Ship Vulnerability Assessment by Forensic Investigation of Critical Damage Scenarios

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ABSTRACT

Forensic level flooding analysis offers the ability to gain a detailed understanding of the manner in which a vessel floods and the mechanisms through which a vessel may be lost. This is made possible through the use of numerical flooding simulations, which provide a wealth of information on the flooding process. However, difficulties arise in processing and handling this information in a manner that allows maximum utility to be gained from the results, without sacrificing time-efficiency. This drives the need to establish a clear and rational methodology for conducting flooding forensic analysis, which forms the focus of this paper. In order to demonstrate the methodology developed, a case study on a large modern cruise vessel is presented. The vessel is subjected to dynamic flooding vulnerability analysis, allowing critical damage scenarios to be identified. These scenarios are then subject to further scrutiny at the forensic level, leading to a comprehensive account of the manner in which the vessel may flood and ultimately be lost. The process culminates in the identification and ranking of critical openings and spaces, providing crucial input in the process of RCO implementation.

Keywords: *Damage Stability, Forensic Flooding Analysis, Passenger Vessel Safety*

1. BACKGROUND

Forensic level flooding analysis is traditionally rooted in accident investigation, where the ability to form a detailed understanding of the flooding process and the causal factors leading to vessel loss is of paramount importance. Pioneering examples of such work include the investigation made by Spouge into the loss of the European Gateway (Spouge 1986), the study performed by Dand following the Herald of Free Enterprise disaster (Dand, 1989), and the accident investigation conducted after the loss of Estonia (JAIC, 1994). Since then, a great deal of process has been made, with more contemporary examples including the work conducted in (Karolius et al., 2020), (Vassalos et al., 2021) and (Valanto, 2023).

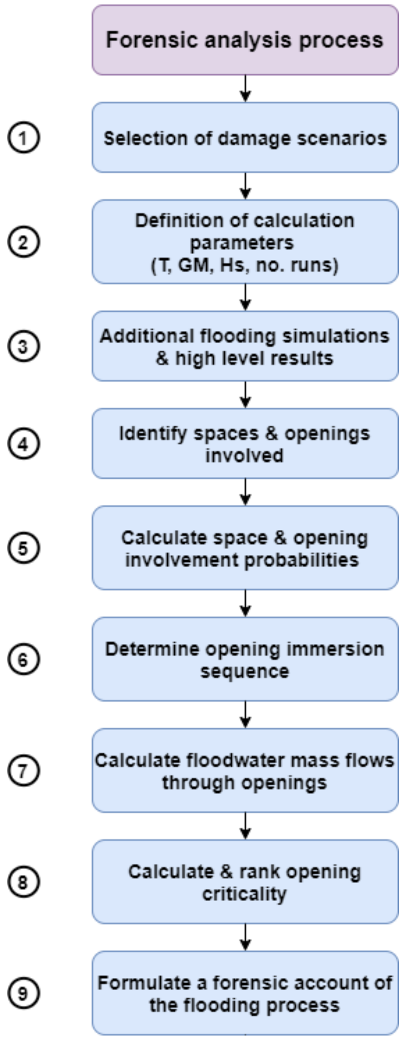
Concurrently, such work has driven the development of advanced flooding simulation tools and tank testing techniques which, unlike hydrostatic analysis, are able to support forensic level analysis. Unfortunately, to date, such tools and techniques have not yet been adopted or utilised in any meaningful way within conventional ship design. Instead, most existing examples of forensic level flooding analysis relate to some form of accident investigation, where the aim is to understand what has gone wrong and why. However, it is the intension of this work to establish a methodology that can be applied during the design phase. As such, the focus shifts from determining what has gone wrong to what could go wrong. This presents a less constrained problem which, in turn, widens the area of investigation. It is here where difficulties can arise in ensuring the forensic analysis process is time-efficient, as one can end up with a lot of ground to cover.

Furthermore, the manner in which floodwater evolves following any given flooding event can be, and often is, a highly complex and stochastic process. This is particularly true in the case of large-scale breaches, where a significant portion of the vessel is affected by damage, thereby broadening the flooding landscape. This, in turn, increases the degree of randomness, complexity, and uncertainty in the flooding process, particularly in higher sea state conditions.

All of the aforementioned can make forensic level flooding analysis a difficult and arduous task. However, as will be demonstrated in this paper, it is possible to approach the analysis in such a way as to streamline the process and provide some clarity amidst the complexity.

2. METHODOLOGY

The methodology that has been developed for forensic level flooding analysis is detailed within Figure 1. In total, the approach consists of 9 distinct stages, which are elaborated upon in the following sections.



Stage 1: Selection of Damage Cases

The objective in conducting forensic level analysis, is to gain a greater understanding of the mechanisms by which a vessel may be lost as a result of flooding. This is generally undertaken with a view to resolving the underlying issues that have led to vessel loss, through the implementation of appropriate RCOs. Given the latter, it is of great importance that the forensic analysis is able to capture and identify as many sources of vulnerability within the vessel design as possible, thus ensuring that the process of implementing RCOs is well informed. In other words, the more information that can be fed into the design process from forensic analysis, the better the outcome is liable to be.

Ideally, forensic level analysis would be conducted with consideration of all loss scenarios identified following any given dynamic flooding vulnerability analysis. However, at present, this is simply not practical due to the time burden such an assessment would entail. Instead, a more efficient process is proposed, whereby a limited number of representative critical damage scenarios are selected for further scrutiny under forensic examination. This is made possible without fear of jeopardising the quality of the analysis as:

- Vulnerability to flooding is not generally found throughout the entire vessel design. Instead, there are typically concentrated areas of vulnerability found in only a handful of locations (generally one or two). In passenger vessels this is normally towards the fore and aft shoulders.
- Damage cases of a given of loss-modality, located around the same region of the vessel, will generally suffer from the same sources of vulnerability.

Given the above, it stands to reason that consideration of representative loss scenarios from areas demonstrating heightened flooding risk, would identify sources of vulnerability common to most, if not all, damage cases affecting that region. Further safeguarding the process, is the fact that the damage stability performance of the vessel is reassessed following the implementation of RCOs, so if any sources of vulnerability were "missed" in the initial forensic assessment, they would be highlighted here as residual loss scenarios.

Stage 2: Definition of Calculation Parameters

In determining the flooding simulation parameters that underpin the forensic analysis, it is important to ensure they reflect the general operation of the vessel and the environmental conditions it is likely to encounter. Only through doing so, can one ensure that all pertinent vulnerabilities are captured by the forensic examination. However, vessels can be subject to a wide range of variations in both loading and environmental conditions, leaving a rather large area to cover. This, in turn, poses problems as regards the time-efficiency of the calculation process and, ultimately, its applicability during the design process.

