter spaces, Quote 19, is rather vague.

Although the opinion expressed by Anders Björkman seems persuasive, it proved rather difficult to authors of this paper to extract any consistent sequence of events concerning the mechanism of sinking. The following is an attempt to deduce the sinking process as explained by AB.

As summarised in §3.2.1, it seems that in the opinion of AB the cause of the initial heeling was flooding of the spaces below the car deck, Quote 56, and at the latter stages, when heel reached values in excess of 40deg leading to the vessel floating on her side (~90deg), Quote 52 and Quote 53, this attitude was principally a result of flooding of the superstructure, starting with decks 4, 5 and 6, Quote 49 and Quote 51. On one hand, AB firmly excludes any flooding of the car deck, Quote 38, Quote 44, Quote 45, Quote 59 and Quote 55, as a cause of this heel, arguing that any water in this space would lead to immediate capsize, Quote 40, Quote 42 and Quote 43. However, on the other hand he admits some flooding through the ramp at the instant windows on Deck 4 broke, Quote 49, although at the same time he argues that the ramp was never opened and therefore no flooding could result from the bow, Quote 55. It is not clear if his insistence on "no water on the CD" is to imply that the vessel did not capsize due to the buoyancy of the CD, as the only directly indicated source of the counterbalancing moment, enabling the vessel to remain in semi stable attitude for a number of minutes, was flooding below the car deck, Quote 46. In his argument it appears that the final sinking was caused by flooding of spaces below the car deck either aft, Quote 58, or forward, Quote 56, the accommodation spaces in the superstructure, Quote 59 and the car deck, Quote 50, although the latter is, again, in contradiction with many other statements discounting any water in the garage. In addition to JAIC's interpretation of the witness statements he emphasises the event of a sudden ship heel of the order of 50deg and subsequent stabilisation back at about 15deg, Quote 53. The proposed explanation is based again on flooding of spaces below the car deck Quote 54, Quote 56 and Quote 58.

There are three main issues in the AB's scenario of the loss, attracting attention. Namely, as explained in §2, for the ship to sink, some 20,000 tonnes of water, (in fact a more accurate figure is 15,590 tonnes when centre/side casings are excluded and permeabilities i.e. load on the car deck accounted for), must flood into the car deck. Therefore, the argument that there was no water on the car deck cannot be valid. Even if every other compartment on the ship was flooded, the vessel could still float on the reserve buoyancy provided by the car deck space. Secondly, it seems unlikely that flooding of Deck 0/1 can induce heel angles of the order of 30-40 deg thus allowing flooding of Upper Decks. Also, deriving from this, the phenomenon of ship heeling to 50deg due to flooding of Deck 0/1 and returning back to 15deg does not seem to display characteristics of a natural physical process. Finally, the assertion that the water on Deck 0/1 would enable the vessel to float on her side is unrealistic.

The German Experts do not seem to dispute directly the mechanics of the sinking process as proposed by JAIC. Apart from the difference in the origin of the initial flooding, Quote 60 and Quote 61, and the observation that the event of sudden heel of 50deg and stabilisation at 15deg, mentioned above, could be an intricate effect of water on deck and dynamic effects due to turning at speed, Quote 63, the process of sinking discussed by JAIC was not challenged, Quote 64.

The above discussion reflects the authors' interpretation of the published material concerning sinking of the MV Estonia. The purpose of this review has not been to criticise any views or judgements, but merely to elucidate points of contention, unclear statements and eventual gaps in attempting to provide a consistent explanation of the loss. It is felt, that a number of issues should be elaborated further, to better explain the sinking of the the ship and to draw attention to peculiarities of the flooding process during a ship's foundering, the latter very often being perceived of trivial significance.

To further substantiate the above deductions the following outstanding issues have been targeted for a dedicated study, the results of which are presented in this paper:

a) Investigate the effect of flooding the spaces below the car deck.
b) Identify the prevailing mechanism allowing the vessel to float at attitudes with heel angles of 40-50 degrees and more.
c) Confirm the timeframe for the flooding of the car deck spaces through the ramp described in Phase 1 of the JAIC scenario, and highlight the effects of flooding the car deck.
d) Study the possible extent and sequence of flooding leading to ship sinking.

4 FORENSIC STUDIES INTO THE LOSS

The above points are addressed by a combination of fundamental static stability analysis, more sophisticated time-domain numerical simulations of sinking, and basic expert reasoning, as described in this section.

4.1 STATIC STABILTY CONSIDERATIONS

The basic numerical data of MV Estonia used in this study are summarised in Table 1 to Table 4 and Figure 4 to Figure 6.

All the static stability calculations were performed without accounting for any free surface effects, other than those specifically indicated in building up the argument in this paper.

