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INVESTIGATION INTO THE SINKING OF THE RO-RO PASSENGER FERRY *EXPRESS SAMINA*

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Abstract

The main findings of the investigation into the sinking of the passenger/Ro-Ro ferry *Express Samina* and specifically the ship's damage stability behaviour are outlined in this paper. In the framework of this investigation, the flooding and sinking of the ship following damage was simulated by use of NTUA-SDL's time domain simulation method and the results could be confirmed by analysis of available testimonies of survivors. Progressive flooding through open left watertight doors was found to be the main reason for ship's sinking.

1. INTRODUCTION

September 26, 2003 marks the dismay 3rd anniversary of the spectacular sinking of the Greek Ro-Ro Passenger Ferry *Express Samina*. The ferry sank at the entranceways to the port of the island of *Paros* after hitting the nearby rocks of *Portes* in the night of September 26, 2000. It drew to death 80 passengers and crewmembers[1].

In January 2001, the interrogating judge of the court of appeal for the *Aegean Sea* appointed a five members committee to investigate the reasons for the sinking of *Express Samina* and to prepare within a very tight time frame its investigation report for enabling the speedy legal processing of the case. The appointed committee was able to complete and issue its main investigation report in September 2001[2].

First indictments against 17 persons (ship crew, coast guard and shipping company officers) were issued in summer 2002 and after an appeal of the High Court Attorney General, as to the indictment charges, the legal process is expected commence in late 2003.

The present paper derives from related research of the Ship Design Laboratory of NTUA on the damage stability of the sunk Ro-Ro passenger ferry *Express Samina*, outlines the basic characteristics of ship's damage stability, investigates the sinking of the ship by use of the numerical simulation code CAPSIM [2] and of her motions taking into account the ship's reported outer shell damages and alternative flooding scenarios, assesses the time available for the safe evacuation of the ship and

[1] Two more victims are due to the SAMINA disaster: in the night of the disaster the port officer on duty died on heart attack and a few weeks later the CEO of the shipping company committed suicide.

[2] The main investigation report was issued one day before the 1st anniversary of the ship disaster (25.9.2001); two supplementary reports were issued in December 2001 and January 2002 [1].

finally concludes with some lessons learnt from this spectacular ship disaster and some proposals for avoiding to the extent possible similar ship disasters in the future.

2. THE ACCIDENT

On Tuesday September 26, 2000 late afternoon (about 17:15) the Greek Passenger/Ro-Ro ferry *Express Samina* left the port of *Piraeus* heading for the island of *Paros*, the first on the route to the island of *Lipsi*. There were 533[3] people onboard, 472 passengers and 61 crewmembers. The ship was reported carrying 17 trucks and 34 cars on her car deck. According to plan the ship was expected at the port of *Paros* at about 22:18 local time, covering a distance of 90.5 nm with an average speed of about 18.5 kn. The weather conditions during the trip were fair, with moderate winds of up to 5-6 Bf, cloudy sky but without rain, the visibility range was reported 7-10 nm.

At about 20:00 the ship passed cape *Kefalos* of *Kythnos* island and thereafter she was heading for *Paros* island sailing for prolonged time on autopilot mode, until just a few moments before the collision happened. At some point during the journey, the starboard stabilizer fin was unfolded to calm down the experienced moderate ship motions, whereas the fin on the port side remained all the time folded[4].

If the ship has followed exactly the planned route she would have passed safely the rocky islet at the entranceways to the port of *Paros-Paroikia* (named *Portes*, about 3 nm from the port), at 22:13 and at a distance 0.4 nm northeast. Instead of, however, obviously due to careless navigation and mastering, the ship operating for a prolonged time on autopilot went off course and hit the *Portes* islet at about 22:12, despite some last moment maneuvers by the bridge officer on duty to avoid the disastrous collision. Figure 1 shows a sketch of the planned and actual route, the location of collision, the destination port and the shipwreck.

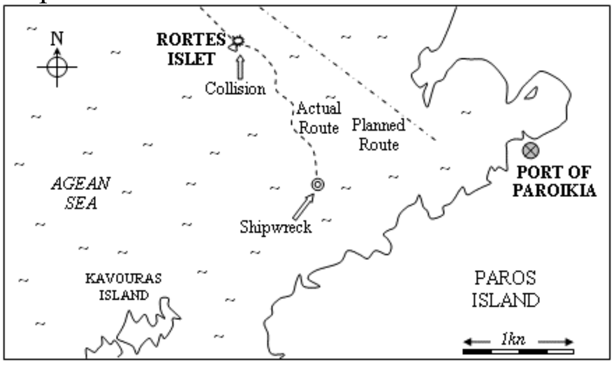

Figure 1 Map of the accident area

The collision of the ship with the rocky islet was on starboard sideways and has had as a consequence three raking damages on the ship's outer shell, of varying extent and location both *below and above* waterline. Two of these damage openings were of particular significance for the flooding process and the later sinking of the ship. The first and only serious damage *below waterline* (see, damage A in figure 3 and Appendix I), located amidships and in the bilge keel area of the main engine room. It was about 3.0 m long and resulted from the hit and backwards movement of the unfolded starboard stabilizer that penetrated the hull shell with its trailing edge like a 'knife'. The second serious hull damage, located about a quarter ship length from the bow, was of larger longitudinal extent but at ship's platform-car deck level, thus about 5m *above waterline* (see, damage C in Figure 3). Smaller, 'spot'-like damages on the ship's outer shell were found around *waterline* below damage C (see, damage B in Figure 3). They had, however, no significant impact on ship's flooding and foundering process.

Immediately following the collision, water started pouring through the fin damage opening

[3] The exact number of persons onboard could be only confirmed in the aftermath of the disaster after crosschecking the number of survivors and lost persons assumed onboard.

[4] The port stabiliser fin was found at the ship's wreck folded.

into the main engine room and progressively into the other compartments through open left watertight doors of the main engine room that else would have prevented the flooding of the entire ship and her foundering.

It took only about twenty minutes for the ship to get to such extent flooded that her embarkation deck reached the sea level and the associated large heeling practically prevented safe evacuation measures and the launching of life boats. Following the collision, the ship's main engines stopped anyway and a few moments later a 'black-out' of the ship's electrical powering occurred[5]. The ship was dragged away from the collision spot at the rocky islet under the effects of her initial speed, wind and waves. It disappeared from the sea surface about 50 minutes after hitting the rocks (at about 23:00 local time), at a distance of 1.4 nm away from the collision spot and merely 0.3 nm from the shallows of *Paroikia-Paros* bay. It is assumed that a significant number of the finally 80 people lost in this accident never managed to evacuate the ship.

3. THE INVESTIGATION

A five members committee of experts was finally assigned the investigation on the causes of the *Express Samina* accident three months after the disaster[6]. The objectives of the committee's investigation was to clarify the causes of the collision, the way of flooding and foundering of the ship, to identify possible technical and operational failures, to assess the ship's life saving equipment and followed evacuation procedure and finally to provide answers to a series of more specific questions of the interrogating judge of particular importance for the later indictments.

