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Decision Making in Uncertainty: The Case of Ship Flooding

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ABSTRACT

One critical aspect of a progressive flooding scenario on a ship is that its crew is uncertain regarding the water ingress rate. Furthermore, the calculation of residual ship stability and structural strength may be very challenging in the absence of ship-specific software. For this reason, this paper presents a decision-making methodology to deal with the option of an early abandoning of a bulk carrier in a flooding emergency. This study used a review of 25 cases from 15 years involving bulk carriers for hazard analysis. Then, a simulation was carried to four ships to identify the changes caused by progressive flooding of various cargo holds in the ship's trim, allowable strength and the time allowable to react. The importance of the ballast pump and water ingress alarm maintenance was also shown. The methodology is useful for ship operators to prepare ship-specific flooding contingency plans for crew familiarization in dealing with uncertain conditions.

1. Introduction.

Flooding of a ship is one of the most catastrophic scenarios a ship crew may experience. Despite new ship designs, it appears to be a significant maritime peril. In a similar study, an examination of EU data in the period 2014-2021 showed that 5.7% of injuries mainly occurred during flooding/foundering (EMSA 2022). Other risks in case flooding of a vessel occurs in a port or a canal where limited resources or repair facilities exist, both ship and port may be subject to commercial damages due to delays. The risk of pollution also applies to most cargo onboard ships.

The flooding may result from other emergencies, such as grounding and collision (Eliopoulou et al., 2023). From 2011-2020, grounding was one of the most common causes of bulk carrier casualties, of which 11.8% led to flooding resulting in 4 losses of life (Nwigwe and Kiyokazu, 2022). There are some critical points to consider when flooding initiates on a ship. The first is the flooding progress that will impact the loss of stability and structural strength. The ship's exposure to severe weather conditions will negatively affect flooding and cause sloshing in the cargo hold (Gao et al., 2011). If a bulk carrier is loaded, the cargo material may affect water ingress depending on its permeability. Experimental studies have shown the significance of permeable volume in flooding scenarios (Vassalos et al., 2022). This permeability is considered for damage stability per rules, typically 0.7 for dry cargo space (Prabu et al., 2020). However, it is common for bulk carriers to sail with empty cargo holds, making them riskier than other types of ships if flooding occurs. (Gao et al., 2011).

During a flooding emergency, the master must make difficult decisions that seriously impact passenger and crew safety (Braidotti and Mauro, 2019). One of the options is to abandon the ship. There are many factors to consider when deciding to abandon a ship. Some include the weather, the proximity of the ship to other ships or ports, and the availability and maintenance of equipment. Current regulations require ships to have a Shipboard Marine Pollution Emergency Plan (SOPEP) dealing with ship emergencies (Kayisoglu et al., 2022). However, although SOPEP includes flooding, it refers to it as a static condition and does not consider the dynamics of an environment, particularly the time constraints (Karahalios, 2017). IMO (2004) has issued guidance for abandoning bulk carriers, as shown in Table 1. Among the issues dealing with the guide, trim and freeboard changes are mentioned, although they are difficult to

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be assessed.

Within this context, the aim of this paper is to provide a decision-making methodology to reveal thresholds in a ship flooding scenario. In this section, it is explained the necessity to research flooding risk and its consequences, especially for the loss of life. Therefore, the methodology is presented in the following third section and the justification for its choice. Then, in section 4, data analysis is presented, demonstrating the application of the method in four ships. In section 5, a discussion of this research's original contribution is presented. Finally, concluding remarks and suggestions for future research and application are shown in the last section.

Table 1: IMO Abandon Criteria for Assessing Flooding.

1. Significantly affect the trim of the ship
2. Reduce freeboard at the bow
3. Sudden changes of heel or trim will indicate flooding
4. Jerky lateral motions can be indicative of large-scale sloshing
5. Increases of water boarding forward decks may indicate flooding of a forward compartment

Source: Author.