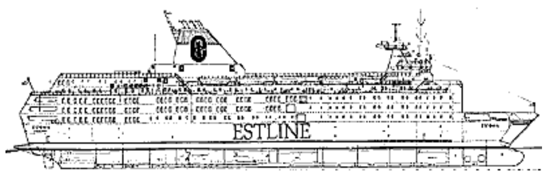


Table 1 General hydrostatics

```
Lpp..............    137.420 [m]
Breadth..........     24.222 [m]
Draught..........      5.390 [m]
Mass............. 12200.000 [t]
CGs..............     -4.662   0.000000     10.620 [m]

After Equilibrium Reached condition:
GMT...............      1.186 [m]
GML...............    282.284 [m]
WPA...............   2772.875 [m2]
CB................     -4.662   0.000000     -2.487 [m]

Trim[deg]   Heel[deg]     TA[m]       TF[m]
   -0.181      -0.000     5.608       5.173
```

Table 2 Aft spaces [m^3] **7456**

4	GM07	9.224	-0.000	2.790	501.098
5	GM06	-0.541	-0.000	3.139	419.319
6	GM05	-10.143	-0.000	3.046	966.121
7	GM0414	-23.684	0.000	4.478	1851.568
8	GM03	-34.900	0.000	3.164	455.352
9	GM02	-42.834	0.195	3.214	474.046
10	GM01	-50.683	0.000	3.277	379.076
11	GST11	-60.229	0.000	6.452	371.602
12	GA11	-50.885	0.000	6.400	462.386
13	GA12	-42.894	0.000	6.375	476.876
14	GA13	-34.903	0.000	6.364	484.966
15	GM15	-10.910	0.000	6.358	613.148

Table 3 Forward spaces [m^3] **5081**

1	GSauna	36.928	0.000	3.204	466.211
2	Gpool	28.158	0.000	3.162	687.215
3	GM08	18.238	0.000	3.133	744.957
16	GA14	-0.510	0.000	6.358	587.392
17	GA15	8.690	0.000	6.358	538.444
18	GA16	18.279	0.000	6.361	633.916
19	GA17	28.247	0.000	6.376	566.996
20	GA18	37.023	0.000	6.406	437.850
21	GA19	45.378	0.000	6.447	418.147

Table 4 Deck Spaces [m^3]

22	Deck2	-5.400	0.104	10.596	**15592**
23	Deck4	-5.710	0.000	14.850	8147.306
24	Deck5	-5.710	0.000	17.800	8428.248
25	Deck6	-5.710	0.000	20.750	8147.306