A significant part of the committee's investigation was carried out by the Ship Design Laboratory of the National Technical University of Athens (NTUA-SDL). The main technical part of this work, namely the investigations related to ship's intact and damage stability and the simulation of the flooding and sinking scenario are herein presented in summary.

Initially, a series of studies were carried out to check the compliance of the ship with relevant regulations, namely for ship's damage stability and safety the EUROSOLAS, EC Directive 98/18, considering the ship as an existing category *B* ship. As far as the ship's damage stability characteristics are concerned, it was confirmed that the ship complied with the provisions of EUROSOLAS regulatory framework, disposing an A/Amax over 0.98[7]. The approved and reassessed damage stability characteristics of the ship were at the time of accident according to the SOLAS 74, one compartment standard.

Considering that the ship's main underwater damage was restricted to the main engine room (one compartment damage), it was confirmed by a series of alternative flooding studies that the foundering was actually the result of open left watertight doors that enabled the progressive flooding of more than one watertight compartments. This confirmed the divers' findings regarding the open left WT doors as will be illustrated in the following.

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[5] After the 'black-out' of the main electrical generators, the emergency generator (located high-up at sun deck level) took over for a very short period of time parts of the electrical supplies, however not for long, as it stopped working too due to technical failure.

[6] Initially, two experts were appointed to investigate and report on the case following the accident. However, the seriousness of the matter and the required expertise to satisfactorily address the present case led the interrogating judge to reorganise and strengthen the investigation committee. The finally appointed five members committee was informally coordinated by the first author of this paper.

[7] According to MSC/ Circ. 574 & Circ. 649 for one compartment standard.

In particular, despite the provisions of ship's safety certificate, the vessel was actually sailing without watertight subdivision and the crew carelessly relied on ship's WT door-closing system that would have been activated in case of an emergency. Unfortunately, following the collision damage and the initiation of flooding in the ship's engine room, the crew was unable or did not make the effort to locally close the neighboring WT doors, nor was this possible from a remote control station at the ship's platform deck or from the bridge, due to the damage of the control station at ship's platform deck respectively the failure of electrical power after the incurred black-out of the ship's main generators located in the flooded main engine room.

A second major objective of the undertaken investigation was aimed at simulating to the extent feasible the sinking of the ship and determining the likely history of the most significant events. To this end, a detailed and systematic analysis of the testimonies given by the survivors was carried out first and it was accompanied by a numerical simulation study regarding the evolution of the progressive flooding and ship's foundering. The simulation studies were carried out by use of a numerical simulation method developed at NTUA-SDL, as detailed in Appendix II.

The most significant contribution of the employed simulation method to the present accident investigation was the identification of the most probable flooding and foundering scenario enabling the assessment of ship's evacuation within the available time to sink. This was achieved by studying the convergence of alternative flooding/simulation scenarios and observations by the survivors as laid down in the available testimonies.

The collection and assessment of data for this investigation was a tedious process, because of the variety of sources of the data: the survivors' testimonies (passengers and crew), the findings and reports of the appointed divers and the ship's technical particulars and safety certificates.

For the efficient analysis of the collected data it was considered necessary to develop a documents and testimonies database. A MS ACCESS database of ship technical and accident related information was developed by NTUA-SDL and this proved an essential investigation tool especially for the systematic analysis of available testimonies, besides it is a useful tool in general as a ship's accident documentary system. The central menu of the developed database is shown next.

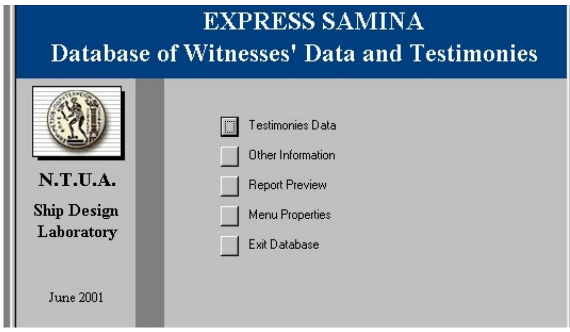

Figure 2 Testimonies database

4. TESTIMONIES ANALYSIS

By use of the developed database the witnesses' data were filed in a specific format enabling the conduct of statistical analyses with respect to certain crucial events. In particular, information regarding the time of collision, the sounding of public alarm, the supposed time of sinking, the failure of electrical power supply and lighting, the evacuation and rescue procedure and details on the usage and quality of lifesaving equipment was systematically collected and statistically analyzed. One hundred and ninety two (192) testimonies of surviving passengers and seventy-five (75) testimonies of crew (from whom twenty-nine (29) testified more than once) were captured in the database and systematically analyzed.

Based on a statistical analysis of the collected testimonial data the accidental time was estimated to be 22:10. This estimate can be considered fairly certain and agrees with the estimated time of arrival at the entranceways to the port of *Paros*.

Regarding the ship's sinking time, there was an obvious vagueness among the passengers in the recognition of the actual sinking event that could not be clarified during the testimonies. Some passengers have conceived the sinking of the ship as the moment the embarkation deck reached sea level, whereas others considered it as the disappearance of the ship from the sea surface. Consequently, a dispersion of the felt sinking time duration between 20÷45 min was observed. Taking into account the testimonies of specific witnesses' categories, like only passengers, only crew, passengers and crew together, a conventional sinking time of about 30 min was estimated, considering herein the ship's sinking as the advanced flooding stage up to the embarkation deck and higher up. The wall clock at the bridge was found stopped at 23:02 providing an evidence of the most prolonged time of sinking.

Another significant issue resulting from the analysis of the testimonies was that about 2/3 of the passengers stated that there were inadequate life saving equipment onboard, particularly life jackets, and that access to the life saving equipment was difficult or impossible. Though, life saving equipment was found in terms of specified numbers according to regulations, as laid down in relevant authority survey reports, it was reported that parts of the onboard life jackets were deficient and not according to regulations. Independently, failure of provision of proper and timely information to the passengers regarding the use of the onboard life saving equipment, insufficient support by the crew and the short time available to safely evacuate the ship finally led to the loss of 80 lives.

5. GEOMETRIC MODELING

Hydrostatic and hydrodynamic calculations presume proper geometric modeling of the ship. A body plan and other relevant plans of the ship are shown in Appendix I. Based on the body plan's offsets the ship's hull surface was created using the NAPA software package and subsequently the ship's General Arrangement and watertight compartmentation.

6. THE DAMAGE OPENINGS

The sideways collision of the ship with the rocky islet created three main damage openings on the ship's starboard outer shell, as described in the appointed divers' investigation reports. As illustrated in the next Figure 3 the first one, denoted by letter A, is located in the main engine room's bilge area, around frame 85, just aft of the starboard stabilizer fin chest. It resulted from the shell penetration by the fin as it moved backwards after the fin collided with the rocks, see Figure 4. The damage is limited to one compartment, namely that of the main engine room, extending from the fore bulkhead of the main engine room and backwards for about 3m. This damage is obviously the dominant opening that determined the flooding procedure of this ferry accident.