2. Literature review.

There have been various studies dealing with ship flooding emergencies. As per EMSA (2022), there are two types of flooding Progressive when if the water flow is gradual and Massive. The flooding rate will depend on the size of the hull breach and the depth under the waterline (Rodrigues et al., 2015). Yet it may be impracticable for the crew to inspect the breach hull's location and size, making calculating the flooding rate very challenging. Therefore, when dealing with a flooding emergency, it would benefit the ship's master and other decision-makers to simulate a condition with actual data. Several examples of real-time decision support systems are discussed in the literature (Liu et al., 2022; Braidotti and Mauro, 2019; Braidotti and Mauro, 2020). However, at the moment, ships are equipped with a loading computer intended to calculate intact stability conditions. The amount of water ingress can be considered an additional load in the respective compartments for the actual loading condition (Liu et al., 2022).

In some cases, a loading computer can also provide damage stability calculations. Yet, the current requirements do not include such advanced software for dynamic conditions like flooding. Ships also have stability manuals required to provide structural stresses under different loading conditions. However, shear force (SF) and bending moment (BM) are affected by buoyancy distribution, trim and still water loads (Gaggero et al., 2017). The weight distribution is also essential for achieving a desired trim of a ship and preventing it from sinking due to structural failure. For instance, a study for bulk carriers showed that the alternate hold loading condition that the hogging bending moments and ultimate strength are reduced by 20% and 37%, respectively (Jagite et al., 2022). One option is the appointment of an emergency response service (ERS), which may respond when it is too late for the crew.

One option for the crew is to calculate the changing ship weight distribution. Many types of ship weight distribution methods involve longitudinal load distribution in still water conditions (Ugodo et al., 2019). There are several approaches to calculating buoyancy force distribution and weight calculations (Cepowski et al., 2019). However, such approximate methods are subject to errors in a range of 6-9% for bending moment and shearing forces (Ivanov et al., 2017). Additionally, for dry bulk carriers, still water loads are subject to uncertainty beyond class rules due to complicated loading conditions (Gaggero et al., 2020).

In the case of one isolated compartment flooding, one critical action from the crew is to pump out the seawater. The flooding depends on the size of the hull breach, which is a typical collision scenario; the concerned area could be 100 x 100 mm (Ozguc, 2019). To achieve this goal, the crew should connect the emergency bilge suction to ballast pumps to discharge seawater from the damaged compartments. In this case, the crew must consider two scenarios. In the first scenario, pump capacity exceeds the flooding rate. As per Lee et al. (2022), a main challenge is that bilge pumps efficiency depends on the suction head and flooding rate. They also conclude that some SOLAS requirements for 2 m3/min bilge pump capacity may need to be revised for most situations. In the second scenario, water ingress (flooding rate) exceeds the available pump capacity. Abandonment of a ship is the most realistic option in this case. A further important aspect of controlling flooding is that the pumps are kept in a permanent standby mode and ready for use at any time.

3. Materials and Methods.

Current research shows that even well-maintained ships may suffer accidents due to human error (Karahalios 2021). Crew training with emergency procedures can be assisted with dedicated software decision support for flooding control (Ölçer and Majumder, 2006). An alternative option suggested by the author is that a ship's captain, to deal with flooding scenarios apart from damage stability, should be able to calculate ship strength permissible level and pumping capacity efficiency, as shown in Figure 1. Figure 2 shows a captain's option in a flooding scenario. Therefore, this study aims to provide a methodology for assessing thresholds in different cases. Therefore, a ship's captain should have an indication when a flooding scenario is rapidly escalating, and abandonment of a ship is required. Thus, the methodology has been designed with the following steps:

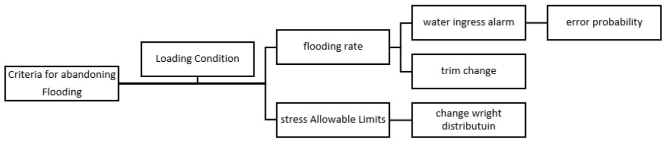
Step 1: Risk analysis from accident cases

Step 2: Simulation of ships in ballast condition

Step 3: Provide thresholds for abandoning

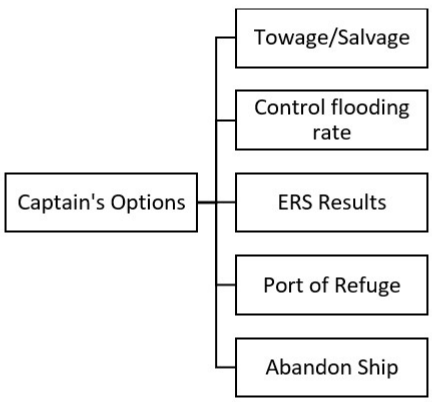
The outcome of this study is to provide a time-based decision-making methodology dealing with uncertainty flooding scenarios for bulk carriers. The examination of case studies will determine the probabilities of catastrophic events. Then simulations are carried out to identify red flags for bulk carrier structural fatigue that need abandonment.