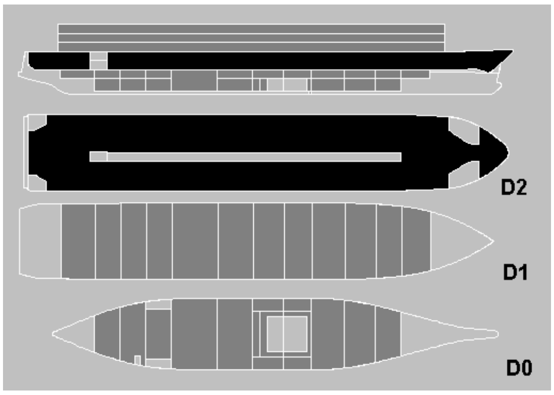


Figure 4: MV Estonia with Car Deck (CD) spaces flooded

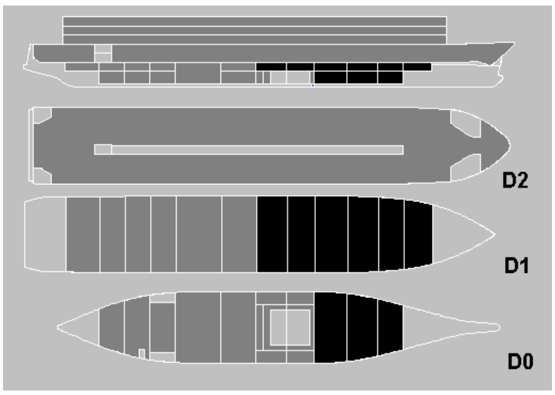


Figure 5: Forward spaces (FS) below CD flooded

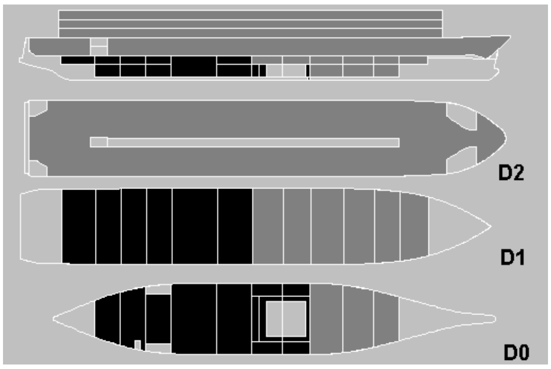


Figure 6: Aft spaces (AS) below CD flooded

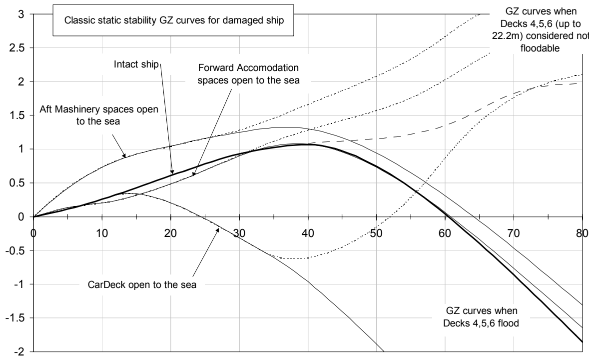


Figure 7: Classic static stability GZ curves for damaged ship

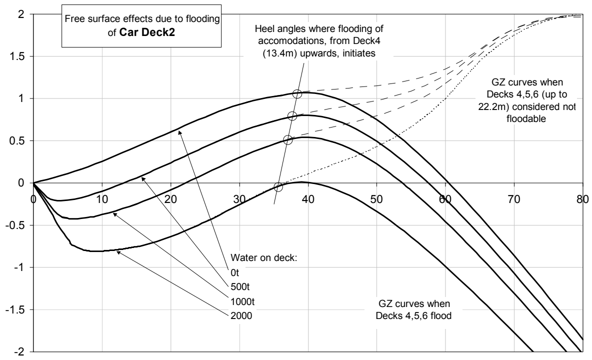


Figure 8: Free surface effects due to flooding of CD

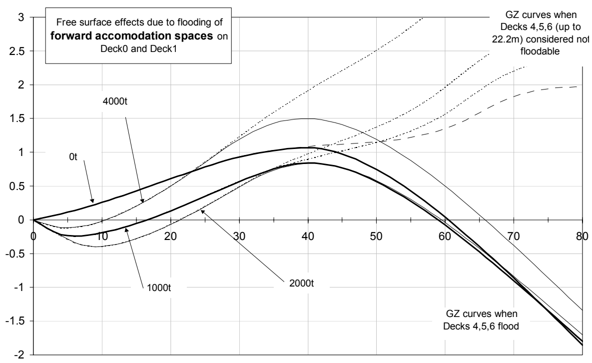


Figure 9: Free surface effects due to flooding of FS

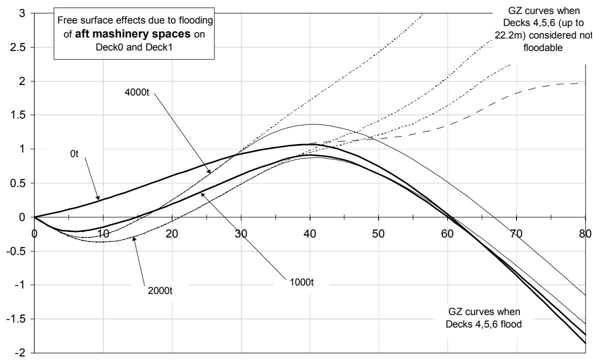


Figure 10: Free surface effects due to flooding of AS

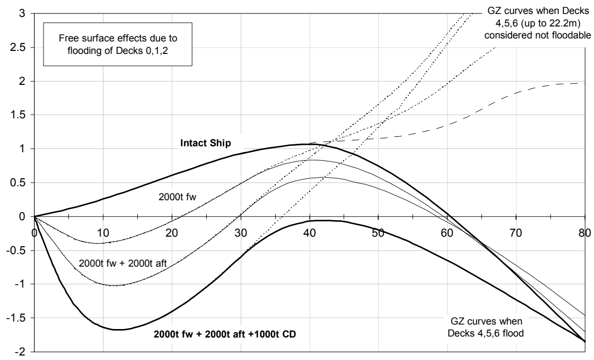


Figure 11: Free surface effects due to flooding of FS, AS and CD

Figure 7 has been provided to demonstrate the properties of the GZ curves when flooding is considered in classical damage stability terms, that is when at every stage of flooding equalisation is reached between the floodwater level in the ship internal spaces and the outside sea. Little use can be made of such information in studies on ship behaviour as discussed here, as the process of this flooding is of fundamental importance in understanding the sequence of events leading to capsizing and/or sinking. Therefore, common assumptions of immediate flooding of the damaged spaces must be abandoned hereafter and consideration given to time factor in this process. This reasoning must address all spaces subjected to flooding, and in case of MV Estonia these are the spaces below the car deck, the CD itself and accommodation Decks 4, 5 and 6.

Deriving from the above, the process of foundering can be analysed by focusing on some hypothesised intermediate stages of flooding and close examining the effect of free surfaces. In this respect, Figure 8 demonstrates that due to free surface effect, flooding of some 2,000 tonnes of water on the Car Deck results in heel angles of approximately 38deg, whereby the accommodation Deck 4 becomes submerged. Assuming that flooding of Decks 4, 5 and 6 happens instantaneously, as is the traditional naval architecture practice, the GZ curve at this point becomes negative, the vessel looses her stability and subsequently tips upside down within seconds. If, however, flooding of Decks 4, 5 and 6 takes place over hypothetically infinitely long period of time, the ship can float in equilibrium with 38deg heel. In reality, this flooding takes place within a finite time, spanning between a few seconds to a few minutes, as is demonstrated in Figure 12.

Returning to free surface effect, Figure 9 demonstrates the ship restoring properties after partial flooding of spaces forward on Decks 0 and 1. Water is assumed to be uniformly distributed between the nine compartments, an overly conservative assumption, as normally the water would flow down to Deck 0 filling it, and thereby increasing ship stability, GM, at equilibrium angles (steepness of GZ curve at intersection with horizontal heel axis). As can be seen the largest heel angle of about 21deg results when the floodwater in the FS amounts to approximately 2,000 tonnes.

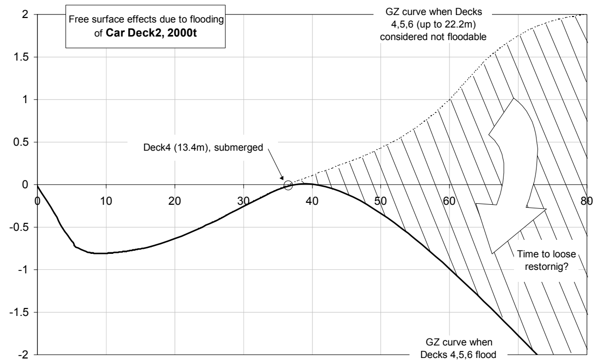


Figure 12: Process of flooding of Decks 4, 5 and 6 takes place within finite amount of time

In a similar manner it can bee seen from Figure 10 that flooding of the aft spaces results in similar vessel stability characteristics as flooding of spaces forward, that is maximum heel of about 21deg is obtained with 2,000 tonnes of floodwater.