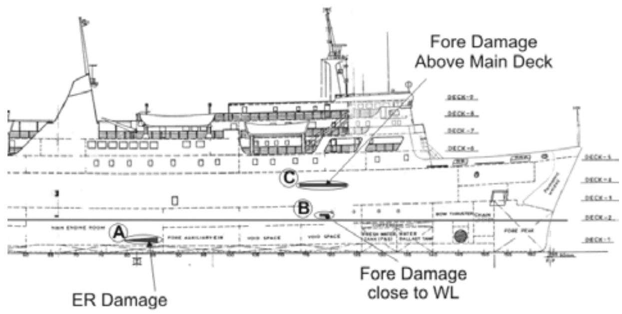

Figure 3 The damage openings

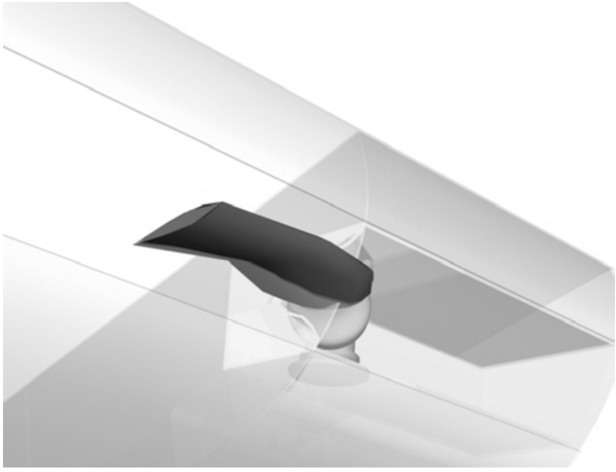

Figure 4 The starboard stabilizer fin penetrating the ship's main engine room

The second damage, denoted as B in Figure 3, is actually a set of three cracks located at about a quarter length form the bow and at the height of ship's waterline on starboard side. The cracks are strip wise shaped openings with the largest one about 60 cm in length. These damages are considered of secondary importance for the accidental outcome, as their size and location close to waterline permitted only limited inflow rates compared to the other openings.

The third damage opening, denoted as C, is a typical raking damage and the largest one observed. It is practically located above damage B at the height of the platform deck on ship's starboard side. Its size could not be exactly determined, as the shipwreck, laying on a sandy seafloor, is partly covering this opening. Based on the divers' reports and testimonies of the crew, its extent is estimated to be about 6.0 m in length and up to 1 m wide.

Damage C (and the minor cracks B) can be regarded as the first damages created on ship's outer shell following the non-successful collision avoidance maneuvers by the bridge officer. Moments later, as the ship kept moving, the unfolded starboard stabilizer fin collided on the rocks and moved backwards penetrating the main engine room's bilge area and creating the major damage A.

7. DAMAGE STABILITY

The vessel[8] was built in 1966 as a Passenger/Car Ferry for routes between *Corsica* (France) and North Africa (original name: *CORSE*). In the period 1981-1987, the vessel was operating for Greek interests on various international routes between Greece, Italy, Cyprus and Israel. From 1987 till the accident, she was on domestic services in Greek waters.

Regarding the ship's compartmentation, she was subdivided by transverse bulkheads into 12 watertight compartments, Figure 5, and disposed one-compartment standard of subdivision according to SOLAS 74.

Figure 5 Watertight compartments subdivision

7.1. Compliance with Regulations

During spring/summer 2000[9] and few months before the accident, the ship underwent significant modifications mainly with respect to her accommodation of passengers and public domain spaces[10]. As could be confirmed by an independent NTUA-SDL study, the ship was in compliance with the currently in-force 'EUROSOLAS, EC Directive 98/18', as an existing one-compartment SOLAS 74 ship. Taking into account the ship's A/Amax ratio (over 0.98), the vessel should comply with the Reg. 8-1 of SOLAS 90 on the first periodical survey after October 1, 2005 and assuming the number of passengers unchanged with Reg. 8-2

[8] The ship's particulars are given in Appendix I

[9] In July 2000, the ship was transferred from *Agapitos Lines* to *Minoan Flying Dolphins*.

[10] From the naval architectural and stability point of view the most significant modification was the extension of ship's sun deck to the stern to allow the enhancement of public spaces.

on the first periodical survey after October 1, 2006 [SOLAS 90, two-compartment standard].

It is noted, however, that following Greece's National Law for domestic services ferries (at that time: age limit of 35 years) the vessel should have been withdrawn from domestic services by the end of year 2001.

7.2.Damage Stability Characteristics

On the accidental voyage, the ship was not fully loaded; therefore additional hydrostatic calculations were carried out considering the ship's actual draught. Three different flooding cases, presented next, were investigated to support by simplified reasoning that flooding through open left watertight doors caused finally the sinking of the ship[11].

Considering, first, that flooding due the incurred damages was limited within the extents of the Main Engine Room, the ship proved satisfactory in terms of reserve buoyancy and relevant stability criteria to withstand the particular flooding.

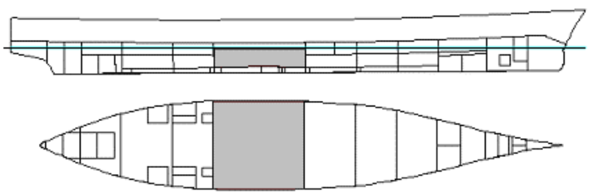

Figure 6 One flooded compartment scenario

Considering the watertight door, connecting the main engine room with the forward auxiliary engine room, open[12], the resulting scenario of flooding leads to flooding of two compartments, namely that of the main engine room and of the forward auxiliary engine room. Though the ship was actually registered as one compartment ship, it proved that for the particular loading condition the ship could survive this damage as well.

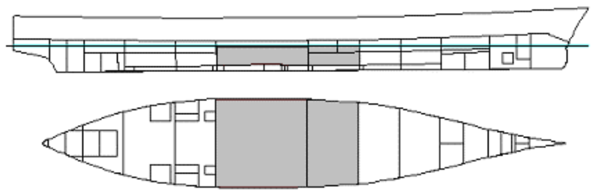

Figure 7 Two flooded compartments scenario: main and forward auxiliary engine room

Figure 8 describes a further hypothetical flooding scenario taken into account the described hull damages A and B, as well as the watertight door between main and forward auxiliary engine room, to be open. According to performed calculations, although in this case the bulkhead deck line immerses at the equilibrium position, the ship would have adequate reserve buoyancy and stability, Figure 9, to avert further progressive flooding. In addition, there was adequate margin of heel to avoid an immersion of the damage opening located above water, at ship's platform deck [Damage Opening C].