Figure 1: Decision Making in a Flooding a scenario.



Source: Author.

Figure 2: Main options of a Ship's in a Flooding a Scenario.



Source: Author.

3.1. Step 1: Risk Analysis from Accident Cases.

One fundamental aspect of this study is a review of accidents to determine the probabilities of events occurring in the event of flooding. By following this approach is then possible to examine worst-case scenarios, such as loss of ship or life. In contrast, another non-catastrophic case may be investigated, such as damage to the ship and injuries. A database review of past case incidents has been used in similar studies for ship collisions and grounding (Zhang et al., 2021; Tunçel et al., 2023). A valuable database for world cases is GISIS, provided by the IMO (Li et al., 2023)

3.2. Step 2: Simulation of ships in ballast condition.

Simulation is used in this paper to examine the effect of flooding progress, such as weight changes, trim changes, and assess the time required to ship structure exceeds permissible limits. Motok et al., (2022) argued that ship design is less sophisticated than other high-risk industries. As an alternative, they proposed reliability assessments in ship design that could include lifetime analyses of loading conditions. Some notable studies involving simulating loading conditions for this exist in the literature. For instance, Gaggero et al., (2020) applied a Monte Carlo simulation on data from 200 voyages to address still-load uncertainties. Other studies show the simulation's applicability in flooding cases (Ruponen et al., 2022) and safety analysis of LNG disasters (Cao et al., 2022).

There are three stages in any flooding progress can be transient, progressive, and steady (Rodrigues et al., 2015). Simulation examined flooding of bulk carriers two of 35,000 DWT and two of 55,0000 DWT. Ship-specific stability software and trim and stability manuals were used for the simulation. The scenarios under examination include water ingress sensor errors and ballast pump malfunction. A particular concern in this study is the use of water ingress alarms, as SOLAS requires for bulk carriers. However, the alarm system can only detect the water at two levels below 0.5 and 2 m (Wu et al., 2023). If the ship has not been lost, then the ship is at a progressive phase where an equilibrium condition may be for several hours, however, subject to sea waves. Therefore, there is a critical point where the ship's master should judge if the ship will remain stable for sufficient time or if abandoning is the best option.

3.3. Step 3: Provide Thresholds.

The purpose is to find when ship seagoing stresses reach 100% in a time-reliable scenario. Since the ship's captain may be unable to estate the extent of damage, different water ingress scenarios were examined. Assumptions for this study are the following flooding is progressive, excluding wind and wave forces. Flooding would likely rapidly escalate in such case scenarios, not allowing the crew to react. Also, heeling is not included in the calculations. The outcome of this methodology is to provide a time frame for the ship's captain. Therefore, assessment of time-based flooding progress can assist if the crew needs to evacuate the ship or wait until assistance arrives.

4. Results.

4.1. Risk analysis.

In 27 cases examined, the flooding was a follow-up action after a collision, grounding, and engine room ingress in 8, 6 and 6 cases, respectively. Overall a flooding scenario will have Very Serious 0.411 results and Serious 0.58. The loss of the ship is 0.185, and the loss of life is 0.148. Further analysis, as shown in Table 2, is that ships with Gross Tonnage (GT) 25-79k are 0.593 of the sample, while larger ships are 0.185 and 0.370 for ships smaller than 25,000 GT. However, when compared to Loss of Ship then, those larger than 80,000 GT have a probability of 0.800. Also, the Loss of Life is 0.600 for the larger bulk carriers. Furthermore, the importance of SAR operation in evaluating crew with the helicopter was evident in several cases.