It can be inferred from these arguments that flooding of either forward or aft spaces below the car deck cannot induce heel angles of more than 20-25deg. Note that the stability at equilibrium in each case is higher than the initial stability of intact ship. Moreover, in case of simultaneous flooding of both, the FS and the AS, a heel angle of not more than 30deg will be induced, see Figure 11.

Therefore, it should be made clear that for MV Estonia to attain heel angles larger than about 30deg, flooding of car deck spaces must take place.

Finally, by combining the information in Figure 8 and Figure 11, it can be indisputably deduced that for the vessel to stay in stable equilibrium with heel angles in excess of 40deg, that is to lie on her side, flooding of accommodation Decks 4, 5 and 6 must have taken place over a prolonged period of time, between 0122hrs and some time after 0135hrs, possibly just before the vessel sank at 0150hrs. This seemingly trivial and yet very important conclusion derives from the fact that when either scenario of flooding takes place, i.e. whether 2,000 tonnes of water floods the CD, or water of some 5,000 tonnes spreads between FS, AS and CD, the Deck 4 submerges at a heel of 30 to 40deg. Hence, the time to flood the superstructure is the time the vessel takes to turn upside down. According to the interpretation of the compiled witness statements as suggested by either of the experts in §3, this did not happen within a few seconds but rather over several minutes.

Based on the above static stability-based arguments no explanation could be derived as to the possible cause of the alleged sudden heeling to 50deg and subsequent returning to stable condition at about 15deg. In this respect, the GGE explanation is not inconceivable, however remains to be confirmed by a combination of physical model tests and/or numerical simulations.

Therefore, further numerical predictions will be used to further enhance clarity of the reasoning presented above and address the remaining issues concerning the rates of water flooding into the car deck, its effects on the ship dynamic behaviour and her sinking.

4.2 SIMULATIONS OF SHIP RESPONSES IN TIME-DOMAIN

The summary of the mathematical model used in this analysis is given in Appendix 1. The software allows for investigations on behaviour of ships in waves at speed and undergoing flooding through internal spaces of any complexity. Thorough validation of the software has been reported in the latest ITTC benchmarking study, [18], whereby comparison of the simulations with physical experiments and a number of other numerical models developed worldwide has been discussed. It can be confidently stated that this tool represents current state-of-the-art in modelling of damage ship dynamics.

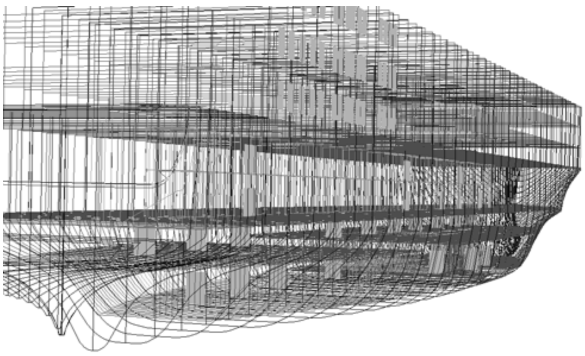
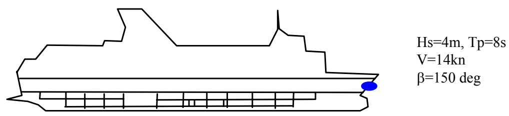


Figure 13: Numerical model of geometry of MV Estonia

Considerable effort has been made to model the internal geometry of the MV Estonia as well as possible flooding openings with high accuracy. All doors have been considered opened, this including doors between car deck and centre casings leading to other ship spaces. Unless otherwise stated, the external windows on <u>starboard side</u> to Decks 4, 5 and 6, have been assumed to be able to withstand <u>equivalent hydrostatic pressure of 6m</u> before breaking and allowing flooding, [14]. No cabins or any internal compartmentation of the spaces in Decks 4, 5 and 6 have been modelled. Thus any floodwater is assumed to spread immediately throughout these spaces. No air compressibility has been accounted for, i.e. the water could freely flood a compartment as determined by Bernoulli's equation.

Three distinctive scenarios have been simulated addressing the main points distinguished in §3.3. The key results derived are presented and discussed next.

Scenario 1: Bow visor opened
Related study: JAIC, Quote 6, Quote 9 and Quote 19
Objectives: Estimate the timeframe of flooding into the CD. Simulate gradual capsize and sinking.



(a) Ramp fully opened, windows breaking pressure 0[m]

A JOHNSWAP wave energy spectrum was used to generate <u>ten</u> different wave realisations, in each of which the vessel response was simulated as shown by a typical example in Figure 14.

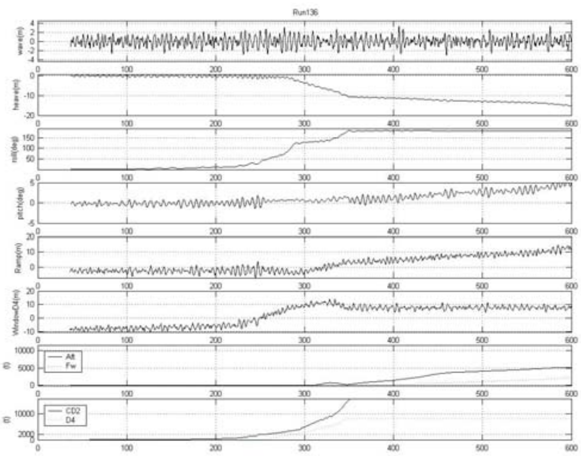


Figure 14: Time series of Scenario 1a: (1) wave, (2) heave, (3) roll, (4) pitch, (5) Relative motion at Ramp, [66.1, 0.0, 7.65], (6) Relative motion at the window in Deck 4, [-64.81, 12.11, 13.9], (7) Aggregate flooding into the forward and aft spaces below the car deck, (8) Aggregate flooding into the Car Deck and Deck 4.