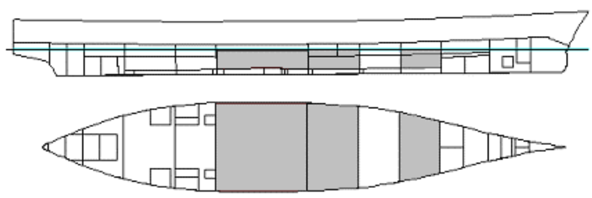

Figure 8 Three flooded compartment scenario

11 Though the majority of the watertight doors were found open by the divers in charge of the shipwreck's investigation, they were claims, that the watertight doors might have opened after ship's sinking due to failure of the doors' hydraulic system

12 This case is trivially the same as the case of a damage extent into the forward auxiliary engine room.

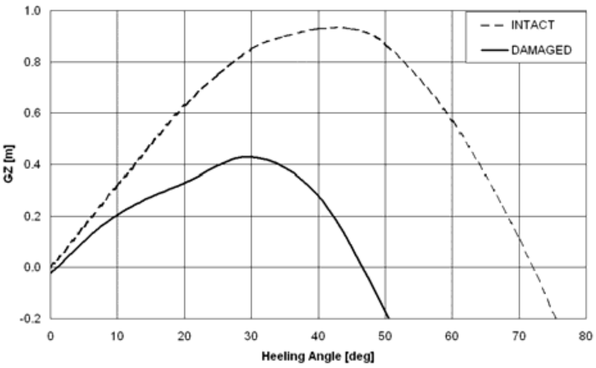

Figure 9 GZ curve for the three flooded compartments case

The above results clearly suggest that if the ship's watertight doors (especially: those of the main engine room) were closed, the ship would most likely have survived the incurred damages or in the worst case she would have sunk after a prolonged time allowing safe evacuation.

8. DETERMINING THE MOST LIKELY FOUNDERING SCENARIO

The following assumptions were made concerning the modelling of the ship.

- The modelling of ship's hull, internal subdivision and compartmentation is based on approved drawings of the vessel.
- The *outer shell openings* (bow and stern door) were assumed closed according to the divers' report.
- Regarding the internal watertight doors only two doors out of 11 were assumed closed (see next figure, it is based on the divers' reports).
- The position and extent of the incurred damage openings were taken according to the divers' reports.

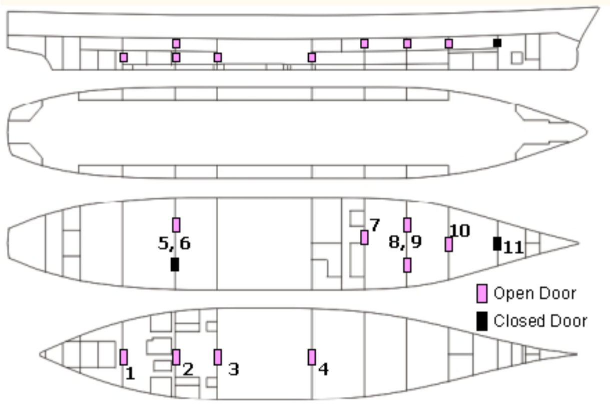

Figure 10 Condition of watertight doors

The ship's loading condition characteristics on the accidental journey were reproduced based on ship's stability booklet and the actual loading, as known to the port authorities and the shipping company (see next Table 1).

Table 1 Particulars of loading condition

Displacement	4731	tons
Min Draught	4.275	m
Trim	0.60	m (by stern)
LCG	52.075	m
$VCG_{(corrected)}$	7.460	m

9. NUMERICAL SIMULATION OF PROGRESSIVE FLOODING

Based on the gathered information regarding the ship's geometric modeling, the modeling of the damage openings, the ship's loading and the environmental (wave) conditions a numerical simulation of ship's flooding and sinking process was carried out, to more closely investigate the sequence of the accidental events after ship's damage.

The most probable flooding scenario, namely considering nine out of eleven watertight doors open, as it was reported by the divers' in charge of the shipwreck's investigation, was numerically simulated to enrich the information about the ship's behavior after damage by scientific evidence and to enable a direct comparison of the obtained theoretical results with the survivors' testimonies. Alternative flooding scenarios, assuming the watertight doors closed (or partly closed) could be also reproduced, leading to the conclusion that the above cited scenario is the only feasible and in compliance the with observations of the survivors.

The numerical simulation was carried out by use of NTUA-SDL nonlinear time domain simulation method, as implemented with the computer program CAPSIM. The method represents a state of the art simulation method employed for the assessment of ship's damage stability in waves. The CAPSIM computer code has been systematically validated with respect to its consistency and robustness in a variety of research projects and international benchmark studies [3]. Details on the simulation code CAPSIM and its background are presented in Appendix II.

There are two significant results of the used numerical simulation method that could otherwise not be obtained. These are in particular the flooding sequence of the compartments and the time series of the various incurred events, including ship's motion and sinking. Hydrostatic calculations might consider fully flooded compartments, as they result in the final flooding condition, or partially flooded compartments externally specified. In the actual flooding case, however, where progressive flooding of adjacent compartments occurs, it is practically impossible to externally specify the flooding stages of the various compartments, even neglecting hydrodynamic phenomena. The numerical time domain simulation method overcomes this problem, enabling the continuous monitoring of the progressive flooding of the various compartments, for specified damage openings and geometry of compartment doors and of internal arrangements.

The results of the numerical simulation for ship's heel angle after damage, assuming the most probable flooding scenario (9 out of 11 WT doors open) are shown Figure 11. Shortly after damage, the ship obtains for short time a transient heel to starboard of about 5 degrees and then goes back to upright, before gradually obtaining large heel angles to starboard, reaching more than 30 degrees merely twenty minutes after the collision.

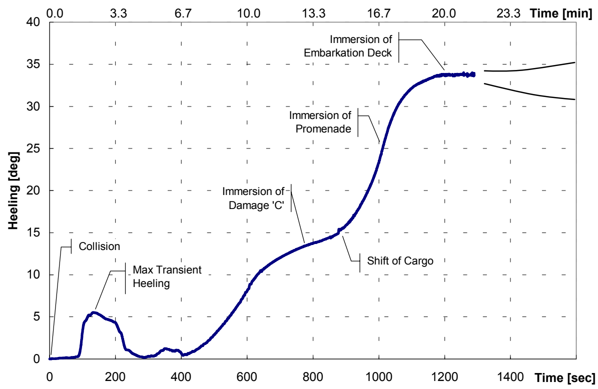

Figure 11 Simulated heeling for the most probable flooding scenario

The above simulation pertains for calm water conditions. The effect of sea waves on the flooding evolution and ship's motions are discussed later in this paper, but were limited.

Commenting on the ship's heeling behavior depicted in Figure 11, the transient heeling angle of about 5 degrees experienced in the first 4 minutes after collision was noted by the passengers, who felt for short time relieved as the ship came back to upright. The simulation analysis showed that this heeling angle is a transient free-surface effect of the floodwater poured into the main engine room, before spreading and flooding the whole engine room and adjacent compartments.

