FLOODSTAND Integrated Flooding Control and Standard for Stability and Crises Management

FP7-RTD- 218532

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SENSITIVITY ANALYSIS FOR THE INPUT DATA IN FLOODING SIMULATION

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Abstract:
A systematic sensitivity analysis is presented. The effect of variation in the applied input parameters for potential openings (pressure losses, leaking and collapsing) on the progressive flooding is studied through extensive simulations for different damage scenarios. The results are compared and analysed with concluding remarks.

Acknowledgements
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1 EXECUTIVE SUMMARY

The main objective of the WP2 in the project FLOODSTAND is to provide data for more accurate and realistic modelling of progressive flooding in time-domain simulations. In the Task 2.1 and Task 2.2 both experimental and numerical studies have been performed in order to develop guidelines on modelling leaking and collapsing structures for use in flooding simulation. Furthermore, discharge coefficients for water flow through typical openings have been evaluated in Task 2.3 and Task 2.4. Experiments related to the effect of modelling details were carried out in Task 2.5. This deliverable, D2.6, utilizes the data gathered in the previous tasks of WP2 and studies the effects of variations in the input data on the outcome of flooding in time-domain simulations.

The undisputable fact is that exact values for discharge coefficients or leakage through a closed door cannot be evaluated for each potential opening in a large passenger ship. Therefore the applied values are always more or less rough estimates.

The effect of variation in this input data on the results of the flooding simulation is studied through systematic sensitivity analysis with three different damage scenarios. The results indicate that the effect on transient heeling in the beginning of flooding is minimal. On the other hand the parameters have notable effect on the time-to-flood. Higher critical collapsing pressure can significantly slow down the flooding process. Also the leakage area ratio has a significant effect on the time-to-flood, especially in a flooding case, where the closed doors do not collapse.

Additionally, the sensitivity of cross-flooding calculations to the applied method for determination of the discharge coefficient for the cross-duct is studied. The results from Task 2.3 and Task 2.4 are used along with the guidelines and regression equations of the IMO Resolution MSC.245(83). The results with experimental and CFD analyses are in perfect agreement. Moreover, the results indicate that the regression equation in the Resolution can significantly under-estimate the cross-flooding time. However, the simple approach for accounting several subsequent openings of the duct provides very similar results to the model test case.

2 INTRODUCTION

2.1 Background

Flooding is a maritime accident, defined as the ingress of water that can result in foundering or sinking of the ship. The various paths that the incoming water may take inside the ship, i.e. what compartments will be filled, to what extent and how quickly, may have strong effects on the consequent occasions onboard and the final state of the vessel. Therefore, the knowledge and awareness of the physical facts and mechanisms controlling these issues are and should be in the central focus in ship design and operation. It is an area of big importance for the ship safety.

The development and status of the intermediate stages of flooding may have big importance on the further development of the flooding and the final status of the ship. In passenger ships the internal structure of the vessel is characterized, as usual, by the watertight subdivision, double bottom, watertight bulkheads and the bulkhead deck. More specifically, it also includes numerous decks and a more or less labyrinthine layout composed of nearly innumerable corridors, nooks and corners. This type of internal structure makes the passenger vessel a special ship type requiring a more challenging approach to the studies related to damage stability.

The progress of flooding is characterised by the amount of incoming water and how it is distributed in the ship, how it affects sinkage and heel of the ship as well as the stability, which are most important factors governing the survivability of the vessel. These factors change during the flooding until a final state is reached. However, depending on the heel and sinkage, as well as the subdivision and the openings, various possibilities for further sequences may exist. Therefore, it is not always so straightforward, how the further outcome of the flooding will develop and what will be the final state.

The use of time-domain flooding simulation tools has expanded as the computing capacity has increased. The applications vary from simple calculations of cross-flooding time to assessments of time-to-flood or time-to-capsize in damage scenarios with extensive progressive flooding.

It is an undisputable fact that the simulation results depend on the applied input data for the openings. Most notably, the leakage and collapsing of non-watertight structures, such as closed fire doors, can have a very remarkable effect on the time-to-flood. This issue was first raised in SLF 47/INF.6, *IMO (2004)*, clearly pointing out the need for further research. One of the main objectives of the research project FLOODSTAND was to provide this much needed information.

2.2 Previous Studies

A couple of numerical studies on the effects of input parameters on the flooding behaviour have been carried out before. However, the main emphasis was on other issues.

The first study by *van't Veer et al. (2004)* included an interesting variation of the critical collapsing pressure head for a sing door. The authors concluded that:

> *"The effect of the type of protection of a single down flooding point can make a large difference in intermediate flooding condition."… "The protection of the down flooding point (escape area) was modelled as open, closed by a fire door, closed by a cabin door, and watertight."*

The studied case and example of results is presented in Figure 1 and Figure 2, respectively.

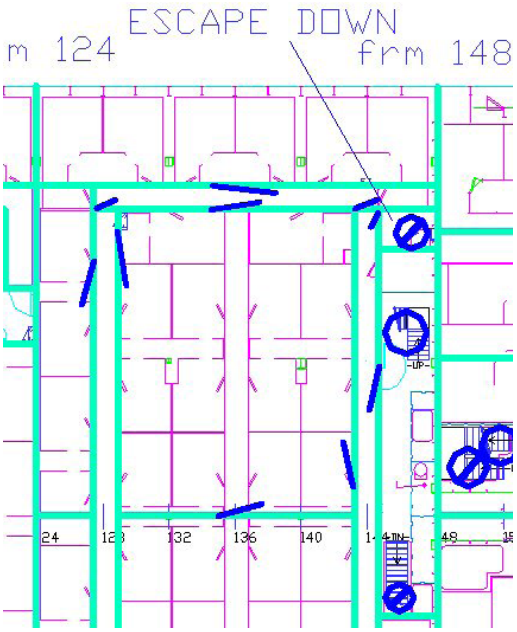

Figure 1: Two down-flooding points near frame 148 in compartment 9 (between frame 124-148) are presented by the circles. The solid lines are compartment boundaries. The door openings are schematically given. The protection of the one near the damage side (marked escape down) has been varied, *van't Veer et al. (2004)*