However, the high number of losses of life in a single case is notable. A review of PSC Paris MOU Defects 2020-2023, shown in Table 3, records of 11,178 bulk carriers reveals that water ingress alarms may not be functional. There is a 0.059% probability that the water ingress system will malfunction, and as a result, flooding may not be detected. In case sensors are operational, the ship's captain can evaluate the flooding rate by measuring the time between 2 sensors in a cargo hold.

Table 2: Water Ingress Level Indicator Defects (Paris MOU 2020-2023).

PSC Findings	Probabilities
Detainable deficiencies	0.059
Detentions	0.045

Source: Author.

Table 3: Probabilities of flooding catastrophic results.

Ship Size	Fleet Distribution	Loss of Ship	Loss of Life
GrossTonnage > 80k	0.185	0.800	0.600
GrossTonnage 26-79k	0.593	0.100	0.000
GrossTonnage <25k	0.370	0.200	0.200

Source: Author.

Table 4: Ship Stresses based on Flooding Scenarios for a 35,000 DWT Bulk Carrier.

Flooding Water Level in Cargo Holds	Cargo Space Volume	BM	SF	Level Tank Meter	New Trim
CH1 expected flooding volume	32.00%	100.00%	80.00%	5.37	2.579
CH2 expected flooding volume	37.00%	80.00%	88.00%	4.6	2.43
CH3 expected flooding volume	30.00%	68.00%	66.00%	4.79	-0.61
CH4 Expected flooding water level	40.00%	55.00%	56.00%	6.03	-2.91
CH5 expected flooding volume	56.00%	100.00%	70.00%	8.5	-6.36

Source: Author.

At the next stage of this research, a series of simulations with different flooding scenarios were carried out for a 35,000 and 55,000 dwt bulk carrier on ballast conditions. The flooding is assumed to stop at the initial water level of the ship. Therefore, higher volumes were excluded from the simulation. It is notable, as shown in Table 4, that bending moments and shear permissible seagoing values, as calculated from ship stability software, reach 100% when cargo holds 1 and 5 are filled to have a volume of seawater of 32% and 56%, respectively. The ship of 35,000 DWT had initial trim of -1.765 meters when at ballast condition, and it is found that trim changes could be several meters. A notable finding is that the cargo holding volume for a bulk carrier may not provide accurate tables for the first 2 meters.

As per Table 1, the worst case is the flooding of cargo hold 1; therefore, the simulation was focused on this case. Table 5 shows a progressive flooding case for cargo hold 1 flooding rate from 37-44 m^3/min when both ballast pumps are fully functional and operate without delay. As the water ingress may exceed the ballast pump capacity, progressive flooding will occur after 23 m^3/min. Consequently, the 32% flooding scenario where stress will be exceeded may require 6-8.8 minutes for cargo hold sensor 1 to be reached. And another 20-40 minutes until the second sensor is reached. Therefore ship's captain has 20-40 minutes from the first sensor alarm to evaluate the flooding scenario.

A simulation scenario for random flooding scenario but also pump failures was calculated for all four ships. An example of the results is shown in Table 6. After 2000 rounds, it appears that 62% of the cases 35,000 DWT ship will have less than 60 minutes to get 32% if water ingress is between 13-100 m^3/min. For a 55,000 DWT, the percentage will be 23%.

Table 5: Time Based scenario based on Water Ingress Alarms in Cargo Hold 1.

Flooding rate (m3/min)	No1 water ingress alarm activation time	No2 water ingress alarm activation time	Time required to reach CH1 32% volume
37	8.8	50.2	114
38	8.3	47.1	103
39	7.8	44.4	94
40	7.4	42.0	85
41	7.0	39.8	78
42	6.7	37.9	71
43	6.4	36.1	65
44	6.1	34.5	59
45	5.8	33.0	54

Source: Author.

Table 6: Simulation examples with defective ballast pumps and 30-100 m^3/min water ingress.