Ideally, it would be feasible to conduct simulations with respect to an extensive range of operational and environmental conditions, though this is simply not practical at present. Instead, it has been necessary to develop a more limited yet efficient approach, whereby a form of selective sensitivity analysis is conducted on key input parameters. This approach is described within the following:

- **Draft:** Only the vessel subdivision draft is considered within the calculations, as the work conducted within (Paterson et al., 2019), has indicated that passenger vessels operate predominantly towards the upper extremity of their draft range. Furthermore, the subdivision draft typically represents the most vulnerable loading condition, resulting from lower freeboard and reserve buoyancy. Therefore, this assumption is conservative in nature, and of a higher propensity to capture vulnerabilities within the vessel design.
- **Trim:** In line with current SOLAS assumptions, if the service trim of the vessel under subdivision draft conditions does not exceed ±0.5% of L, then a single level trim value should be considered. However, if this is not the case, then consideration should be given to assessing the vessel under service trim conditions.
- **Heel:** Level heel conditions are assumed, as the vessel is typically upright in the intact condition.
- **GM:** Two GM values are considered within the calculations, one reflecting the statutory subdivision draft loading condition, and the other relating to the limiting GM condition. Through doing so, it is possible to assess the vessel in a manner more reflective of its true operation and, also, with respect to the most adverse condition permitted by regulations.
- **No. of Realisations:** As the simulations are conducted within random waves, the manner in which the vessel floods and the final outcome is non-deterministic. For this reason, it is prudent to consider a number of simulations realisations, if one wishes to account for the stochastic nature of the flooding process. To this end, five simulation realisations have been considered for each of the assessed damage scenarios.
- **Vessel Heading:** Two vessel headings are considered (90 deg, 180 deg), such that the approaching wave train is always acting upon the vessel in the beam direction for both port and starboard damages.
- **Exposure Time:** An exposure time of 30 minutes has been considered, which is in line with current SOLAS standards. However, consideration could be given to extending this period for larger passenger vessels.
- **Wave Spectrum:** In selecting an appropriate wave spectrum, one must consider the area of operation of the vessel and the nature of the wave environment. As the vessel under consideration is an internationally operating cruise vessel, the Pierson-Moskowitz Spectrum has been selected. This spectrum assumes a deep sea and a fully developed sea state, which is appropriate for the operational environment of such vessels.
- **Significant Wave Height (Hs):** As the survivability of passenger vessels tends to be largely influenced by significant wave height, a more refined form of sensitivity analysis has been conducted on this parameter. In total, four Hs values have been considered ranging from still water conditions up to Hs = 7 m. This upper limit has been selected on the basis of global wave statistics, which is appropriate given that cruise vessels tend to operate on an international level. However, if the vessel under consideration was known to operate in a particular location, local statistics regarding significant wave height could easily be utilised instead.

Stage 3: Additional Flooding Simulations & High-Level Results

Within this stage, further flooding simulations are conducted on the damage scenarios selected within Stage 1, under the conditions outlined within the previous stage. This serves to provide the simulation results that will ultimately inform the subsequent forensic analysis process.

In addition, a high-level summary of the results is created at this stage, indicating for each damage scenario:

- TTC values for each simulation realisation and Hs condition considered.
- Mean TTC values for each damage scenario, conditional on Hs.
- Capsize probabilities for each damage scenario, conditional on Hs.

Stage 4: Identification of Spaces & Openings Involved

Here, with respect to all simulations conducted, the spaces and openings found to be involved within the flooding chain are catalogued. This is achieved by observing which rooms have been subject to water accumulation at any stage during the simulations, and also by observing which openings have been engaged in the passage of floodwater. By doing so, it is possible to assess:

- The total number of openings and rooms affected by each flooding scenario.
- The demographic of openings and rooms involved, including the total number of openings and rooms affected with respect to type/purpose, and the combined volume of affected rooms according to purpose.
- The location and properties of each room and opening involved.

Stage 5: Calculate Space & Opening Involvement Probabilities

Here, both room and opening involvement probabilities are calculated, which provides an important first indicator of criticality. This is conducted with respect to each damage scenario, accounting for involvement probabilities conditional on Hs, and in overall terms with respect to all simulated cases (mean values). The involvement probabilities are calculated by assessing the frequency with which a given opening or room was found to be involved with respect to the total number of simulation realisations. For example, if a certain opening featured in 3 out of 5 simulations, then the involvement probability would be 0.6 or 60%. The mean involvement probabilities have then been calculated with respect to all four of the Hs conditions assessed.

Further analysis conducted at this stage also includes the following:

- Investigating the number of openings/rooms found to have an involvement probability of 1, relative to the total number involved. This provides an indication of the degree of randomness present within the flooding process, with fewer openings/rooms possessing an involvement probability of 1 indicating a higher degree of randomness within the process.
- Analysing the impact of Hs on the number of openings/rooms with involvement probabilities of 1, allowing the influence of sea state on the degree of randomness within the flooding process to be observed.
- Determining the manner in which Hs impacts the total number of openings/rooms involved, and thus the scale and complexity of the floodwater evolution.

In the case of rooms, a further step is taken in which a heatmap is created, indicating each rooms respective involvement probability. An example of this diagram is provided in Figure 2**Hata! Başvuru kaynağı bulunamadı.**, where breached rooms are indicated in red, and progressively flooded spaces are colour coded in accordance with the probability scale shown at the bottom.

Such analysis can be highly useful in gaining a greater understanding of the nature and severity of the flooding process, in a format where this information is easily digestible.

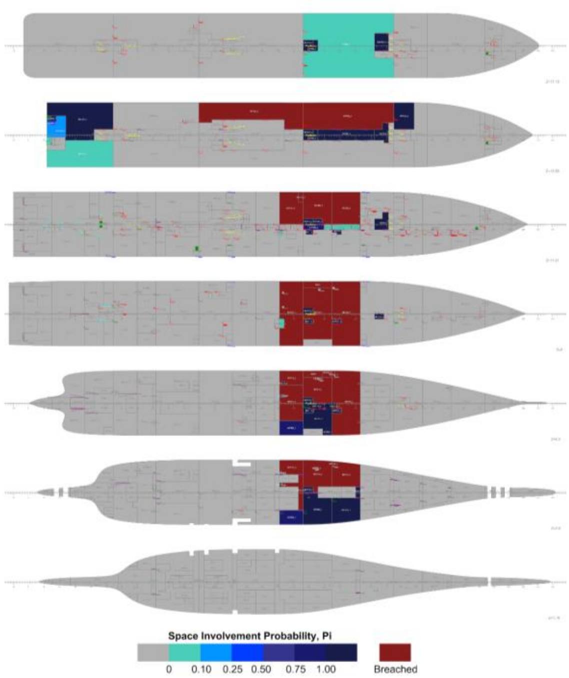


Figure 2: Example room involvement probability heat map

Stage 6: Determine Opening Immersion Sequence

At this stage, the flooding chain is evaluated by examining the immersion time of each opening, i.e., the point at which floodwater initially begins to flow through an opening. This provides important information on the sequence in which the vessel floods, and also provides useful input as regards the implementation of RCOs which may be time sensitive. The opening immersion sequence is generated for each flooding scenario, firstly with respect to Hs, and secondly in average terms. Following this process, all openings are then ranked in relation to the immediacy of their immersion.