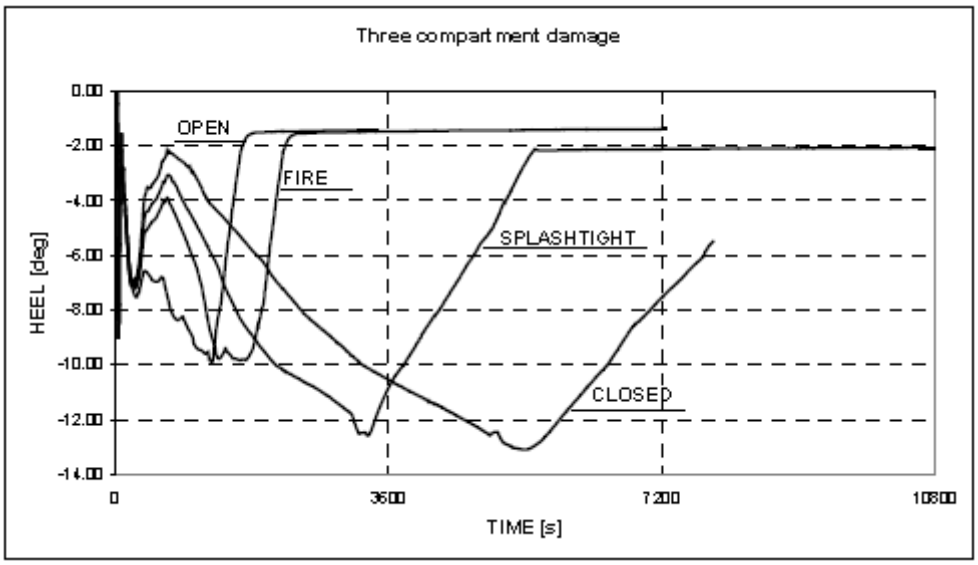

Figure 2: Effect of the protection of a single down flooding point on intermediate flooding conditions in calm water, *van't Veer et al. (2004)*

The second study by *Ruponen (2007b)* included also variation of leakage parameters. The studied case is a two-compartment damage in a medium sized passenger ship of 40 000 GT. The flooded compartments contain crew cabins and store areas. All doors are considered to be initially closed. The modelled rooms and openings (i.e. the computational grid) are shown in Figure 3. Some B-class boundaries on the cabin area were also modelled.

The values for leaking and collapsing pressure heads and leaking ratios, presented in IMO SLF47/INF.6 (2004) were used as a basic case. However, the presented A_{ratio} values in that document

are quite high. Therefore, these values were reduced by 50 % for the other simulations. In all cases, H_{leak} = 0.0 m and C_d = 0.6 were used for all openings.

The results for heeling angle and total volume of floodwater are presented in Figure 4. The flooding case is rather symmetrical and thus the maximum heel angle is small. The leakage area ratio has a significant effect on the time-to-flood. On the other hand, the small increase of the critical collapsing pressure head for the closed doors has much smaller effect on the results.

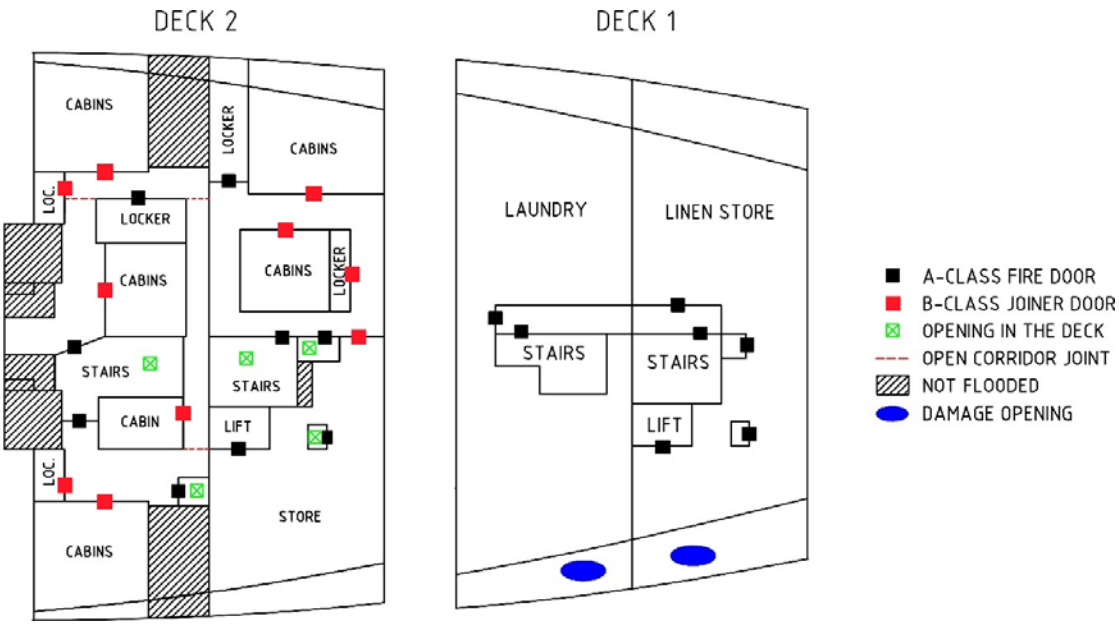

Figure 3: General arrangement of the flooded compartments in the sensitivity study by *Ruponen (2007b)*

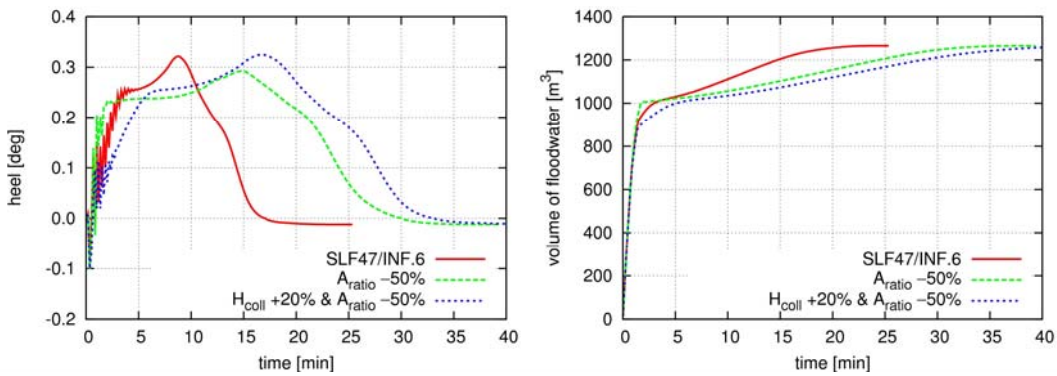

Figure 4: Results of the sensitivity analysis by *Ruponen (2007b)*

3 MODELLING OF LEAKING AND COLLAPSING STRUCTURES

Typically, the simulation tools are based on Bernoulli's theorem and the pressure losses in the openings are taken into account by applying semi-empirical discharge coefficients. In principle, the flooding rate Q through a small opening can be calculated with the following equation:

$$Q = C_D A_{eff} \sqrt{2gH_{eff}} \tag{1}$$

where:

C_D	effective discharge coefficient (pressure losses in the opening)
A_{eff}	effective area of the opening (taking into account e.g. leakage)
g	acceleration due to gravity
H_{eff}	effective pressure head

Flooding through a closed door is considered to start when the effective pressure head on the door H_{eff} exceeds the critical pressure head for leaking, H_{leak}. Before that the effective area is zero. The leaking can take place through the possible gap between the door and the sill or because of structural deformation of the door due to the floodwater pressure. In flooding simulation the leaking process can be modelled by modifying the effective area of the opening, e.g. *Ruponen (2007a)*.