In the simulation analysis the effect of shift of cargo was also considered, which as an event certainly occurred as the ship obtained large heeling angles and the not lashed cars on ship's car deck fell to the side. Taking also into account relevant testimonies according to which a strong sound was heard about a quarter after the collision and also considering that a shift for this ship could occur at an angle of about 15 degrees, a constant inclining moment due to the anticipated shift of cargo was added as external moment after this heeling angle. This additional moment was estimated assuming a transverse shift of the trucks and cars on board by 1 m to starboard. The undertaken analysis as to the importance of the shift of cargo led to the conclusion that this effect is of subsidiary importance for the evolution of the flooding process and ship's sinking.

One of the uncertainties of the simulation results is the flooding of *non-watertight* compartments. Obviously, whereas the lower ship compartments, namely those located under the subdivision deck, can be easily modeled as three dimensional spaces with certain openings connecting to adjacent compartments or the external sea environment, it is not so with the higher compartments, namely the ship's superstructures, which are not built as watertight spaces, permitting flooding through various openings like non-watertight doors, staircases or leaking/broken windows. The flooding resistance of these spaces cannot be modeled in detail and consequently with high accuracy. Consequently, when flooding of the superstructures starts the uncertainty introduced into the calculations increases. Practically, this uncertainty is effective for times later than about 15 min and its impact on the results is limited to the advanced stages of flooding. Considering this, the curve of heeling angle depicted in Figure 11 ends with an upper and lower boundary implying the level of uncertainty for the predictions of later stages of flooding.

All ship compartments were to the extent possible geometrically exactly modeled based on the ship's general arrangement plans. The permeability of compartment was taken according to SOLAS regulations. The modeling of the main engine room was more carefully pursued, so that the space occupied by the main and auxiliary machineries could be considered (see Figure 12 below).

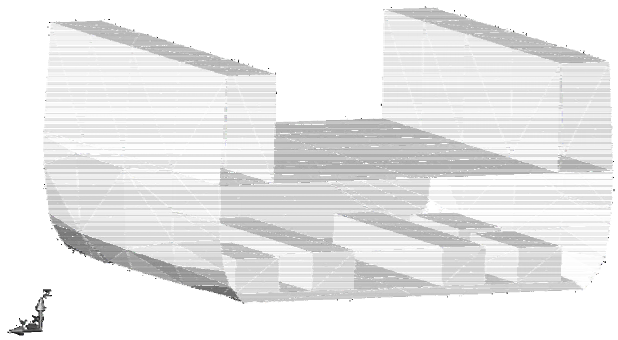

Figure 12 Geometric modelling of main engine room including car deck side casings

In Figure 13 the results of the simulation method for the vertical distance between the *floodwater free surface* at the main and the forward auxiliary engine rooms and *the still water sea surface* are presented[13]. This information is of particular importance, as these two compartments were the first flooded compartments in time sequence after the collision.

As observed in the above diagrams the floodwater is quickly pouring into the main engine room reducing the free surface distance from the still water plane by about one meter within the first minute. In later stages, the free surface level in this compartment gradually approaches the still water free surface while having a continuously lower level compared to the still water plane. This continuous difference in free surface levels indicates a continuous flooding through the damage opening 'A' and that there is a pressure head difference between the main and forward auxiliary engine room

[13] This kind of information is available for every modelled compartment and enables valuable conclusions, e.g. as to the time left to safely evacuate the relevant compartment etc.

causing a flow through the two compartments connecting door.

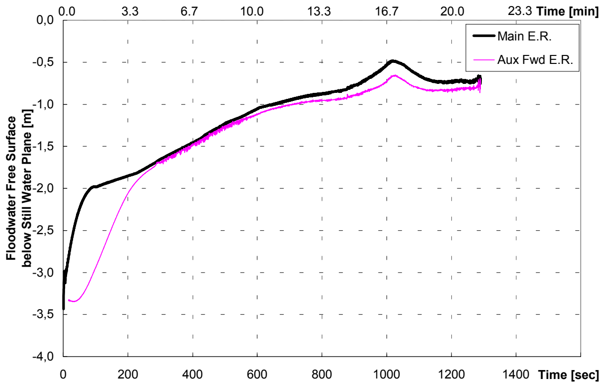

Figure 13 Floodwater free surfaces at engine rooms with respect to the still water plane

Some conclusions may be drawn from the results of the applied numerical simulation method, as to the time the launching of lifeboats was possible. According to the Figure 11 the launching of the backboard side lifeboats was greatly impaired and later impossible merely about 15 minutes after the collision, as the ship's heeling surpassed 15 degrees to starboard[14]. Obviously this is a very short time to effectively respond considering, also, the time lag between the collision and the decision to abandon the ship by the master. The timing of the public announcement to abandon the ship by the ship's master is an issue to be clarified by the Court. It is evident, however, that in view of the very short time available, before the ship sunk, and additionally the lack of sufficient lighting, that the ship's evacuation was a tremendous task even for a best trained and experienced crew.

10. THE EFFECT OF SEA WAVES

The reconstruction of the ship's sinking history, employing the numerical time domain simulation method, as presented in the previous paragraphs, was first established assuming calm water conditions. This enabled the investigation of the fundamental behavior of the damaged ship's sinking, a phenomenon known to be driven mainly by ship's hydrostatics. The effect of waves excitation was studied in two stages: First, the responses of the ship during the journey and at the accidental position were evaluated by use of a 3D panel, 6 DOF frequency domain code, namely NEWDRIFT [5] and it was found that responses were moderate and without a significant effect on ship's accident. At a later stage, as reported in the following, the effect of sea waves on the sinking process was more carefully studied by including the sea wave excitation as an external force in the employed nonlinear time domain simulation method.

The sea conditions at the time of the accident were determined by analysis of the best available data. The prevailing weather conditions in the sailing area at the time of accident were assumed about 6 Bf corresponding to a significant wave height about 1.5-2.0 m and wave period 4.8-5.6 sec and main direction of winds north to south. These data were according to the National Meteorological Office and projections of the weather forecast model *Poseidon* of the National Center of Marine Research [4].

The above range of sea conditions was investigated with the simulation method to detect the effect of sea waves on the flooding process and ship's foundering. The sea waves were assumed described by a JONSWAP spectrum having an enhancement factor γ=3.3.

The heeling time series for the most prevailing seaway scenario is depicted in the next Figure 14 for both cases, with and without sea wave excitation.

[14] It is noted that half of ship's lifeboats were never launched.

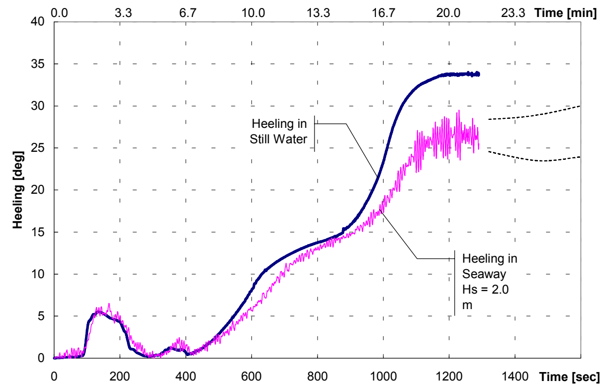

Figure 14 Heeling angle in calm and wavy sea

As observed in the above diagram, the history of the heeling angle in both cases is quite similar at least for the first quarter of hour after collision. The observed difference of about five degrees for the later stages of flooding increases the uncertainty of the predictions as the time passes beyond about 15 minutes. However, the simulated overall sinking process does not change and particularly the impact of sea waves on the crucial first stages of flooding is quite limited.