Stage 6: Calculate Floodwater Mass Flows Through Openings

Within this stage the net floodwater mass flowing through each opening is calculated, providing a second important indicator of opening criticality. The simulation results provide values relating to the floodwater mass transferred through each open for every time step, with inflow indicated by positive mass values, and outflow negative values. From this, the total floodwater mass flowing through each opening is calculated by summing up the floodwater mass values relating to each time step. This is conducted for individual damage scenarios, producing opening-specific floodwater mass quantities for each simulation realisation. From these, average mass values are then calculated with respect to each Hs condition, in addition to a global average value, derived with respect to all cases assessed. Openings have then been ranked in accordance with the average magnitude of floodwater found to pass through each.

Stage 7: Calculate and Rank Opening Criticality

During this stage opening criticality is determined on the basis of the involvement probability and net floodwater mass flow values associated with each opening. Specifically, the product of these two values is calculated in order to determine opening risk. The logic behind this approach is that likelihood will be captured by involvement probability, and consequence by the net floodwater mass passing through each opening, meaning that the product of these two values should provide some indication of risk.

Further analysis conducted at this stage include:

- Assessment of the distribution of risk across all openings involved.
- Assessment of risk by opening type.

Stage 8: Formulate A Detailed Forensic Account of Flooding

The final stage in the methodology involves the creation of a detail forensic account the manner in which the vessel floods. As part of this process, all elements of the previously conducted analysis are combined in order to give a complete picture of the flooding process for each damage case. The results are presented in the form of a general arrangement plot, Figure 3, which indicates various key components of the results in different ways. Specifically, the following is included:

- Information bubbles for each opening, colour coded in accordance with the magnitude of floodwater mass found to flow through each. In addition, the information bubbles indicate the opening ID, mean involvement probability and mean time of immersion.
- Initially breached compartments plotted in red.
- Progressively flooded compartments are coloured in accordance with their involvement probability.
- Unaffected compartments coloured in grey.
- The damage breach extent, including fore and aft extremities, in addition to damage length.

The impetus behind presenting the results in this fashion derives from the need to make the results easily interpretable, allowing the designer to gain a greater understanding of the flooding process in a time-efficient manner. In particular, such plots enable rapid assessment of the manner in which the vessel floods, while also indicating the causal factors leading to vessel loss. This, in turn, provides an indication which areas should be targeted for RCO implementation.

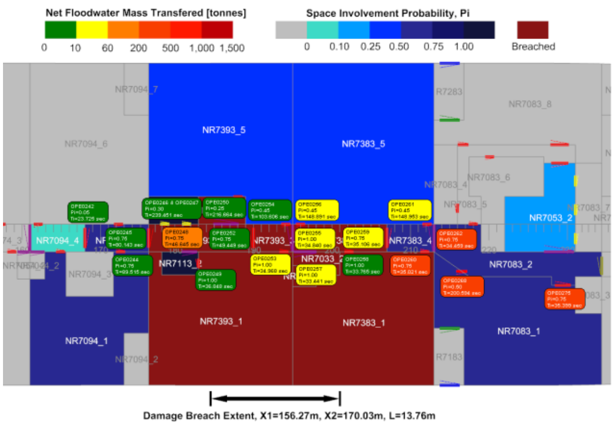


Figure 3: Example forensic analysis plot (bulkhead deck)

3. CALCULATION PARAMETERS

Within this section an overview of the calculation parameters and key inputs is provided.

3.1 Vessel Properties

The vessel under consideration, is a large cruise vessel with main particulars as specified in **Hata! Başvuru kaynağı bulunamadı.**. In addition, the internal ship arrangement is presented in **Hata! Başvuru kaynağı bulunamadı.**.

Table 1: Ship particulars

Parameter	Value
Length overall (LOA)	≃300 m
Length between perpendiculars	270.00 m
Subdivision Length	296.74 m
Beam (B)	35.20 m
Subdivision draft (HSD)	8.20 m
Height of the main deck	11.00 m
Number of Passengers	2,750
Number of Crew	1,000
Gross tonnage	95,900
Deadweight	8,500 t
No. of pax cabins	1,270

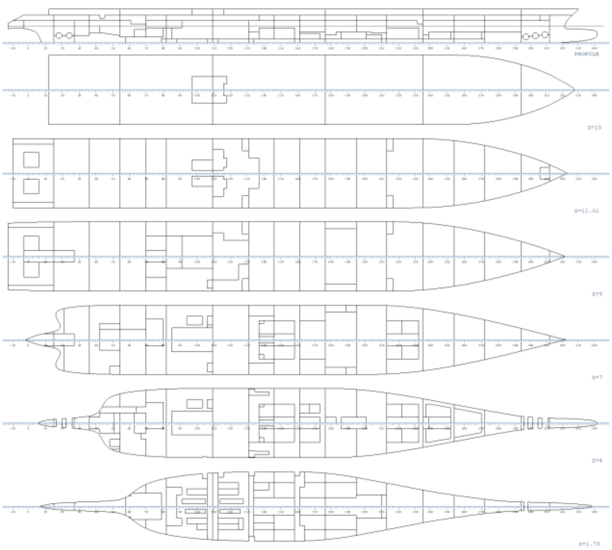


Figure 4: Vessel General Arrangement

3.2 Simulation Properties

An overview of the conditions evaluated in the flooding simulations is provided in **Hata! Başvuru kaynağı bulunamadı.**.

Table 2: Simulation input parameters

Parameter	Assumptions
Draft (m)	8.2
Trim (m)	0
Heel (deg)	0
GM (m)	2.114, 2.802
No. of Realisations (-)	5
Heading (deg)	90/270 (beam seas)
Exposure Time (min)	30
Wave Spectrum (-)	Pierson-Moskowitz
Hs (m)	(0, 2, 4, 7)

3.3 Damage Selection

In order to select the damage scenarios to be considered as part of this assessment, the results of an initial dynamic vulnerability screening have been used to inform the process. The results of this initial assessment are provided within Figure 5 and Figure 6, showing all loss scenarios and indicating their location, damage length, centre, and loss modality. From these results, two clear areas of concentrated loss scenarios can be identified towards the vessel fore and aft shoulders. In light of this, cases have been selected from these two areas, including examples of transient capsize and progressive flooding loss from each.

Furthermore, two criteria failing cases have also been selected in these areas, including one case failing ITTC capsize criterion and another failing the SOLAS final floating position heel criterion.

Within the figures, the selected cases are highlighted in red circles.