The different phases of the leaking and collapsing of a closed non-watertight door are illustrated in Figure 5. The effective pressure head is calculated as:

$$H_{eff} = H_{wU} - \max\left(H_{ope}, H_{wD}\right) \tag{2}$$

where:

H_{ope}	height of the lowest point of the door (from a common reference level)
H_{wU}	water level height on the upstream side (from a common reference level)
H_{wD}	water level height on the downstream side (from a common reference level)

The **leakage area ratio** (A_{ratio}) is defined as the **dimensionless** ratio between the leaking area of the opening and the submerged geometrical area of the whole door:

$$A_{ratio} = \frac{A_{leakage}}{A_{submerged}} \tag{3}$$

Consequently, the effective area for calculation of leakage water flow through the door is:

$$A_{eff} = A_{ratio} A_{submerged} \tag{4}$$

When the effective pressure height on the door is larger than the critical pressure head for collapsing the door is considered to collapse, and thereafter the effective area is the submerged area of the opening. Naturally, the structural failure of a closed door is irreversible, meaning that if the door has been damaged it will not be repaired (or closed) even if the effective pressure head decreases.

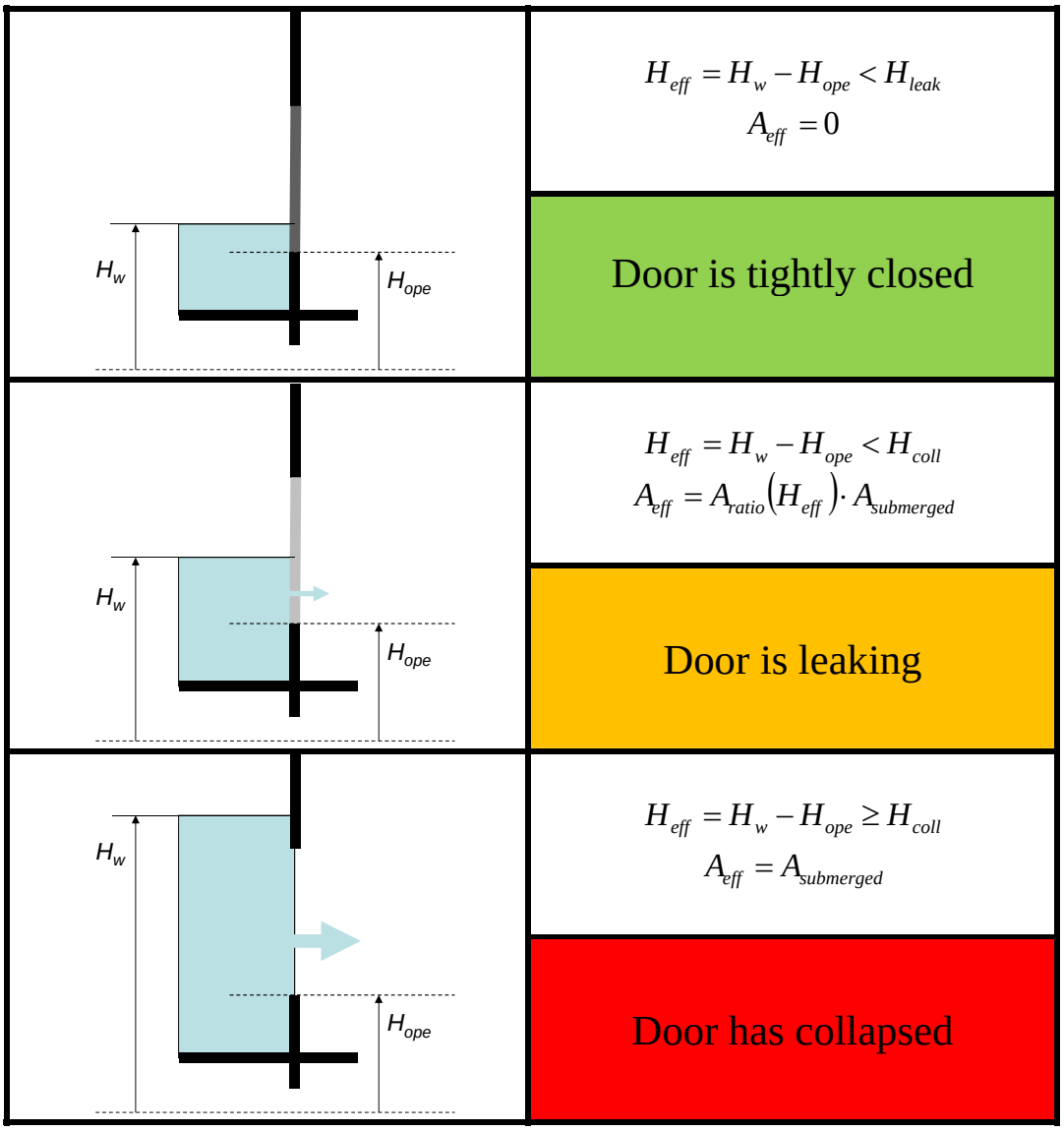

Figure 5: Modelling of leaking and collapsing of closed doors

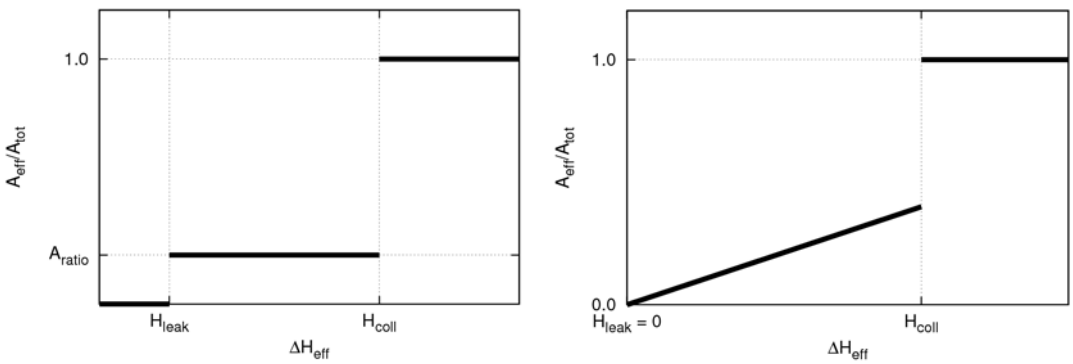

Figure 6: Constant (left) and increasing (right) leakage area ratio

In the previous studies (*van't Veer et al., 2004* and *Ruponen, 2007b*) the leakage area ratio has been assumed as constant. However, the analysis of the full-scale experiments[1] at CTO has shown that the leakage area ratio is in most cases practically linearly dependent on the pressure height, *Ruponen and Routi (2011)*[2]:

$$A_{ratio} = a \cdot H_{eff} + b \tag{5}$$

Moreover, in most cases the coefficient $b = 0$ since the leaking starts practically immediately when the door is submerged, i.e. $H_{leak} = 0$.