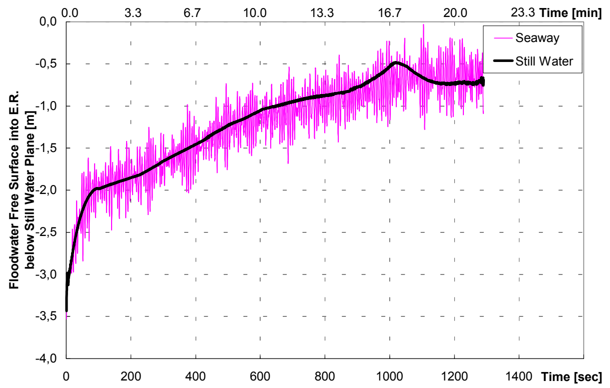

Figure 15 Floodwater free surface in the E.R.

In above Figure 15, the prediction of the floodwater level in the main engine room with respect to the still water surface is shown for the case of sea wave excitation, likewise the diagram of Figure 13 (calm water case). The floodwater level of the still water case seems to represent the mean value of the oscillatory level in case of flooding in waves.

In summary, the overall effect of the sea waves on the evolution of the flooding history is rather limited to the later stages of flooding, whereas beyond that the waves appear to not give any substantial effect.

11. THE OPEN DOORS

The results from the undertaken hydrostatic analysis, the divers' findings and relevant testimonies of the crew all converge to the conclusion that almost all watertight doors below the subdivision were open and enabled the progressive flooding and the subsequent sinking of the ship. This could be also verified by the presented time domain simulation of the most probable flooding scenario and ship's sinking, considering that the predicted heel angles at specific times after collision were in agreement with relevant data from testimonies.

In the following, the numerical simulation study for the hypothetical scenario of three flooded compartments, presented in Figure 8, is reproduced. It is noted that it was shown earlier by hydrostatic reasoning, that in this case the ship reserves enough buoyancy and stability to survive.

Only the watertight door connecting the main with the forward auxiliary engine room was assumed left open whereas the rest doors assumed closed. The behavior of the damaged ship under these conditions was simulated and the heeling angle in the time domain is presented in the next Figure 16. The predicted heeling history is accompanied by the results of Figure 11 for direct comparison purposes.

As shown by the simulation method, in this case the ship would remain continuously close to the upright position without any heeling. It would obtain in the final flooded-equilibrium condition a slight trim by bow and a margin line immersion at the fore part of the ship.

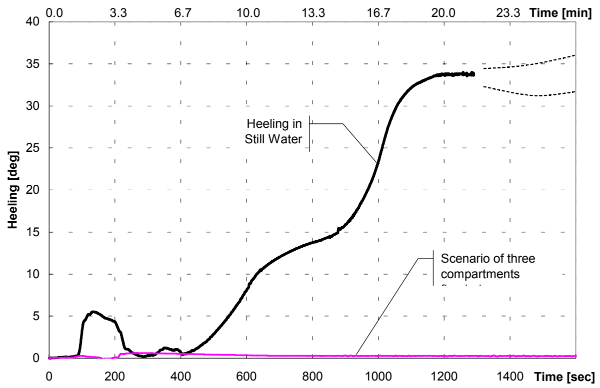

Figure 16 Ship heeling in case of only one open door (main to fwd aux. E.R.)

This heeling evolution, however, is clearly against the observations of the survivors and the final disastrous outcome of the investigated disaster; therefore this scenario can be certainly considered impossible. This scenario shows however that the ship even with these three damaged compartments flooded would have survived.

12. RECOMMENDATIONS

The experience of the authors resulting from the investigation on the sinking of Passenger/ Ro-Ro ferry *Express Samina* is invaluable and cannot easily summarized in one paragraph. An attempt is made to address in the following some major lessons learned, to contribute to the improvement of relevant investigations and to the avoidance of similar disasters in the future.

The sinking of a ship is an always-possible event, even if, particularly for passenger ships, this probability is extremely low. In fact, statistics prove that the probability of loss of life by sea transportation is significantly lower than by any other transportation mode.

Given ship's sinking as a possible fact and beyond current efforts to build enhanced safety ships, increased efforts should be made to improve ship evacuation procedures, especially as many existing and aged passenger ships do not dispose inherently survivability levels comparable to modern ships, calling for the 'grand father clause', when new safety regulations enter into force. Evacuation studies for any type of ship exploiting modern analysis tools can rationalize and further improve the evacuation procedures in case of a disaster, minimizing the risk of loss of lives.

As presented in the paper, two important parameters greatly characterize ship's sinking and have a direct effect on ship's evacuation: the time to sink and the heeling time history. The treatment of these two parameters namely the extension of time to sink and the stability preservation during flooding from the early design stage substantially improves the evacuation conditions.

As in the operation of all complex systems, so for the ship, an efficient operation-control system to ensure the desired performance is required. Proper implementation of the ISM code in practice is a crucial matter for ship operators and the controlling authorities. In particular, the responsibility assignments to the crew and company officers and the follow up of specified procedures in practice needs careful review and continuous control.

The watertight subdivision of a ship is the most essential part of ship's safety and as such it should be subjected to surveys at any time. Thus, the condition of the watertight doors should be continuously recorded in Voyage Data Recorders and records should be at any time accessible to the controlling authorities, not only after an accident when the recorded data are retrieved. Beyond that, the recording and survey of other vital systems of the ship, like the emergency generator and the powering system for the WT doors closing should be also recorded and the records be accessible to the authorities. Finally, current provisions in force for existing passenger ships as to the closing of WT doors from the bridge and the emergency lighting in case of failure of the main generators should be reviewed towards establishing equal standards to newbuildings.

13. CONCLUSIONS

This paper outlines the major part of undertaken investigations regarding the damage stability and sinking of the passenger/ Ro-Ro *Express Samina*. The employment of a nonlinear time domain simulation method facilitated the identification of the most probable flooding scenario, the ship's heeling time history and the estimation of the time to sink.

Besides the scientific interest, this type of information is essential for the support of forensic studies. The present simulation method results could be verified by testimonies of survivors, therefore the undertaken study should greatly contribute to the fair trial of a marine disaster that has shaken Greek society and the international maritime community.

14. ACKNOWLEDGEMENTS

Taking into account that the public hearing of this disaster has been delayed and is still pending at the time of editing this paper, the authors took care to herein present only generally known facts about the investigated marine disaster and focused on the scientific documentation of the applied investigation method.