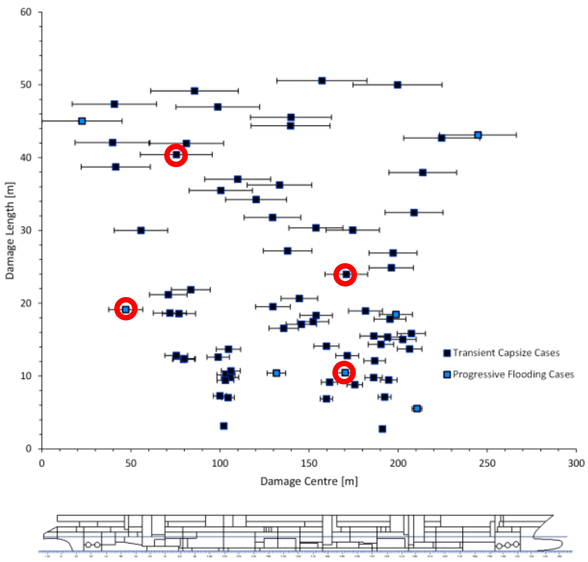


Figure 5: Transient & Progressive Flooding Capsize Cases

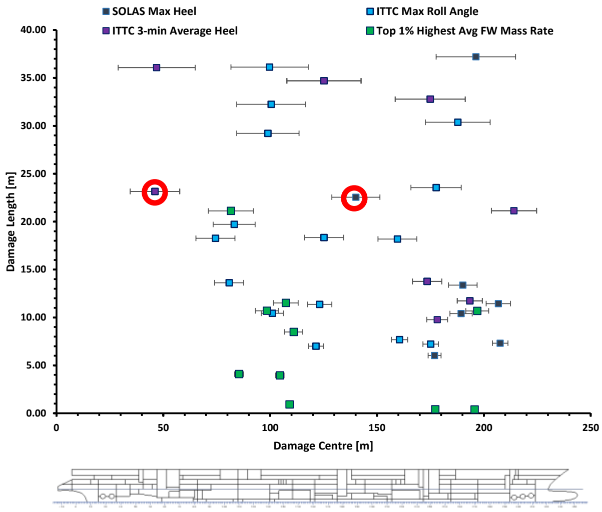


Figure 6: Criteria Failing Cases

It should be noted, that while the six scenarios have been selected and analysed as part of this study, for the sake of brevity only one transient and progressive flooding loss scenario are elaborated upon within this paper.

4. TRANSIENT CAPSIZE CASE

4.1 Description of Damage Case

The first case considered is a transient capsize scenario located on the vessel fore shoulder, see Figure 7. The breach is situated across two transverse bulkheads, thus affecting three compartments. The resultant damage is asymmetric in nature, which is exacerbated further as the three lower affected spaces each have restricted transverse channels connecting port and starboard sides. The vertical extent of the damage lies above the double bottom and extends to Deck 05 (one deck below the uppermost deck modelled).

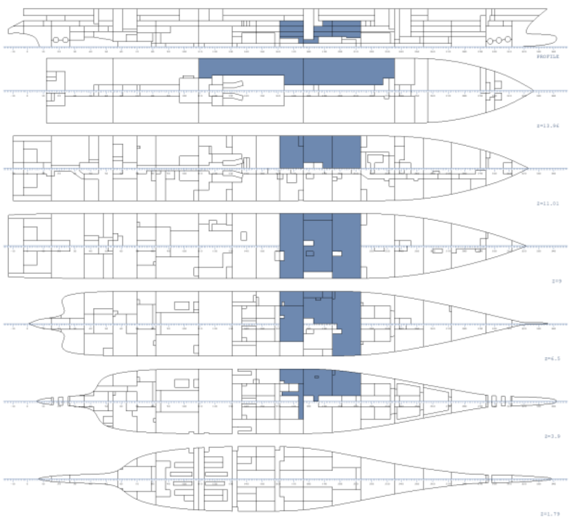


Figure 7: Transient capsize, initial breach plot

4.2 Additional Simulation High-Level Results

This section provides a summary of the additional flooding simulation that have been conducted on the damage case in question, under the conditions outlined within section 3. As no capsize scenarios were witnessed under the higher GM condition, only results pertaining to the lower GM simulations are presented. The results are provided within Table 3, indicating TTC values relating to each significant wave height (Hs) and simulation realization, along with mean TTC values and the resultant capsize probability.

Table 3: High-level results of additional simulations

	DMC0671 - Transient Capsize Case			
	TTC [sec]			
Realisation	Hs=7 m	Hs=4 m	Hs=2 m	Hs=0 m
1	47.8	60.3	67.3	52.5
2	64.2	63.6	67	52.5
3	53.4	63.6	70.8	52.5
4	48.7	61.3	67.9	52.5
5	64	64.1	68.6	52.5
Mean TTC [sec]	**55.6**	**62.6**	**68.3**	**52.5**
Pc [-]	**1**	**1**	**1**	**1**

4.3 Opening Involvement Probability

The results relating to the calculation of opening involvement probability are provided in Figure 8. From this, the following observations can be made:

- 61 openings (75%) were found to have an involvement probability of 1.00, with the remaining 20 openings (25%) having probabilities ranging from 0.05-0.95. This indicates only a marginal degree of randomness within the flooding process which is to be expected when considering a transient capsize case.
- To determine the effect of significant wave height on the degree randomness observed within the flooding process, the percentage of openings found to have involvement probabilities of 1.00 with respect to each significant wave height has been calculated, resulting in the following:
  - Hs=7m, 80% openings
  - Hs=4m, 87% openings
  - Hs=2m, 88% openings

- Hs=0m, 100% openings

These findings serve to demonstrate the tendency of increasing Hs to lead to a greater degree of randomness within the flooding process.

- An additional study has been performed looking into the impact of HS on the number of openings found to be involved within the flooding chain. As one would expect, there is a tendency for an increased number of openings to be involved at higher sea states, as shown in the following:
  - Hs=7m, 77 openings
  - Hs=4m, 76 openings
  - Hs=2m, 77 openings
  - Hs=0m, 67 openings

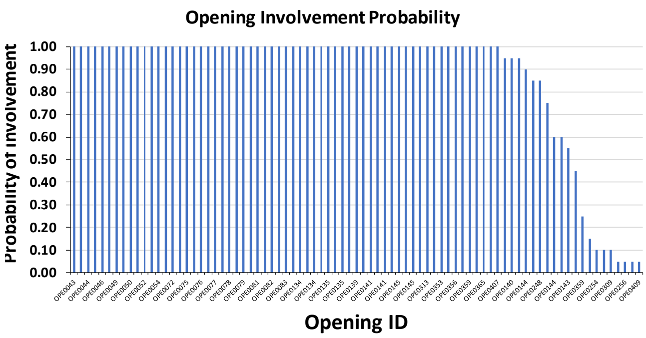


Figure 8: Opening involvement probabilities

4.4 Opening Immersion Time

The calculated opening immersion times are provided in Figure 9 and serve to indicate the flooding sequence. As can be observed, all openings involved are subject to rapid immersion (within 80 seconds or breach opening), which is typical of a transient capsize case.

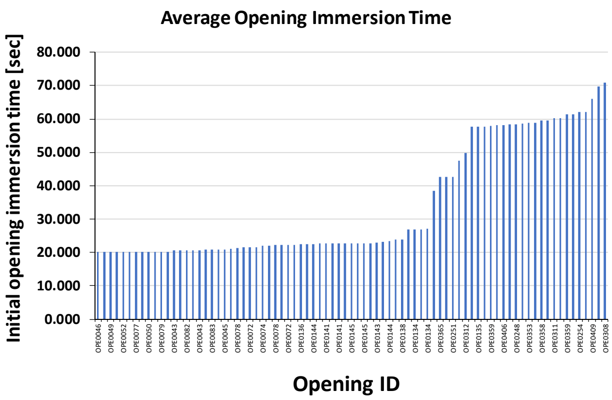


Figure 9: Opening immersion times

4.5 Net Floodwater Mass Flow Through Openings

The calculated net floodwater mass flow through each opening involved within the flooding sequence is provided within Figure 10. From these results the following high-level observations can be made:

- A total of 51 openings (63%) were found to have flood water mass flows less than 1 tonne.
- Furthermore, of the 81 openings involved, on average just 18 openings (22%) were found experience floodwater mass flows greater than 10 tonnes.
- In fact, it was found that the top 1% of highest ranked openings are responsible for a greater floodwater mass flow than all the remaining openings combined. This would indicate that there are only a limited number of openings that significantly contributing to the flooding process.