Flooding rate (m3/min)	No1 water ingress alarm activation time	No2 water ingress alarm activation time	Time required to reach CH1 32% volume	No1 ballast pump rate (m3/min)	No2 ballast pump rate (m3/min)	Bilge pump rate (m3/min)
95	1.48	8.40	29.05	2	0	1
99	1.49	8.49	29.37	5	2	1
96	1.62	9.20	31.82	1	10	1
97	1.74	9.91	34.27	9	10	0
82	1.81	10.31	35.64	4	2	1
84	1.92	10.89	37.65	7	4	2
71	2.00	11.37	39.31	2	0	1
79	2.00	11.37	39.31	10	0	1
81	2.09	11.89	41.12	10	5	1
69	2.23	12.67	43.82	3	5	0
63	2.39	13.56	46.89	0	6	0
54	2.67	15.16	52.41	0	3	0
56	3.32	18.85	65.20	6	7	2
60	3.40	19.33	66.83	10	9	1
52	3.68	20.89	72.24	10	4	1
49	4.00	22.74	78.62	7	8	0
36	4.69	26.66	92.17	2	3	2

Source: Author.

5. Discussion.

The review of case studies shows how fast a situation may be developed. It is clear that a flooding emergency is a major threat to a ship's crew. There is also a possibility of a ship lost with its entire crew. However, there are cases where flooding was contained and controlled where some damages occurred only. Analysis of accident reports shows that engine room flooding could be in any cargo hold or engine room. It also appears that flooding could be a consequence of a collision or grounding. Similar results are shown after a simulation of four ships of different sizes. The Cargo Hold 1 flooding at 32% could reach the maximum allowable seagoing bending moment and shearing forces faster. The simulation clarifies how vital it is for the ballast pumps to be fully functional and used as soon as possible. This requires a well-drilled crew. The time of element is crucial even in case of progressive flooding.

Trim changes may be undetected at the first stages of flooding. Both pumps must be fully operational for small water ingress conditions. In case of underperformance of ballast pumps or the ship's crew will likely have less than 60 minutes to react. The reaction includes assessing the damage, activating a damage control plan, informing interesting parties and preparing for abandoning the ship. The weather condition was not taken into account. However, effects such as sloshing and healing should alert the crew for immediate action.

In this study, water ingress alarms were used. However, having more sensors on cargo holds and engine rooms may be useful. It is of high importance early detection of a flooding emergency. Existing procedures and contingency plans need to be revised to include such time-based scenarios. It is also valuable for planning to link emergencies such as collision and grounding as the triggering events for flooding.

The practical implementation of the methodology is that simulations can use advanced calculation or inexpensive software without the use of advanced math or expensive software. For example, following a threshold approach ship's crew could be provided with time-based tables and following actions. However, software with various simulation conditions may benefit crew training. For example, for each ship, thresholds may differ depending on size. Further could use more parameters such as adverse weather, sloshing, and various cargoes that were not feasible to be used in this study.

Conclusions.

This study revealed some interesting facts about the flooding risks of bulk carriers. However, a small sample of case studies was found in the IMO database and other sources. The sample was not large enough to define higher risks ships based on their characteristics such as age, size or flag. However, the risks of rapid escalation ad the possibility of losing a ship with its entire crew were clear. The study focused on bulk carriers due to the structural lack of compartments making compartment isolation due to water ingress more challenging. The scenario of ballast condition was chosen since it is the worst-case scenario. Accident reports also clearly show that ground and collision could initiate flooding. Therefore, the crew should be prepared for such escalation cases.

The simulation approach followed in this study was beneficial for examining certain parameters in a flooding scenario, such as change of trim, malfunction of ballast pumps, and time thresholds of reaching maximum bending and shearing forces. However, as IMO (2004) emphasised, detecting water ingress could be very difficult. Furthermore, in some cases, the crew may not have access to see the actual ship damage as it affects the submerged part of the ship or the weather is adverse. Therefore, the only meaningful stage to examine is progressive flooding. Otherwise, the other crew may not have time to react, or the psychological pressure of s ship's captain will make him decide to abandon. Therefore, this study emphasises how important it is for companies to prepare ship-specific procedures and dynamic action lists for such catastrophic scenarios. Thus, the captain will have a clear timetable detailing actions, including abandonment.

The methodology used in the paper was a combination of simulation and risk analysis methods. It is capable of revealing threats under different conditions that may not exist in literature or case studies. The results were useful in providing thresholds used for abandoning a ship. It also revealed the significance of maintenance of ship machinery and particularly ballast pumps and cargo hold sensors. However, it would be valuable to access more data from different types and sizes of cargo ships where water ingress sensors and strength design requirements differ from the bulk carriers.

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