It was found consistently that the vessel in such a scenario capsizes and floats upside down within 5-8minutes from the beginning of the simulation. The average water inflow rates until an instant when 2,000 tonnes accumulates on the car deck, has been assessed to be between 300 and 600 [t/min]. Once the windows on Deck 4 become submerged (2,000 tonnes of water on the CD) the process of ship capsizing takes place within 2 minutes. A few hypothetical zero-speed cases considered revealed that the time to accumulate approximately 2,000 tonnes of water on deck increases approximately twofold. However, capsize still takes place within two minutes.

Thus established flooding rates into the ship can be considered to concur with the JAIC estimates, Quote 6 and Quote 7. It is rather difficult to obtain these predictions with any higher accuracy due to the randomness of the non-stationary process of relative motions, and lack of detailed knowledge on the loss of the bow visor, see also relevant Quote 9.

The simplified modelling of the internal geometry on Decks 4, 5 and 6 as well as the assumed zero strength of the external windows to withstand flooding can be considered representative to address the JAIC opinion on the expected fast filling of these spaces with water and subsequent loss of this buoyancy, see e.g. Quote 18. It can be seen that the JAIC reasoning regarding this process is confirmed in Figure 14, where the time from the instant the windows on Deck 4 submerge at about 250[s] to total flooding of Deck 4 at about 350[s] is only 100[s]. For reference to static stability considerations see Figure 12. However, the subsequent explanation of the sinking in Quote 19 is invalid as until the instant where the vessel rotates by 180deg and the car deck floods almost fully, virtually no water enters the spaces below the car deck even considering all doors in the centre casing opened.

Note, however, that flooding of the spaces on Decks 0 and 1 "from above" can not be ruled out based on the above result, in view of other arguments presented in this paper concluding that accounting for the superstructure is the only viable route to explaining how the ship sustained heeling up to 50deg and more, between 13-28minutes. It has not been assessed what extent of flooding on the car deck could be supported by the reserve buoyancy of the upper decks and therefore the possibility still exists that some mechanism allowed flooding below "from above". This scenario remains to be investigated.

(b) Ramp opened partially (20deg), windows breaking pressure 0[m]

In this scenario an attempt was made to assess what difference the extent of the forward ramp opening could make on the average flooding rates. The 20deg opening denotes the ramp leaning forward from the vertical plane. As can be seen in a typical example given in Figure 15, the time for the vessel to capsize is of the order of 45-60min. However, once the windows on Deck 4 submerge, the vessel capsizes within 2 minutes. This scenario on one hand confirms the uncertainty in assessing the rates of flooding the car deck, but on the other reaffirms the conclusion derived above that the JAIC description of sinking is lacking consistency. The vessel cannot float on her side with the superstructure flooded (as is taken for granted in JAIC statements), thus the spaces below cannot be flooded "from above", and the vessel cannot sink.

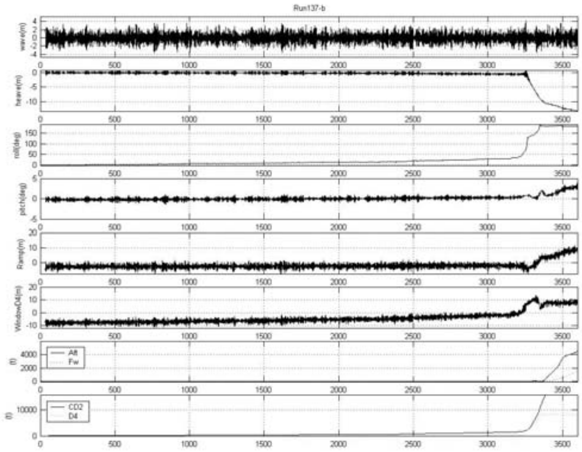


Figure 15: Time series of Scenario 1b

Note again the last remark in Scenario 1(a), underlining the unresolved uncertainty as to the possible mechanism for flooding Decks 0 and 1 once the vessel is stabilised for some time by the superstructure.

(c) Ramp fully opened, windows breaking pressure 6[m]