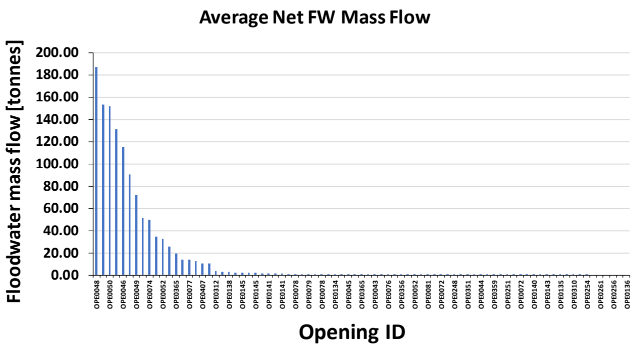


Figure 10: Net floodwater mass flows through openings

4.6 Room Involvement Probability

The calculated room involvement probabilities for the case in question are provided within Figure 11, leading to the following observations:

- Of the 28 rooms found to be affected, 17 (60%) were found to have an involvement probability of 1.00, indicating on a marginal degree of randomness within the flooding process.
- The remaining 11 rooms (40%) were found to have involvement probabilities ranging from 0.05-0.95.
- A to be expected, a tendency for a greater number of rooms to be involved at higher sea states was observed, as demonstrated in the following:

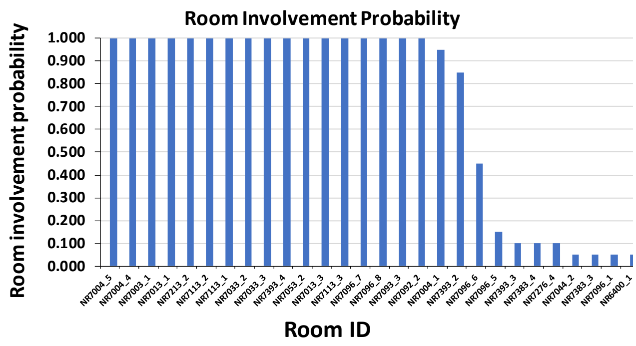


Figure 11: Room involvement probabilities

In addition, a heat map of the room involvement probabilities calculated across all case-specific simulations is provided within Figure 12**Hata! Başvuru kaynağı bulunamadı.**. Here, It can be observed that the flooding process is for the most part deterministic as far a room involvement is concerned. Only a limited degree of randomness has been observed within the flooding process, resulting from rare occurrences of progressive flooding in the aft of the vessel and up-flooding to Deck 06.

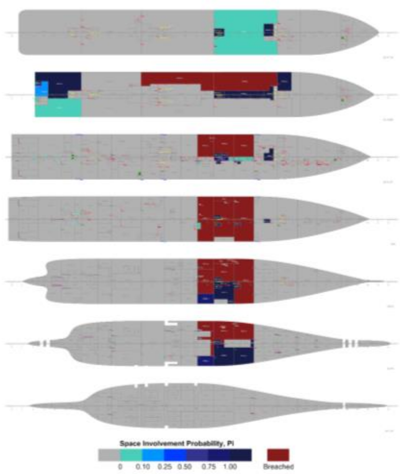


Figure 12: Room involvement probability heat map

4.7 Ranking of Openings by Criticality

The final opening criticality ranking, made on the basis of both involvement probability and the floodwater mass flow through each opening, is provided within Figure 13. Furthermore, information relating to the top ten highest risk openings is provided within Table 4. Based on these results, the following observations can be made:

- The top 5% most critical openings possess a higher combined risk than all other openings combined. This indicates that despite a rather large numbner of openings being involved, only a select few lead to significant flooding progression.
- The risk contribution deriving from each opening type has also been calculated as a percentage of the total risk, leading to the following results:
  - Holes: 58%
  - Hinged Double Fire Doors: 13%
  - Hinged Escape Doors: 11%
  - Sliding Lift Doors: 10%
  - Hinged Weathertight Doors: 3%
  - Hinged Fire Doors: 2.8%
  - Escape Hatches: 1%

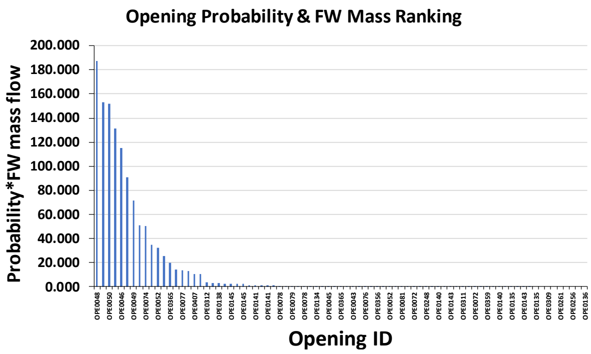


Figure 13: Opening criticality ranking

Table 4: Top ten highest criticality openings

Unique OPE ID	Opening Type	Immersion Time [sec]	Probability Pi	Net FW Mass Flow [tonnes]	Pi*FWM
56	Hole	20.287	1.00	187.078	187.078
64	Hole	20.289	1.00	153.005	153.005
59	Hole	20.289	1.00	151.764	151.764
96	Hinged Double Fire Door	20.289	1.00	131.446	131.446
54	Hole	20.284	1.00	115.317	115.317
63	Hole	20.608	1.00	90.719	90.719
57	Hinged Escape Door	20.284	1.00	71.657	71.657
89	Sliding Lift Door	22.087	1.00	51.166	51.166
88	Sliding Lift Door	22.064	1.00	50.115	50.115
489	Hinged Weathertight Door	38.508	1.00	34.676	34.676

4.8 Detailed Forensic Account of Flooding

The final stage in the process is to combine all the information previously outlined, in order to build up a clear picture of the way in the vessel may flood when subject to the damage scenario in question. As detailed within the methodology, this is achieved through the creation of a forensic level flooding diagram. To provide a flavour of the information one can readily deduce from such a diagram, a single deck example is provided within Figure 14, followed by the observations that can be made on the basis of this diagram.