The first of the authors likes to express his sincere thanks to the interrogating judge of appeal Mr. N. Karadimitriou, the members of the investigation committee Mr. I. Ventouras, Mr. G. Dimitriadis, Prof. T. Loukakis and Mr. E. Manios and the staff of NTUA-SDL for the excellent collaboration in investigating this tragic marine disaster under most difficult conditions.

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15. APPENDIX I

SHIP PARTICULARS	
Ship Name	EXPRESS SAMINA
Ship Type	Passenger / Car Ferry
Builders	CHANTIERS DE L' ATLANTIQUE - St. NAZAIRE
Date of Built	01/01/1966
Area of Operation	AEGEAN SEA
Type of Trip	Day / Night
Length over all, [m]	115
Breadth moulded, [m]	18.1
Depth to the upper deck, [m]	10.7
Depth to the main deck, [m]	6.01
Subdivision Draught, [m]	4.55
Service Speed, [kn]	18.0
Gross Register Tonnes	4407
Deadweight, in tonnes	1089
Passengers according to summer certificate	1038
Passengers according to winter certificate	335
Number of persons in Boats	674
Number of crew	62

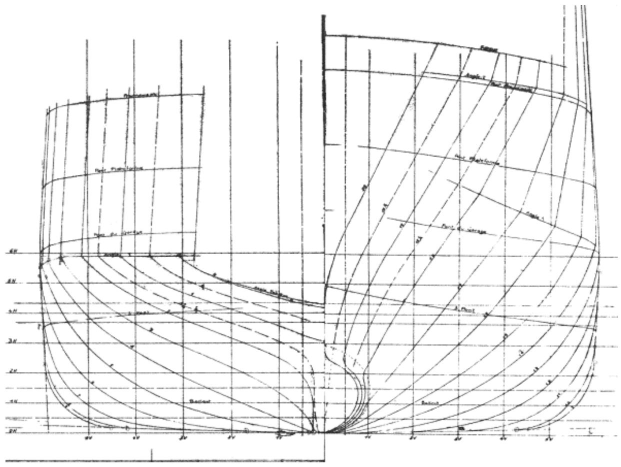

Figure 17 The ship's body plan

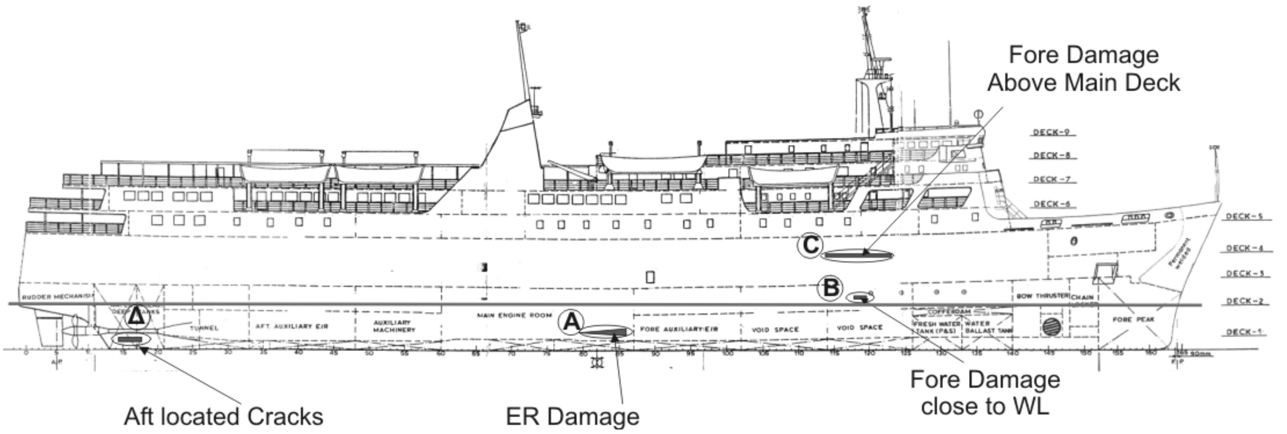

Figure 18 The reported damage openings

16. APPENDIX II

16.1. The Ship Motion and Flooding Simulation Method of *CAPSIM*

A suitable mathematical model accounting for the ship motion in the presence of floodwater has been developed in recent years at the Ship Design Laboratory of NTUA and implemented by the computer code *CAPSIM*. It provides an efficient way to investigate the motion of the coupled system consisting of the ship and floodwater mass as well as the flooding procedure and the stability of the overall system under the effect of sea waves. The model is nonlinear allowing the consideration of large amplitude motions and the stability of the vessel in extreme heeling angles and environmental conditions.

The flooded ship, herein consisting of the intact ship with the presence of floodwater, is considered as a system of masses, namely that of the intact ship and that of the floodwater assumed inside the flooded compartment. Further, the ship is considered as a rigid body having six degrees of freedom. The floodwater mass is variable in time, having a free surface approximated by a plane free surface which moves in the three dimensional space obtaining any position resulting under the interaction with the surrounding walls of compartment. In this way the floodwater is a mass having three degrees of freedom.

The governing equations of motion of the *coupled* ship-floodwater mass system can be derived by application of the momentum conservation theorem, namely by considering the linear and angular momentum of the ship and the linear momentum of the floodwater mass. In cases of multiple flooded compartments one floodwater mass is defined for each compartment. In this case one conservation equation for each compartment is introduced. Background details of the simulation method can be found in [1], [2], [3] [4].

The external to the inertia system acting forces and moments that appear in the equations of motion express the entire set of forces acting on the present inertia system and causing its motion. These forces may be analysed into seaway and wind force components; others might be added in a straightforward way (current forces, etc). Wave exciting forces, as the dominant dynamic part, can be further analyzed into Froude-Krylov or incident wave, radiation and diffraction forces, following linear potential theory. It is acknowledged that higher order effects (like drift forces, second-order Froude-Krylov, radiation and diffraction forces) could be considered by the same herein applied concept.

Incident wave forces together with the hydrostatic ones are herein calculated through direct integration of the dynamic and hydrostatic pressure over the instantaneously wetted surface of the vessel, defined by the undisturbed incoming wave. Radiation forces are herein calculated by the added mass and damping coefficients, calculated in frequency domain and properly transformed into the time domain applying the impulse response function concept. Elementary diffraction forces corresponding the elementary wave frequencies of an assumed irregular seaway spectrum are taken to be directly proportional to the corresponding elementary diffraction forces calculated in frequency domain. Finally, the consideration of nonlinear roll viscous effects is herein accomplished by using a quadratic roll velocity model, with semi-empirical damping coefficients. The time rate of change of the floodwater has been approached by use of Bernoulli's equation, modified by a semi-empirical, weir flow coefficient to account for the local flow effects at the damage opening.