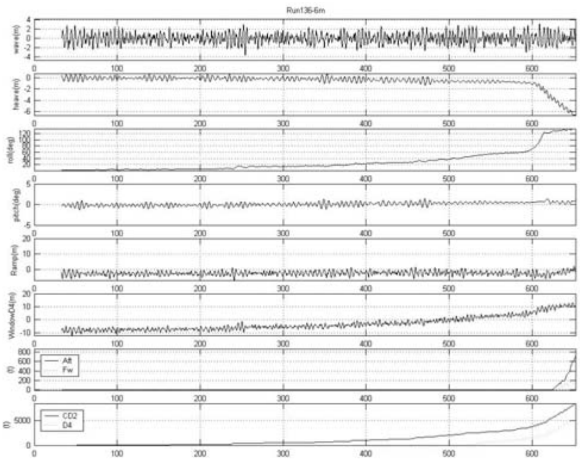


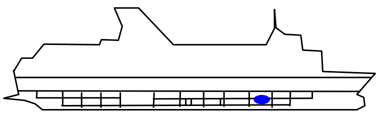
Figure 16: Time series of Scenario 1c

Although it is traditionally assumed that superstructures of passenger RO-RO vessels cannot withstand flooding, the details of this process should not be ignored in forensic studies such as the Estonia case. For instance, from the elementary recommendations on windows strength, [14], it is known that the breaking pressure can vary between 2.5 to about 10m. Therefore, this scenario has been considered to test the effect of window strength on the ship capsizing/sinking process. Note, however, that only static head pressure has been modelled in this study and no dynamic pressures due to waves have been accounted for.

As can be seen in Figure 16, the main effect deriving from consideration of the strength of external windows is to slightly prolong the process of capsizing. Since the submergence of Deck 4 must now be deeper for the windows to break, some additional time will elapse until the floodwater on the car deck reached somewhere between 2,000 and 3,000 tonnes. Once the first windows break and Deck 4 starts flooding, the capsizing follows within a minute. Thus the overall effect of windows strength is marginal simply because once 2,000 tonnes of water flooded the car deck, the flooding rate increases dramatically, thus exposing windows on higher decks to excessive pressures.

This leads to the conclusion that the element of flooding through the windows is of lesser influence on the ship critical behaviour than the water propagation through the cabins on Decks 4, 5 and 6. It is probably this process of flooding one cabin after another that allowed the vessel to sustain stable attitudes with heel in the range of 50-100degrees. This, however, remains to be confirmed by further numerical studies.

Scenario 2: Opening to forward spaces
Related studies: AB, Quote 46, Quote 56 and Quote 57
Objectives: Testing of possible stabilising effects of flooding spaces below the car deck thus allowing floating attitudes with heel of 90[deg]. Testing possibility of sinking through flooding of forward spaces.



Hs=4m, Tp=8s
V=0kn
β=-90 deg (waves to starboard)
Ramp **closed**
Windows brk pres **6m**

This scenario is aimed at testing assertions by AB that the sinking was a result of flooding of forward spaces below the CD. A hypothetical opening of approximate 1m^2 area into the swimming pool and compartment on Deck 1 above it has been modelled and the ship response tested in starboard-on-coming seas. All the doors between watertight compartments have been assumed opened.

A number of simulations revealed that once flooding of spaces below the car deck took place the ship loses her stability and attains new equilibrium at angles of some 10deg or less. It was noted, however, that the vessel becomes vulnerable to the action of waves in such a condition in that she intermittently changes her attitude between port and starboard sides. Examining Figure 9 leads to concluding that this is a result of a rather low restoring energy (area under GZ) in the range of heel of –10 to 10deg once flooding below the car deck spaces took place. The resultant outcome of such case studies was ship survival for at least an hour, where the simulations were terminated. Therefore, for simulations of this scenario, 500 tonnes of floodwater on the car deck has been assumed as a starting condition to ensure that the vessel floats with heel angles to starboard side.

As is shown in Figure 17, approximately 3,200 tonnes of water accumulate in forward spaces within about 10 minutes from the start of the simulation, resulting in a trim angle of some 2-2.5deg by the bow and subsequent loss of the forward freeboard. The heel angle to starboard side reaches approximately 15deg. Water starts flooding the CD “from below” through the doors in the centre casing (assumed opened), leading to heel angles up to about 30-40deg within 5-10 minutes, when the windows on Deck 4 submerge. Once this takes place the ship capsizes within 1-2 minutes.

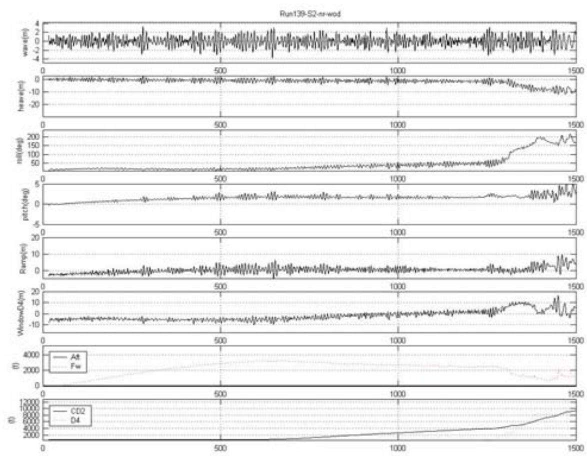


Figure 17: Time series of Scenario 2

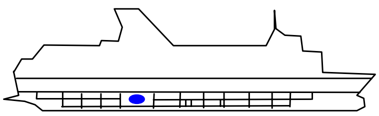
Although not in agreement with any of the AB descriptions of <u>causes</u> of large heel angles, the conclusion from this test is that MV Estonia could capsize due to flooding of spaces below the car deck, deriving from the simple mechanism mentioned above. Once the vessel attains s given attitude (heeling mainly) the water level in the lower compartments can reach the doors leading to the car deck. Thus, once the car deck is flooded, the vessel will heel to the extent when windows on upper decks will be exposed to excessive pressures and breaking, with the spaces then undergoing progressive flooding. If this flooding is assumed to spread unobstructed, as is done in this simulation, the vessel will capsize quickly. Such a rapid capsize in this simulation demonstrates that no stabilising effects due to flooding of spaces below the CD are present, which rather undermines the opinion expressed in Quote 46.