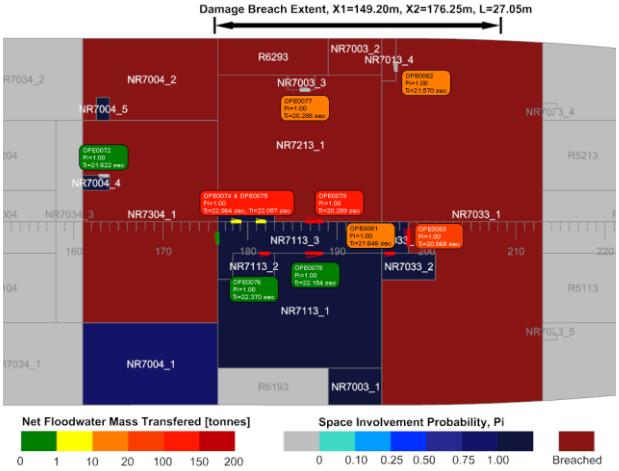


Figure 14: Forensic level flooding diagram

Observations:

- On Deck 02, floodwater almost immediately begins to equalise within the mid affected compartment, flowing transversely through double fire doors OPE0079 and OPE0078. However, the degree of floodwater delivered to NR7113_1 on the starboard side is minimal (< 1 tonne), indicating asymmetry within the flooding process.
- There are also signs of moderate up-flooding through openings OPE0074 & OPE0075, through the lift trunk NR7213_2.
- Further progressive flooding can be observed in the fore affected compartment through the double fire door OPE0083 and into stairwell NR7033_2 via OPE0081, however this is in fairly mild quantities (<20 tonnes)
- Within the aft breach compartment only minimal up-flooding can be observed through the escape trunk OPE0072 (< 1 tonne).

5. PROGRESSIVE FLOODING SCENARIO

5.1 Description of Damage Case

The damage case under consideration is a progressive flooding loss scenario, located on the vessel fore shoulder, as shown in Figure 15. The breach is situated across a single transverse bulkhead, thus affecting two compartments. The vertical extent of the damage is significant and ranges from a position just below Deck 02 up until the uppermost deck.

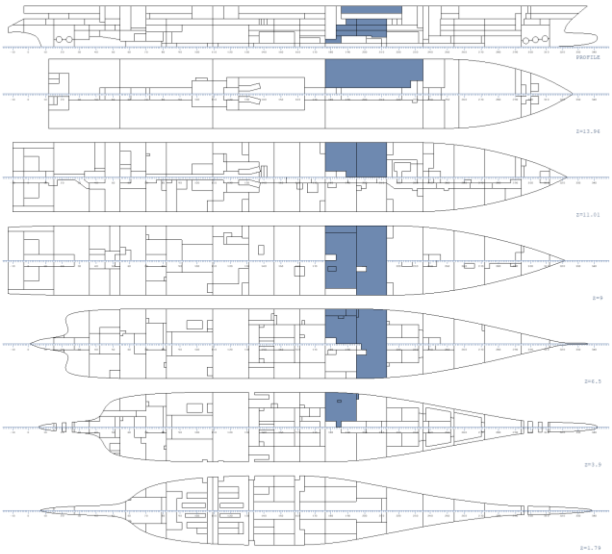


Figure 15: Prgressive flooding loss, initial breach plot

5.2 Additional Simulation High-Level Results

This section provides a summary of the additional flooding simulation that have been conducted on the damage case in question, under the conditions outlined within section 3. As no capsize scenarios were witnessed under the higher GM condition, only results pertaining to the lower GM simulations are presented. The results are provided within Table 3, indicating TTC values relating to each significant wave height (Hs) and simulation realization, along with mean TTC values and the resultant capsize probability.

Table 5: High-level results of additional simulations

Realisation	DMC0671 - Transient Capsize Case			
	TTC [sec]			
	Hs= 7 m	Hs= 4 m	Hs= 2 m	Hs= 0 m
1	708.1	1658.1	1820	1820
2	678.3	1384	1820	1820
3	797.1	1551.2	1820	1820
4	657.1	1587	1820	1820
5	830	1288.3	1820	1820
Mean TTC [sec]	**734.1**	**1493.7**	**N/A**	**N/A**
Pc [-]	**1**	**1**	**0**	**0**

5.3 Opening & Room Involvement

The following provides a summary of the openings and rooms found to be involved within the flooding sequences analysed. In total, 160 openings affecting 58 rooms were identified across all simulations conducted.

A short summary of the demographic of spaces involved is provided within the following:

- 35 crew spaces, totalling 9,873 m³ in volume.
- 12 passenger spaces, totalling 12,717 m³ in volume.
- 6 technical spaces, totalling 3,129 m³ in volume.
- 3 engine spaces, totalling 1,207 m³ in volume.
- 2 store spaces, totalling 44 m³ in volume.

In addition, a short summary of the opening types involved and their quantity is provided within the following:

- 34 hinged fire doors and 42 gaps.
- 21 holes
- 12 escape hatches (comprised of 4 openings each)
- 10 sliding lift doors
- 10 hinged double fire doors and 11 gaps.
- 5 hinged escape doors and gaps
- 4 hinged weathertight doors
- 3 sliding fire doors and gaps
- 5 sliding cold room doors

Of the openings involved 59 (37%) were found to lie below the bulkhead deck and 101 (63%) above. This is typical of a progressive flooding scenario, where floodwater tends to predominantly propagate along the bulkhead deck.

5.4 Opening Involvement Probability

Figure 15 summarises the calculated opening involvement probabilities. On the basis of these results, the following observations can be made:

- 36 openings (23%) were found to have an involvement probability of 1.00, with the remaining 124 openings (77%) having involvement probabilities ranging from 0.05-0.90, indicating a large degree of randomness in the flooding process.
- Generally speaking, it was observed that the number of openings involved within the flooding sequence increases with respect to significant wave height. For example, simulations at Hs=7 m were found to have four times as many openings involved relative to Hs=0m, thus signalling the importance of accounting for variations in sea state.

- To determine the effect of significant wave height on the degree randomness observed within the flooding process, the percentage of openings found to have involvement probabilities of 1.00 with respect to each significant wave height has been calculated, resulting in the following:
  - Hs=0m, 100%,
  - Hs=2m, 98%,
  - Hs=4m, 95%,
  - Hs=7m, 33%

  The above indicates that as sea states rises, so too does the randomness observed within the flooding sequence. In this instance, the impact is only slight in conditions up to Hs=4 m. However, there is a substantial increase in randomness under Hs=7 m conditions, with 67% of openings found to have involvement probabilities <1.00.

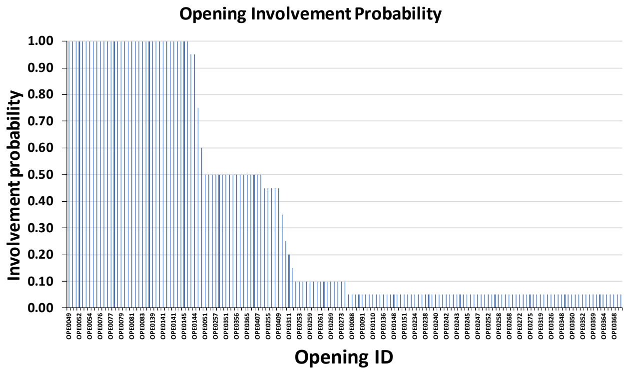


Figure 15: Opening Involvement Probabilities

5.5 Opening Immersion Time

The average opening immersion times, calculated in accordance with all simulated cases, is provided within Figure 16. This serves to illustrate the flooding sequence. On the basis of these results, the following observations can be made:

- On average, 125 openings (78%) were found to be immersed within the transient phase.
- The remaining 35 openings (22%) were immersed in the progressive flooding stage, with the last opening immersed following 24 minutes.