However, for some of the tested structures, such as A-class sliding door, the analysed leakage area coefficient was almost constant, i.e. in equation (5) the coefficients are $a = 0$ and $b > 0$..

The approach of both the constant and increasing leakage area ratio are illustrated in Figure 6. The guideline report, *Ruponen and Routi (2011)*[2], provides values for the coefficients a and b for various tested structures.

[1] **These tests and their results have been reported by CTO in FLOODSTAND Deliverable D2.1b, v.1.6**
[2] **FLOODSTAND Deliverable D2.2b, v.1.03**

4 SENSITIVITY ANALYSIS

4.1 Case Study Ship

4.1.1 General

A large passenger ship design "Sample Ship A", developed by STX Finland for the FLOODSTAND project is used as a case study ship for the sensitivity analysis, Figure 7. Details of the ship are given by *Kujanpää and Routi (2009)*.

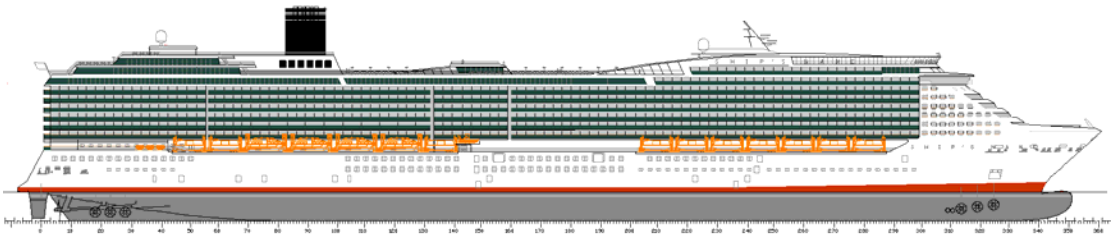

Figure 7: Profile of the Sample Ship Design A

Unless otherwise mentioned, the simulations are done for the intact condition DS (deepest subdivision draught). In this condition the ship is at even keel with a draught of 9.0 m and the initial metacentric height is 2.4 m.

4.1.2 Modelling of Flooded Rooms

All steel bulkheads and Decks on the flooded compartments were included in the 3D model of the ship. The only exception is that each staircase was modelled as a single room, similarly to the lift trunks. No B-class structures, such as cabin walls, were included. (as their limiting effect on flooding was considered small, based on the tests at CTO (in D2.1b) and their further analysis in D2.2b)

4.1.3 Openings

All the connections between the potentially flooded compartments have been modelled. The door dimensions are based on the doors that were tested at CTO in Task 2.1 of the FLOODSTAND project.

Only the doors and other connections between the potentially flooded rooms in the studied damage cases were modelled. Total of 60 internal openings were modelled in 5 watertight compartments, Figure 8. The different types of (initially closed) openings are listed in Table 1. The full opening definitions in the NAPA 3D ship model are given in Appendix C. The general arrangement with the room names is in Appendix D.

In general, all doors are assumed to be initially closed. In some cases certain watertight doors are considered to be open in order to allow more extensive flooding. This is later emphasized, case by case. In addition, some corridor connections between the rooms were modelled as openings (with the status: always open).