Obviously, the successful motion simulation depends equally on the proper modeling of the inertia terms of the equation of motion and the ship's geometry, but also on the valid modeling of the external forces. It is essential to dispose an efficient method to provide accurate information on the exerted wave forces. Radiation and diffraction forces in the frequency domain were herein calculated by applying the computer code *NEWDRIFT*, [5]. It is a six DOF three-dimensional panel program for the calculation of motions and wave induced loads, including drift force effects acting on arbitrarily shaped bodies in regular waves. The code is based on a zero-speed Green function pulsating source distribution method and employs triangular or quadrilateral panels for the discretisation of the wetted ship surface.

17. REFERENCES

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18. APPENDIX III

18.1. The sinking in summary

In this appendix a brief outline of ship's sinking is provided illustrated with appropriate images of a developed computer animation. Given the flooding course of the vessel as resulting from the numerical simulation analysis and discussed in the main body of the paper the characteristic instances have been extracted to create the sinking history.

Following unsuccessful last moment maneuvers, the ship collides with the rocky islet, Figure 19, a few minutes before arrival to the destination port. Three damage openings occurred on the starboard side of the vessel. The ship started immediately to be flooded by the lower damage, when the stabilizer fin penetrated the bilge area of the main engine room.

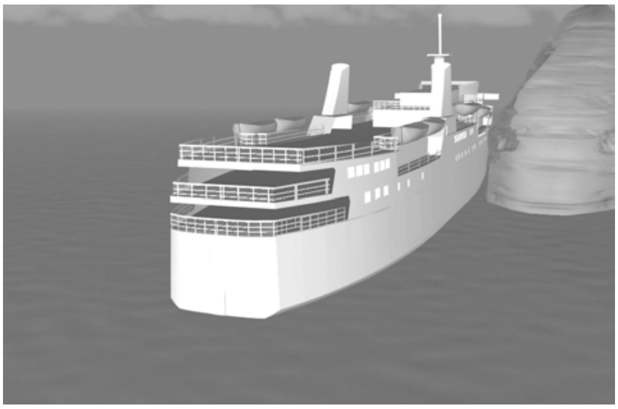

Figure 19 Ship collides with the rocky islet, time 0.

Shortly after the collision and within about 3 min the ship obtained a transient heeling of 5 degrees, as shown in the Figure 20. This immediate heeling was noted by the passengers. Later the ship returned back to the upright position in 5 min from the collision. The flooding mainly through the damage 'A' at the engine room continued.

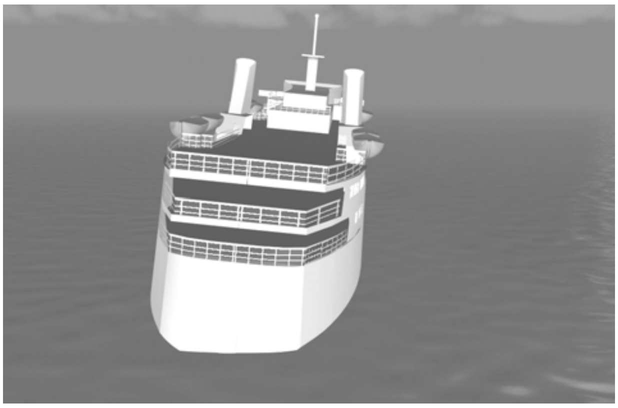

Figure 20 Transient heeling of 5 deg, +3 min

One after the other the ship's compartments were progressively flooded and the ship gradually heeled again to the right side. About thirteen minutes after the collision the ship obtained almost 15 degrees heeling as depicted in the Figure 21. In this moment the larger damage ‘C’ at the height of platform deck immerses into sea water, while the backboard life boats could practically not anymore be launched.

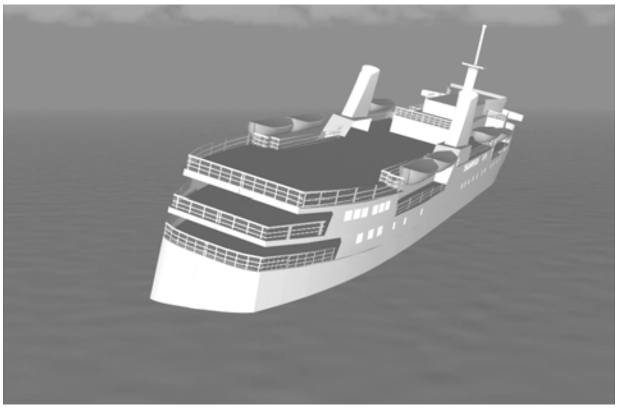

Figure 21 Immersion of damage ‘C’, heel 14 deg, time +13 min

After the first 15 minutes and having the larger damage opening ‘C’ immersed the flooding process was speeded up. Soon the sea water level reached the promenade deck as shown in Figure 22. From this point on the superstructures started be flooded, the heeling continuously increased and clearly the ship has surpassed the point of no return.

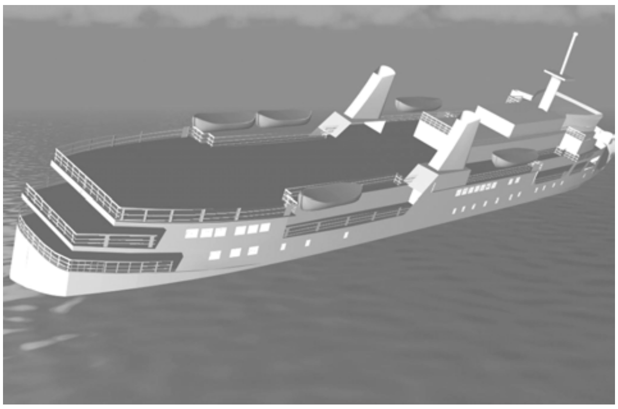

Figure 22 Immersion of promenade deck, heel 23 deg, time +17 min

At twenty minutes after collision the seawater level reached the embarkation deck and the ship has obtained a large heeling angle of over 30 degrees, Figura 23. Walking on the ship is practically impossible and the majority of the passengers were already off board.

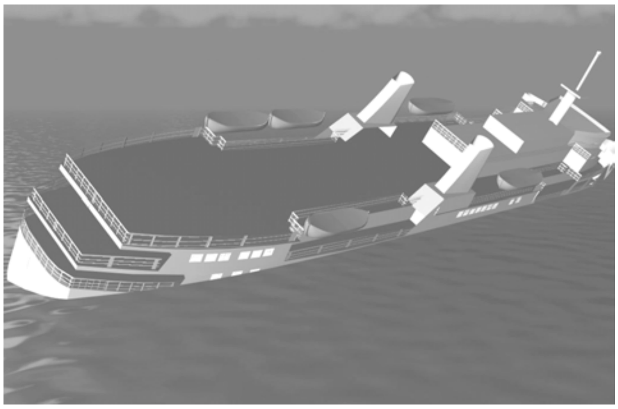

Figure 23 Immersion of embarkation deck, heel 33 deg, time +20 min

After that stage water gradually flooded up the upper spaces until the ship disappeared from the sea surface. It was according to the found bridge wall clock 23:02 local time on September 26, 2000, about fifty-two minutes after the disastrous collision.