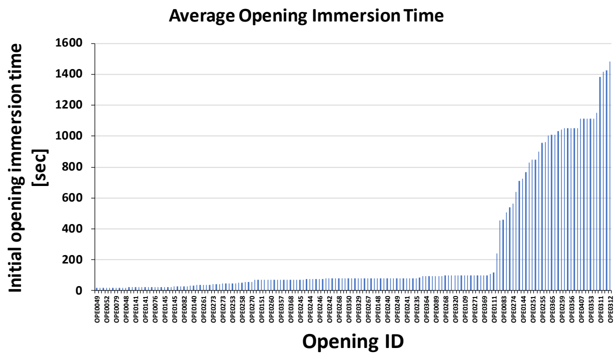


Figure 16: Opening Involvement Probabilities

5.6 Net Floodwater Mass Flow Through Openings

The calculated average net floodwater mass flow through each opening is presented within Figure 17. On the basis of these results, the following remarks can be made:

- Of the 160 openings involved, on average just 31 openings (19%) were found experience floodwater mass flows greater than 10 tonnes.
- Furthermore, 112 openings (70%) were found to have flood water mass flow rates less than 1 tonne. This demonstrates that, despite what can appear as a highly complex flooding event, there often exist only a limited number of openings that play a significant role in the flooding process.
- To further illustrate the above point, the top 5 highest ranked openings, out of the 160 found to be involved within the flooding sequence, are responsible for 60% of the total progressive floodwater mass.

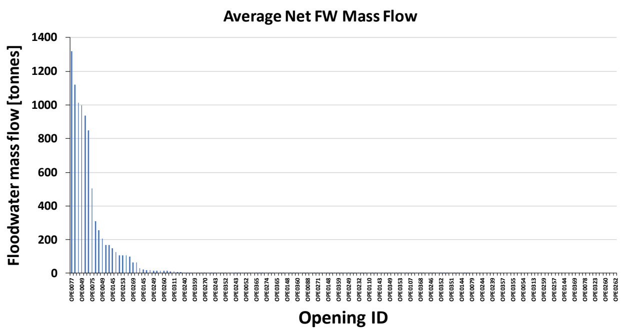


Figure 17: Opening Involvement Probabilities

5.7 Room Involvement Probability

The calculated room involvement probabilities are provided within Figure 18, from which the following observations can be made:

- Of the 58 rooms found to be affected, just 10 (17%) were found to have an involvement probability of 1.00.

- The remaining 48 rooms (83%) were found to have involvement probabilities ranging from 0.05-0.50. This is indicative of a large degree of randomness within the flooding process, which is to be expected from a progressive flooding scenario in a complex vessel.
- As in the previously examined cases, a tendency for a greater number of rooms to be involved at higher sea states was observed, as detailed in the following:
  - Hs=7m, 58 rooms
  - Hs=4m, 23 rooms
  - Hs=2m, 10 rooms
  - Hs=0m, 10 rooms

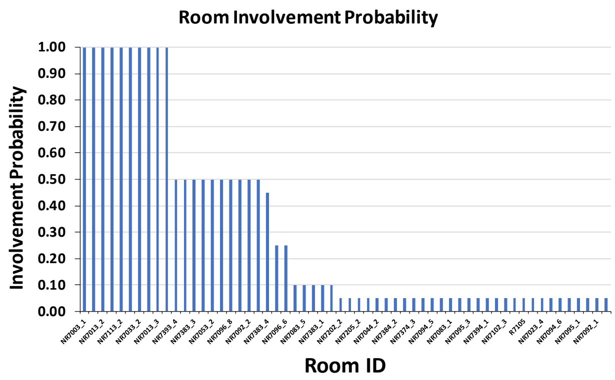


Figure 18: Room involvement probabilities

In addition, a heat map of the room involvement probabilities calculated across all case-specific simulations is provided within Figure 19**Hata! Başvuru kaynağı bulunamadı.**, where several instances of widespread progressive flooding can be observed.

This works to illustrate the potential scale of floodwater dispersion throughout the vessel, particularly when the upper decks become involved in the flooding sequence, where watertight integrity is marginal. Fortunatley, such widespread flooding was only realised in 5% of cases, though there are still signs of significant progressive flooding occurring within the upper decks in up to 50% of cases.

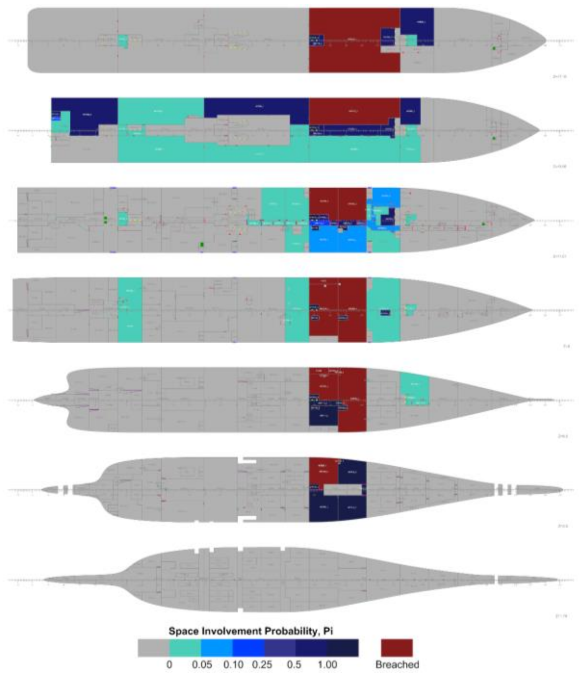


Figure 19: Room involvement probability heat map

5.8 Ranking of Openings by Criticality

As in the previous example, a final ranking of opening criticality has been made on the basis of involvement probability and floodwater mass flow. The results of this process are summarised within Figure 19. Furthermore, information relating to the top ten highest risk openings is provided within Table 6. Based on these findings, the following observations can be made:

- The upper 1% of critical openings are responsible for 28% of the risk, with the top 5% of critical openings representing 80% of the risk. This again serves to indicate that only a handful of openings hold a significant bearing on the severity of flooding.
- Once again, the risk contribution deriving from each opening type has also been calculated as a percentage of the total risk, leading to the following results:
  - Holes: 46%
  - Hinged Escape Doors: 29%
  - Hinged Double Fire Doors: 11%
  - Sliding Lift Doors: 5%
  - Escape Hatches: 5%
  - Hinged Fire Doors: 2%