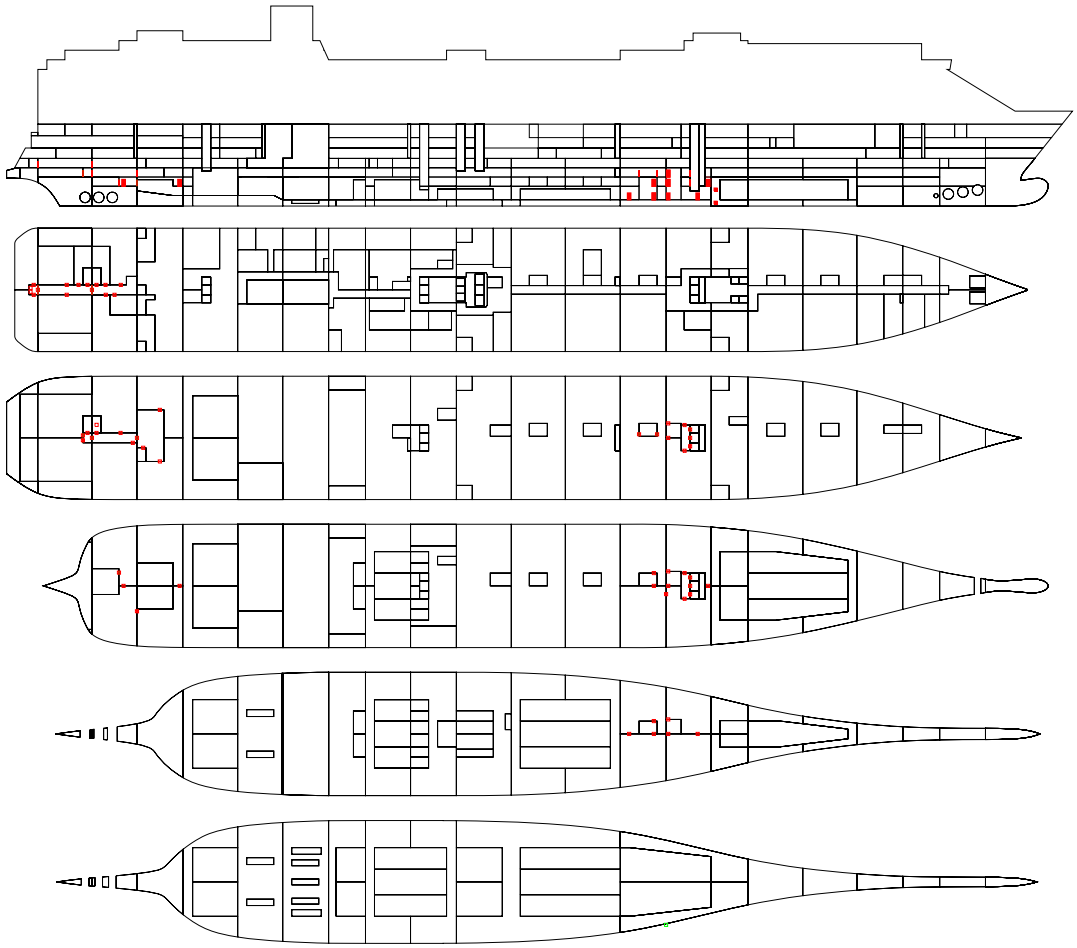

Figure 8: Modelled openings in the 3D model of the ship

Table 1: Different door types in the 3D model of the ship

Door type	Description	Note
WT	Watertight door	-
A-HINGED	A-class hinged fire door, width 950 mm	Tested, both directions
A-SLIDING	A-class sliding fire door, width 1100 mm	Tested, both directions
COLDROOMDOOR	Cold room sliding door, width 1100 mm	Tested, one direction
LIFT	Service lift door, width 1300 mm	Not tested

4.2 Opening Parameters

The reference parameters of the openings were selected based on the guideline report, *Ruponen and Routi (2011)*. These values are based on the systematic full-scale tests at CTO, *Jakubowski and Bieniek (2010)*[3] and the FEM calculations by MEC, *Naar and Vaher (2010)*[4].

For all tested doors and panels the critical pressure head for leakage was practically zero, except for the light watertight door.

The cold room sliding door (and surrounding panels) was tested only to one direction. Thus it is assumed that the same values are applicable also when the water pressure acts out from the door frame.

[3] FLOODSTAND Deliverable D2.1b
[4] FLOODSTAND Deliverable D2.2a

In the most forward flooded compartment the water progresses also through lift trunks. However, lift doors were not included in the set of tested structures. Based on the other tests, it seems logical that also H_{leak} = 0 m also for these doors. In addition, the collapsing pressure height was assumed to be H_{coll} = 1.5 m and the leakage area ratio was estimated to be constant A_{ratio} = 0.03 (to both directions. These values were selected based on the test results for B-class structures.

Table 2: Rough guidelines for modelling doors and boundaries for flooding simulation, the values marked with an asterix (*) are estimations that are not based on experimental or FEM results *(Ruponen and Routi, 2011)*

Type	direction	H_{leak} (m)	A_{ratio}	H_{coll} (m)	Notes
LWT	into	–	–	8.0*	minimal leaking at lower pressures, full collapse likely for H > 8 m; note that only direction "out" was tested
	out	–	–	8.0	
A-class sliding	into	0.0	0.025	1.0	almost constant leakage area ratio
	out	0.0	0.025	1.0	
A-class hinged	into	0.0	$0.02 \cdot H_{eff}$	2.5	A_{ratio} depends on the gap size
	out	0.0	$0.03 \cdot H_{eff}$	2.5	A_{ratio} depends on the gap size
A-class double leaf	into	0.0*	0.025*	2.0*	**Not tested!** Assumed to be independent on direction
	out	0.0	0.025	2.0	Collapsing could not be tested due to high leaking, value based on FEM
Cold room sliding door	into	0.0	$0.01 \cdot H_{eff}$	3.5	Only one direction tested; collapsing pressure height assessed with numerical methods
	out	0.0*	$0.01 \cdot H_{eff}$*	3.5*	
B-class joiner door	into	0.0	$0.03 \cdot H_{eff}$	1.5	panels around the door will fail first, A_{ratio} expression is very approximate
	out	0.0	0.03	1.5	door is distorted, A_{ratio} increases slowly
Windows	–	–	–	> 18	can be excluded in simulations

4.3 Simulation Method

All the time-domain flooding simulations were carried out with the NAPA software (Release 2011.1), using the state-of-the-art pressure-correction method. The details of the method are presented in *Ruponen (2007a) & (2007b)*. The flow rates in the openings are calculated by using Bernoulli's equation.

In this study all compartments were assumed to be fully vented.

Roll motion of the ship is calculated with a simple method, assuming linear damping. The applied natural roll period of the intact ship is 20 s and the critical roll damping ratio is 0.05. Trim and heave motions are considered to be quasi stationary.

Applied time step is 0.2 s, which was found out to be short enough to have no effect on the results. It was also checked that the applied convergence criterion was strict enough to have no effect. For practical purposes, much longer time step (up to 1 s) could be used. However, in this sensitivity analysis it was considered to be justified to exclude, as far as possible, all effects from the numerical solution of the governing equations.

5 CASE A – A-CLASS FIRE DOORS

5.1 Damage Case

The main purpose of this test case was to study the effect of modelling leaking and collapsing of A-class fire doors. All doors are considered to be initially closed.

The store room and laundry on the Deck 01 are damaged in this damage case. The flooding progresses upwards to the stores on Deck 02, through the staircases and the service lift trunks, and further up to cabin areas on Deck 03. The A-class doors to the staircases are hinged and the other doors are sliding. The watertight door at the frame #218 is considered to be closed.

On the Deck 01 and Deck 02, there is an additional longitudinal A-class bulkhead at the centreline in order to ensure more asymmetry in the initial stages of flooding. In these bulkheads there is one A-class sliding door in each compartment, depicted by grey arrows in general arrangement. It is noteworthy that in these bulkheads were not included in the original design that clearly meets the SOLAS 2009 requirements.

Also the void in the double bottom is damaged in order to achieve somewhat larger transient heeling. The damage is located on the starboard side and the extent of the damaged area on the hull is following:

- 5.0 m^2 to the double bottom
- 2.0 m^2 to the store on Deck 01
- 3.0 m^2 to the laundry on Deck 01

The asymmetry of flooding is further emphasized by using only two small cross-flooding openings in the centreline for the flooded double bottom tank.

The effect of varying different parameters of C_d, H_{coll} and A_{ratio} will be discussed in the light of heel angle and floodwater accumulation. The trim angle is proportional to the amount of flooded water, (with small angles, assuming that the longitudinal centre of gravity of the flooded water is constant). For this reason, trim will not be separately discussed. However, graphs concerning the trim angle are presented.