Note again that capsizing or large heeling (in case support from the superstructure is accounted for) are possible provided the doors between the car deck and the centre casing remain open (or easily forced open by the floodwater in the centre casing) and subsequent flooding of the car deck takes place.

No sinking was predicted in this simulation. Although such outcome is quite conceivable, for this to happen some water must still reach the spaces aft, as although there is buoyant space in the forward parts of Decks 0/1, allowing flooding of up to about 5,000 tonnes of water, see Table 3, there still remains about 2,700 tonnes of reserve buoyancy within the ship, capable of keeping the vessel afloat.

Finally, as expected, due to flooding of spaces forward the vessel trims by the bow, at least initially, which is in contradiction to the fairly well established final attitude resulting in "sinking by the stern". See note in the next Scenario regarding flooding of the Upper Decks and its implied role in the sinking sequence (by the stern).

Scenario 3: Opening to aft spaces
Related studies: AB, Quote 58 and Quote 59
Objectives: Testing possible stabilising effects of flooding spaces below the car deck thus allowing floating attitudes with heel of 90[deg]. Testing possibility of sinking through flooding of aft spaces.



Hs=4m, Tp=8s
V=0kn
β=-90 deg (waves to starboard)
Ramp **closed**
Windows brk pres **6m**

Results from simulating this scenario are given in Figure 18. The first to note is the initial loss of stability and heeling to about 20deg (note that 500 tonnes on the CD is assumed as initial condition) as flooding reaches amounts of about 2,000 tonnes. Similar observations can also be deduced from static stability characteristics such as shown in Figure 10. Any further flooding renders the vessel more stable and therefore the heel decreases to approximately 10deg. As was already pointed earlier, the restoring energy in the so flooded conditions and with heel angle in the range of –10 to 10deg is very low, hence the ship could change her attitude intermittently, heeling to port or starboard sides, as shown in Figure 18 at 1400[s]. She floats in such attitudes for the whole duration of one-hour simulation, and she neither capsizes nor sinks.

The fact that she does not sink in these circumstances is another revealing proof that the car deck spaces have to be flooded, as it is this buoyancy that keeps the vessel afloat and with a mere 2-3deg aft trim. Also, the fact that she does not capsize in any of the intermediate stages of flooding of the spaces on Decks 0 and 1, proves that water on deck is the only possible explanation of large heel angles.

It is probable that over longer period of time more water would flow onto the car deck "from below" via the staircase door between the machinery and the CD, as was the case with flooding forward. The difference here is, however, that it is only one pair of doors that connect these spaces, and therefore the rate of flooding of CD is much lower. In fact it seems that at some attitudes and level of flooding on Decks 0 and 1, this process slows down quite dramatically.

Nevertheless, it is highly likely that this scenario can eventually lead to flooding of CD and thus to vessel capsizing to the side, where she would gain temporal support from the superstructure. It is also likely that she would sink in these circumstances with the stern first.

<u>Note</u> here, that sinking with the stern first is very likely a result of the mode/sequence of flooding of the upper decks. Namely, as the vessel lies on her side, the aft parts of the superstructure could flood faster than the forward, and hence she could sink stern first.

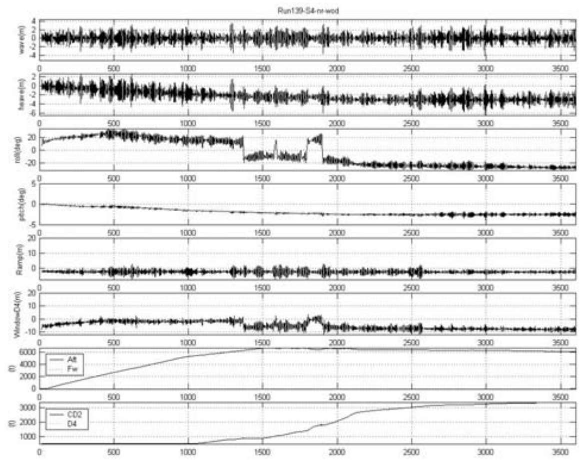


Figure 18: Time series of Scenario 3

It should be noted that similar conclusions as discussed above have already been reported briefly elsewhere, e.g. in [17].

5 CONCLUSIONS

This study attempted to highlight and clarify some of the fundamental mechanisms likely to have prevailed in the process of foundering of the MV Estonia. Use was made of state-of-the-art tools available for advanced research on damaged ship dynamic behaviour. Although the analysis can be considered extensive, by no means can it be deemed exhaustive or conclusive. Effects of uncertain variables such as internal compartmentation on Decks 4, 5 and 6, and capacity to oppose flooding, strength of external windows, extent of opening of the forward and possibly aft ramps, possible external hull openings below the waterline, watertight doors operation, cargo shifting, speed, heading, ballasting during the casualty, other range of environmental conditions, wind effects, and many other, remain to be determined if any loss scenario fitting the witness statements as well as other well established facts can be put forward with confidence.

Notwithstanding these uncertainties, however, some firm conclusions not reached and expressed explicitly before have been derived in this paper. These can be stated as follows:

- MV Estonia sank. Therefore, Car Deck, Upper Decks and to a great extent spaces below the Car Deck had to flood.
- MV Estonia attained heel angles in excess of 40deg. Therefore, large scale flooding of the Car Deck spaces had to take place.
- MV Estonia floated on her side. Therefore, progression of flooding of the Upper Decks had to be slow, taking place within 13-28minutes.