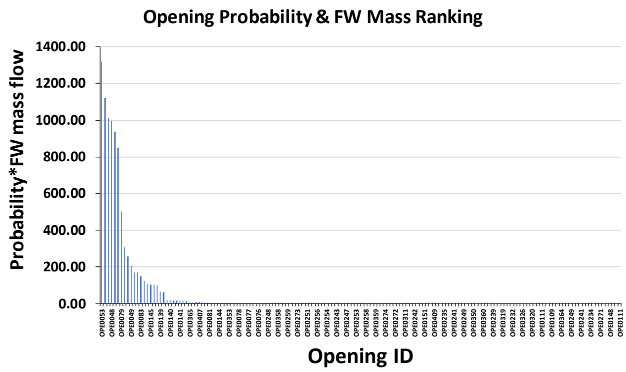


Figure 19: Opening criticality ranking

Table 6: Top ten highest criticality openings

Unique OPE ID	Opening Type	Immersion Time [sec]	Probability Pi	Net FW Mass Flow [tonnes]	Pi*FWM
63	Hole	55.689	1	1318.561	1318.56
61	Hinged Escape Door	20.291	1	1122.000	1122.00
101	Hinged Escape Door	28.014	1	1014.755	1014.76
56	Hole	20.411	1	997.709	997.71
64	Hole	30.622	1	937.870	937.87
59	Hole	20.408	1	849.185	849.18
96	Hinged Double Fire Door	20.339	1	503.990	503.99
94	Hinged Double Fire Door	24.608	1	308.092	308.09
92	Hinged Escape Door	20.342	1	255.418	255.42
57	Hinged Escape Door	20.284	1	205.609	205.61

5.9 Detailed Forensic Account of Flooding

As was conducted in the previous example, a detailed forensic account of the flooding process has been generated in graphical form. An example of the results of this process is provided for a single deck in Figure 20, followed by the observations that can be made.

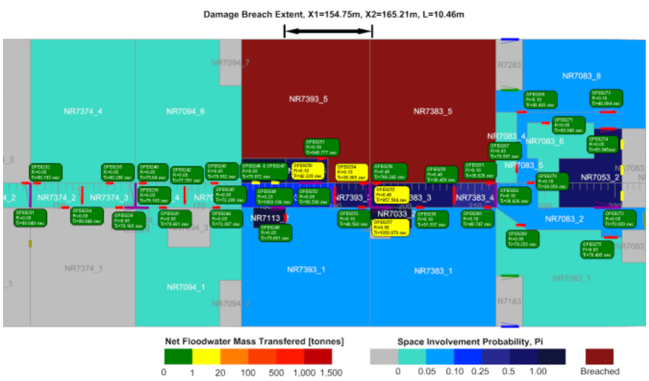


Figure 20: Forensic level flooding diagram

Observations:

- On Deck 04 the most widespread progressive flooding was observed which is typical given that there is generally a reduction in internal watertight integrity beyond the bulkhead deck, as the internal geometry begins to open up.
- However, it is interesting to note that the magnitude of progressive flooding and associated frequency of occurrence are both considerably low.
- The primary conduit for progressive flooding in this case is the service corridor, which allows floodwater to pass both forward and aft of the breached area and into several surrounding spaces. However, the mass of floodwater engaged in this progressive flooding was identified as less than 1 tonne on average. Furthermore, this occurred in only 10% of cases in relation to fore progressive flooding and in just 5% of cases regarding aft progressive flooding.
- Also present here are several signs of up-flooding, most significantly through stairwell NR7033_2 and opening OPE0257.
- Other examples of up-flooding include stairwell NR7113_2 and lift trunk NR7213_2, where negligible quantities of floodwater progression were identified (<1 tonne).

6. POST PROCESSING RESULTS FOR RCO IMPLEMENTATION

Ranking openings in terms of criticality provides an indication of which should be targeted for the implementation of RCOs. However, the question remains as to how many openings should be considered. In order to answer this, the cumulative opening risk has been evaluated as a function of the number of openings considered, as shown in Figure 21. This enables the point of diminishing returns to be identified, which represents the optimal number of openings to be considered for additional protection. This process is based on the combined results from all damage scenarios considered, in order to provide the overall optimal number of openings to be considered. The results of this process have indicated that the top 40 highest risk openings should be considered, though further filtering is required, as described in the following section.

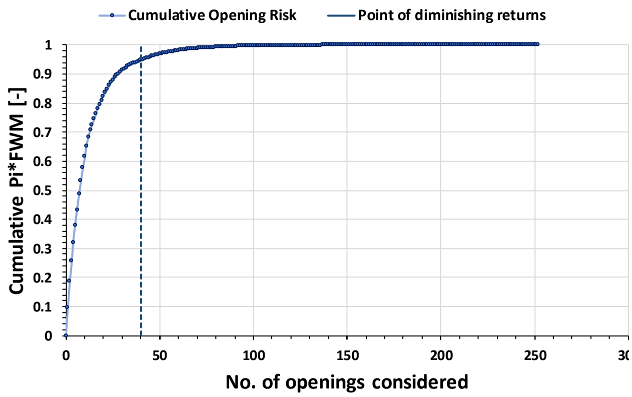


Figure 21: Cumulative Opening Risk

The final stage in the process is to filter out those openings engaged in positive forms of progressive flooding e.g., cross-flooding. Conducting this process leads to just 20 openings that should be considered for additional flooding protection through the implementation of suitable RCOs, see Table 7.

Table 7: Filtered critical openings to be considered for RCOs

OPE ID	Opening Type	Pi*FWM	Flooding Type
61	Hinged Escape Door	379.07	Up/Downflooding
24	Hinged Escape Door	103.97	Up/Downflooding
148	Hinged Escape Door	90.71	Up/Downflooding
103	Hinged Double Fire Door	86.68	Prog. flooding
90	Hinged Fire Door	76.36	Up/Downflooding
406	Hole	66.8	Prog. flooding
295	Hinged Escape Door	46.94	Up/Downflooding
484	Hinged Weathertight Door	31.49	Prog. flooding
403	Hinged Fire Door	30.82	Prog. flooding
426	Hinged Double Fire Door	28.3	Prog. flooding
402	Hinged Fire Door	28.06	Progressive flooding
204	Hinged Fire Door	26.24	Up/Downflooding
21	Hinged Escape Door	24.92	Up/Downflooding
382	Hole	20.58	Up/Downflooding
102	Hinged Escape Door	19.59	Up/Downflooding
413	Sliding Fire Door	18.74	Prog. flooding
400	Hinged Double Fire Door	17.29	Prog. flooding
563	Hinged Fire Door	14.13	Prog. flooding
77	Hinged Escape Door	11.89	Up/Downflooding
489	Hinged Weathertight Door	11.79	Prog. flooding

7. CONCLUSIONS

On the basis of the results presented in this paper, the following conclusions and recommendations can be made:

- A methodology has been developed, allowing one to obtain a detailed and comprehensive account of the manner in which the vessel may be lost due to flooding.
- The methodology created allows openings and rooms to be ranked in terms of involvement probability, immersion time, floodwater mass flow, and finally the risk they pose to flooding.
- It has be observed that of all rooms and openings within the vessel, only a limited number pose significant risk. As such, the results of the forensic analysis can be distilled in order to isolate only a handful of the most critical openings/rooms to be targeted for application of RCOs.
- It has been observed that higher Hs values, lead to a greater degree of complexity and randomness within the flooding sequence.
- No capsize scenarios were observed for the vessel under consideration with respect to operational GM values, as such it has been necessary to explore reduced GM values in order to produce capsize scenarios to inform the analysis undertaken.

- A process has been developed in order to create a detailed account of the flooding process at the forensic level, with recommendations made on how best to convey the results of the analysis, such that they are easily digested by the designer.
- Looking forward, further automation within the process would help aid in time-efficiency and the scale at which the analysis can be conducted.

8. REFERENCES

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