The apparent flooding directions are depicted on Figure 11, the flooding order of reference case in Figure 12. Damage hole is situated on starboard side of the hull, thus causing the transient heel towards that very same side. The flooding to Deck 02 and Deck 03 takes place through staircases. In addition, the water penetrates to elevator lobby on Deck 02 through doors 11 and 12 and from there through elevator shafts to Deck 03. Changing flooding parameters of openings might cause the water to reach elevator lobby on Deck 03 through doors 21 and 22 first, instead of doors 23, 24 and 25 (in Figure 11). Air-conditioning duct (denoted as “A” in Figure 11) is filled independently through Deck 01 and is not directly in interaction with any other space.

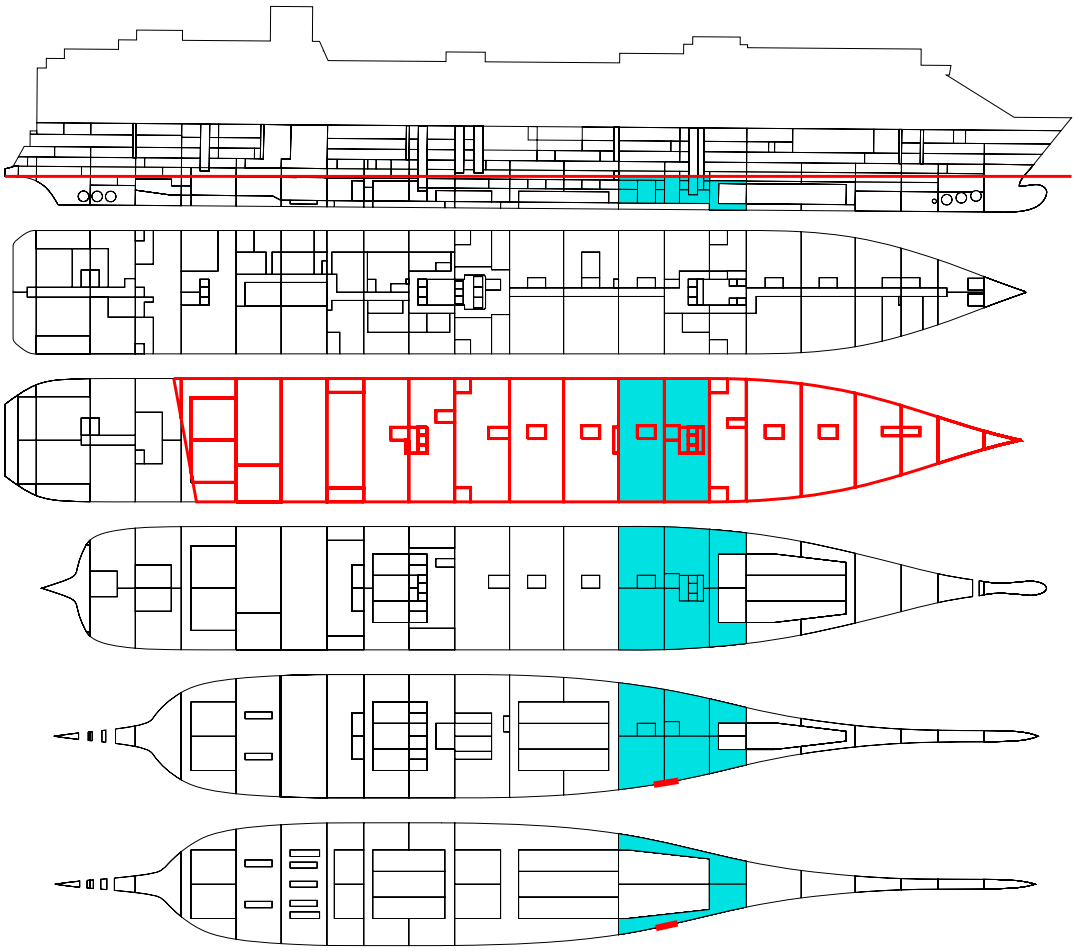

Figure 9: Studied damage scenario for Case A

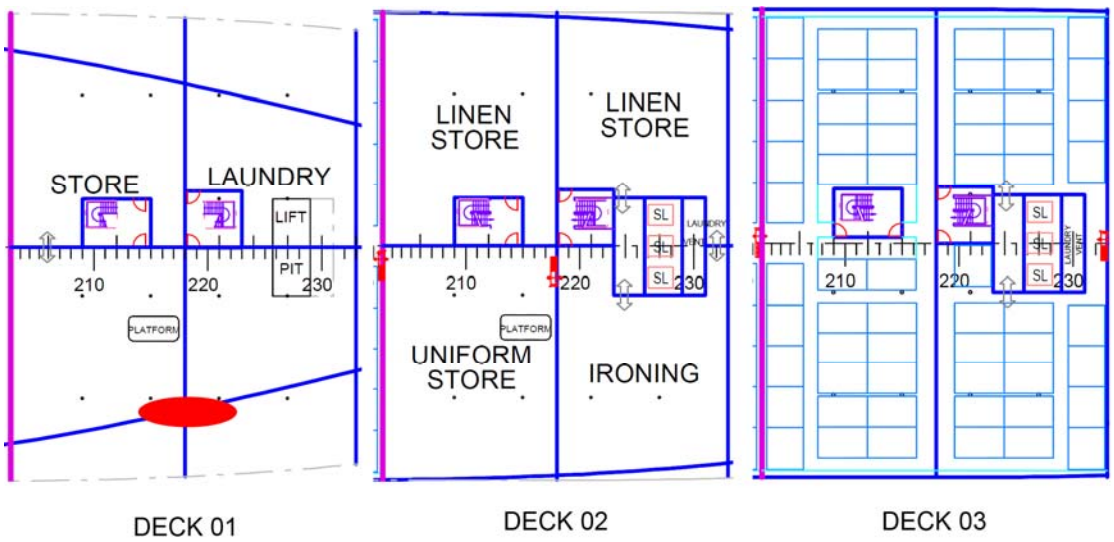

Figure 10: General arrangement of the three topmost flooded compartments. Damage area on Deck 01 marked as a red ellipse.

Type	Door ID											
A-SLIDING	1	6	11	12	16	21	22					
A-HINGED	2	3	4	5	7	8	9	10	17	18	19	20
LIFT	13	14	15	23	24	25						

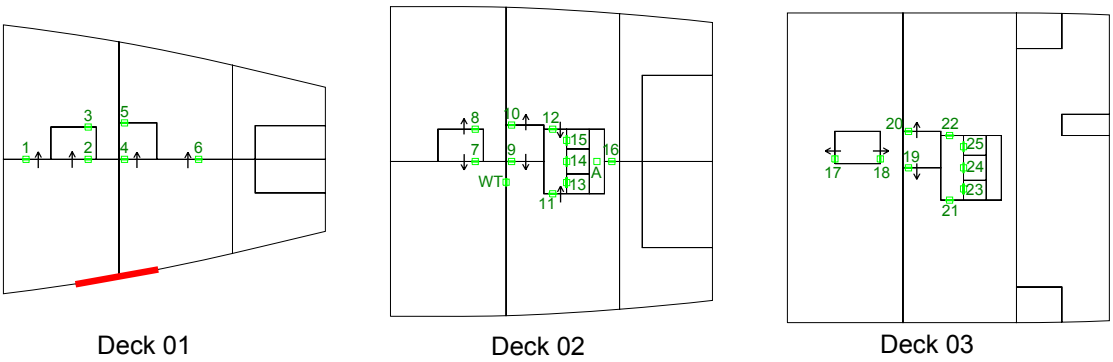

Figure 11: Openings, their ID numbers, types and some apparent flooding directions.