To date, no chain of events has been proposed explaining the above intricate processes in a consistent manner that could withstand scientific scrutiny.

The main remaining question is whether the Car Deck was flooded first and during some stage allowed flooding of the spaces below "from above" or whether the spaces under the Car Deck were flooded first and the Car Deck was flooded "from below".

Some clues for further investigation in search of THE TRUTH have been provided in this paper.

Until answers to the questions posed are given, the loss of MV Estonia shall remain a mystery.

6 ACKNOWLEDGEMENTS

This paper has been dedicated to all those affected by the tragedy of the MV Estonia accident, particularly families and friends of the victims.

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APPENDIX 1
NUMERICAL MODEL FOR TIME DOMAIN SIMULATIONS OF DAMAGE SHIP RESPONSES

Behaviour of damaged ships has been the subject of focused study at the University of Strathclyde for over 15 years. The reported recently in [12] and [13] mathematical model has been coded into the numerical software PROTEUS3, V18D.

Summarising, the underlying equations of the model are derived from fundamental motion principles: conservation of linear and angular momentum. The law applied for rigid bodies, whereby this definition is also extended on the internal fluid mass, is resolved in body-fixed system of reference. Rigorous derivation leads to a set of 6 scalar equations for linear and angular motions. Three such equations for angular motions are presented here in vector form (1).

$$
\begin{aligned}
&(I'_s+I'_w)\cdot\frac{d}{dt}\vec{\omega}'+M_w\cdot\left[\vec{r}'_w\times\left[\frac{d}{dt}\vec{v}'_{Gs}\right]\right]+\\
&+M_w\cdot\left[(\vec{\omega}'\times\vec{r}'_w)\times\vec{v}'_w\right]+\\
&+M_w\cdot\left[\vec{r}'_w\times\left[\frac{d}{dt}\vec{v}'_w+\vec{\omega}'\times(\vec{v}'_{Gs}+\vec{v}'_w)\right]\right]+\\
&+\frac{d}{dt}M_w\cdot\left[\vec{r}'_w\times(\vec{v}'_{Gs}+\vec{v}'_w)\right]+\\
&+\left(\frac{d}{dt}I'_w\right)\cdot\vec{\omega}'+\vec{\omega}'\times\left[(I'_s+I'_w)\cdot\vec{\omega}'\right]=\vec{M}'_{Gs}
\end{aligned}
\qquad (\ 1\ )
$$

The right hand side of the equation, $\vec{M}'_{Gs}$, and respective force vector in the set of equations for rectilinear motions, represents all the external forces and moments acting on the vessel expressed in a body-fixed system of reference, G_sxyz, located at the ship centre of mass. These forces are predicted with conventional for Naval Architecture methods. The Froude-Krylov and restoring forces and moments are integrated up-to the instantaneous wave elevation, the radiation and diffraction forces and moments are derived from linear potential flow theory and expressed in time domain based on convolution and spectral techniques, respectively. The hull asymmetry due to ship flooding, is taken into account by a "database" approach, whereby the hydrodynamic coefficients are predicted beforehand, and then interpolated during the simulation. The correction for viscous effects on roll and yaw modes of motion is applied based on well-established empirical methods. The second order drift and current effects are also catered for, at present, based on parametric formulations. Naturally the gravity force and moment vectors correspond to ship and flood water weights.

The whole system, after re-arranging into matrix form as a set of twelve differential equations of the first order, are solved for position in space of the centre of gravity of the intact ship $\vec{r}_{Gs}=\int\vec{v}_{Gs}\cdot dt$ and three rotations through a 4th order Runge-Kutta-Feldberg integration scheme with variable step size.

Undetermined in equation (1), are the relevant vectors for floodwater location, velocity and acceleration, $\vec{r}'_w$, $\vec{v}'_w$ and $\frac{d}{dt}\vec{v}'_w$, respectively. These are the quantities that must be derived from a model representing the sloshing water phenomenon. In case of application of the CFD techniques, these vectors and relevant forces and moments can be derived from pressure integration due to fluid motion. Here, however, simplified modelling was adopted. The fluid free surface is assumed to always remain horizontal and the resultant displacements of the fluid mass is predicted from geometrical analyses. The ensuing velocities and accelerations are obtained by backward differentiation.

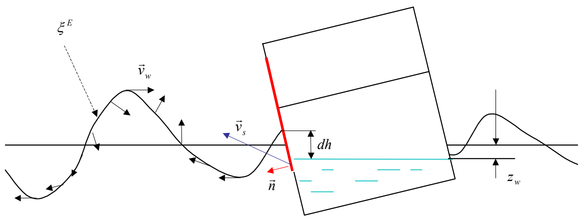

Figure 19 Water ingress/egress modelling

Water inflow is modelled by basic continuity equation with some corrections for wave and ship kinematics:

$$\frac{dQ}{dt}=\operatorname{sgn}(dh)\cdot K\cdot v_f\cdot dA$$

Where:

$$v_f=\sqrt{2\cdot g\cdot dh}+(\vec{v}_s\cdot\vec{n})-(\vec{v}_I\cdot\vec{n})$$

$K=0.6$	discharge coefficient
dA	area of the opening
$\vec{v}_s$	vessel rectilinear motions velocity
$\vec{v}_I$	wave particle velocity

More details of full implementation of the mathematical model can be found in [12] and [13].