PHASE	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
TIME (min)	0.00	0.24	0.27	0.32	0.90	0.97	1.07	1.13	1.15	1.20	1.23	1.27	1.37	1.52	1.59	1.96	1.97	2.06	2.17
PHASE	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	END	
TIME (min)	2.25	2.54	2.84	2.97	3.13	3.62	3.64	3.67	3.76	3.79	3.98	4.01	4.04	4.11	4.25	5.14	5.19	121.33	

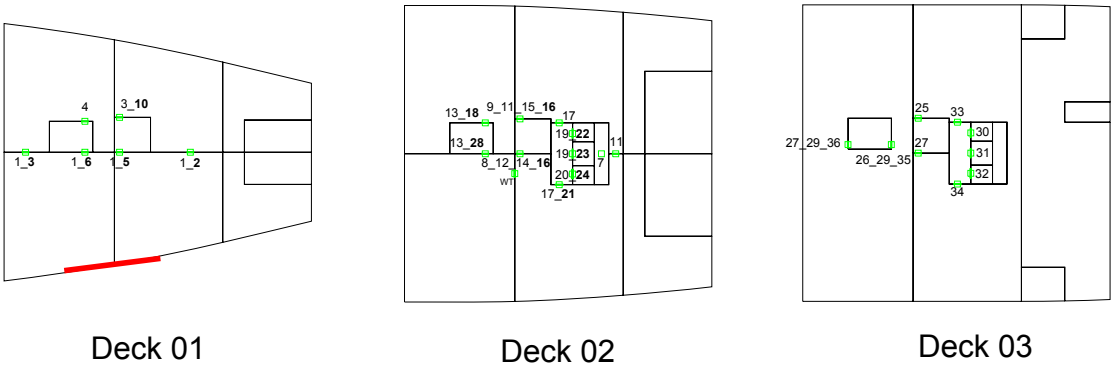

Figure 12: The flooding phases of reference case.

Behaviour of the ship and the order of flooding and collapsing of doors are different with different flooding parameters. The progressing of flooding in the reference case is depicted on Figure 12, where the first or a single number by a door expresses the time at which leaking starts. A bolded number expresses the phase at which a door collapses. If there are three or four numbers referring to one door, the second number expresses the phase at which flooding stops, and the third one at which phase it continues again. The phases for all variations are presented in appendix A. The opening directions of different doors can be seen on general arrangement (Figure 10).

5.2 Effect of the Discharge Coefficient

5.2.1 Parameters

The base value of discharge coefficient for all openings is C_d = 0.6. The experimental research carried out in FLOODSTAND within the Task 2.3, *Stening (2010)*, shows that this is a relatively good approximation for the tested manholes. In addition, this value has been applied as an "industry standard" in several previous numerical studies. Thus, it is used here for all openings, including the damage holes.

Comparative simulations were performed with C_d = 0.5 and C_d = 0.7, i.e. ±16.7%.

5.2.2 Results

Flooded water

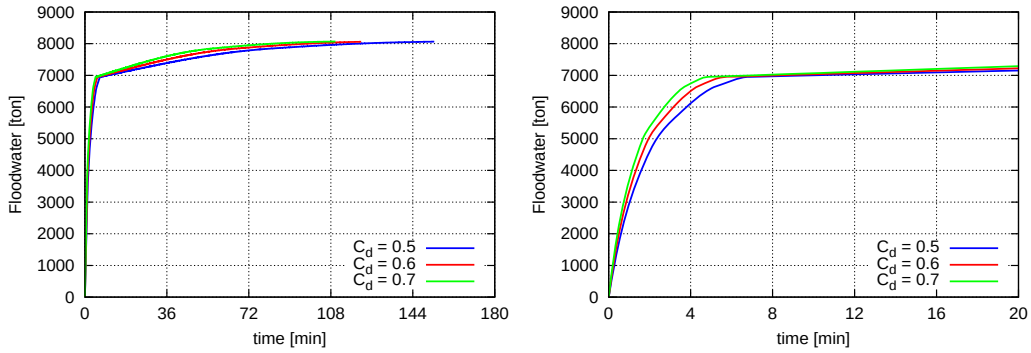

Figure 13: Time history of floodwater mass with different discharge coefficients

- The decrease of C_d naturally increases the time for the compartments to be fully flooded. Significant differences do not occur.
- In the beginning the flow rate is at its highest. Gradually the flow decelerates. At around six minutes there is a clear decrease in the flow rate. The flooding has progressed to such state, that all flooding is leaking through closed doors.
- The closer to the sea level the flooding has reached, the less there is pressure head and thus flooding.
- The differences are small, but can be still seen. The flooding order through different openings does not have apparent effect on the flow rate. However, the C_d -parameter is proportional to the derivative of floodwater mass i.e. the mass flow, and this can be seen clearly throughout the simulation.

Trim

Time history of trim with different discharge coefficients is presented in Figure 14. The general change in trim is much similar to the change of heel, which is described in more detail later on.

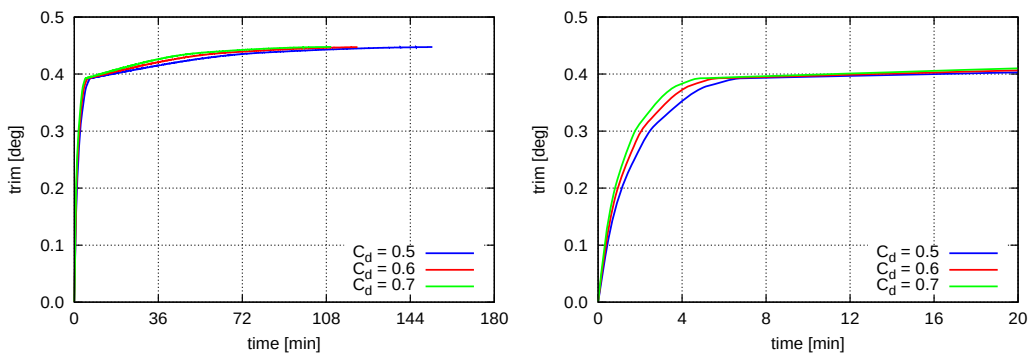

Figure 14: Time history of trim with different discharge coefficients

Heel

- The increase of the discharge coefficient decreases the time for maximum heel to occur. This is due to the increased flow rate.

- The second peak in heeling takes place between 2 and 6 minutes with different C_d values. When C_d = 0.5 the heeling direction is different, compared to the heeling with reference value. The side of inclination is dependent on to the heeling position of the ship at the time of water reaching Deck 02. This determines the accumulation side of water in the staircase and thus the next collapsing door. In this case, the critical doors are 7 and 8. Collapsing of one of these doors will leave the other one uncollapsed.

- The reason for the C_d variation having such great impact on the behavior of the ship, is that in this particular case the heeling angle is very close to zero when the water starts accumulating on Deck 02. Thus minor changes in the flow rate can determine the direction of inclination.

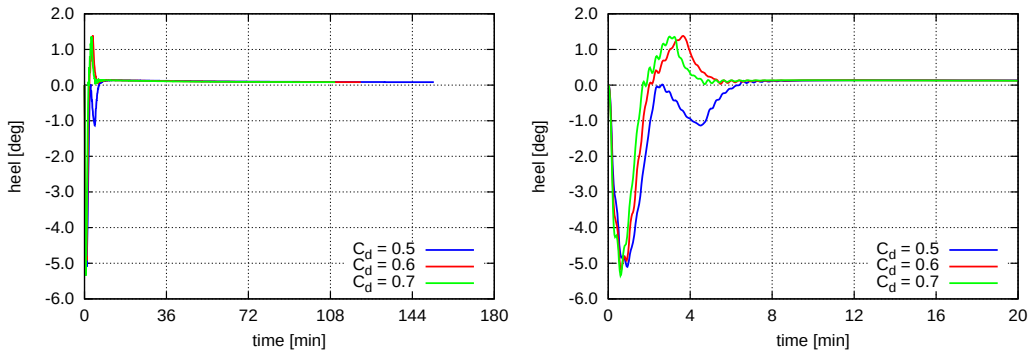

Figure 15: Time history of heel with different discharge coefficients

- This result indicates that in some cases, the discharge coefficient may have significant impact on the behaviour of the ship. The dependency of the heeling direction on the water accumulation is illustrated in Figure 16 with two different C_d values, at t = 2.5 min.

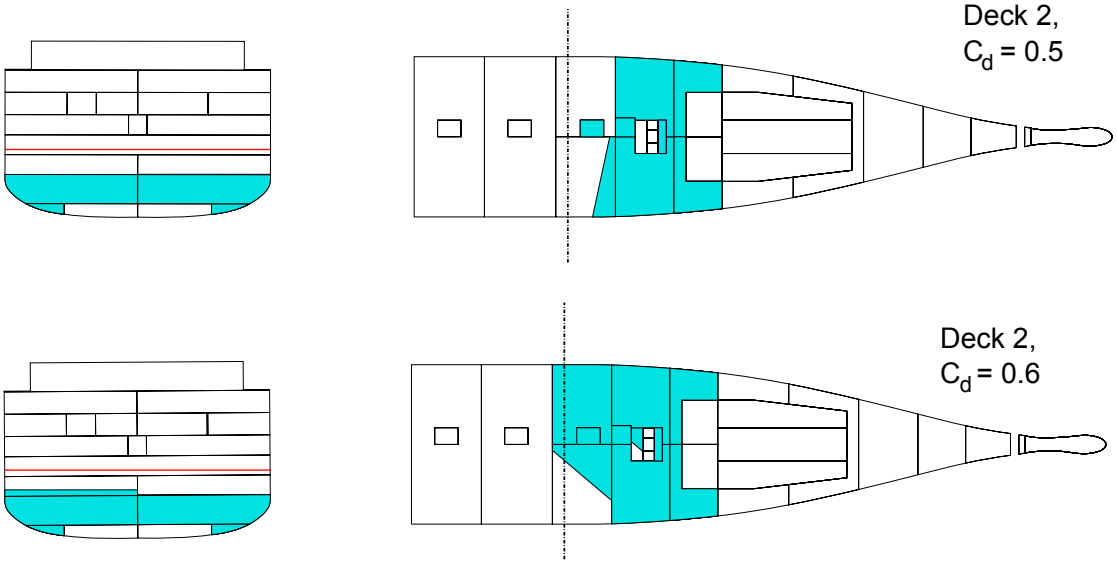

Figure 16: Water accumulation with different C_d values, t = 2.5 min

5.3 Effect of the Collapsing Pressure Head

5.3.1 Parameters

The guideline values for collapsing pressure heads, Table 2, *Ruponen and Routi (2011)* are used as a reference. These are varied by -25%, +25% and +50%, and the results are presented below. The collapsing pressure head is modelled to be the same, regardless of the direction.

5.3.2 Results

Flooded water

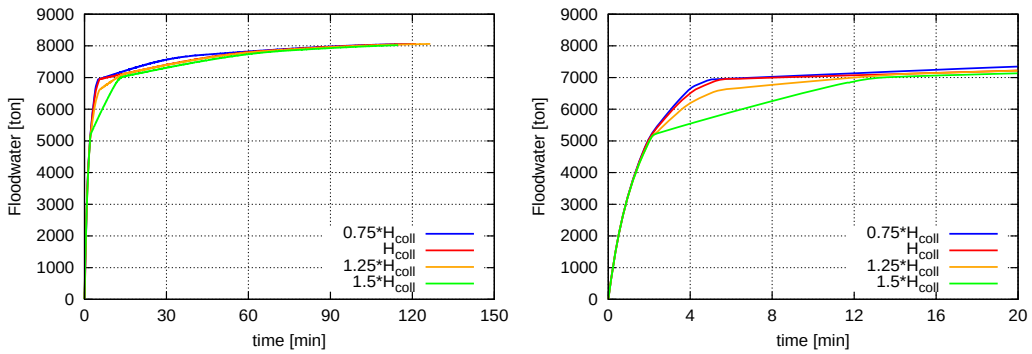

Figure 17: Time history of floodwater mass with different collapsing pressure heads

- In general, the higher the H_{coll}, the more does it hinder the flow. This is a result of smaller amount of collapsing doors, which results in smaller effective area of openings

- Increasing H_{coll} causes the flooding to progress faster to Deck 03.

    - This is due to spaces or a space by staircases on lower decks filling faster, which is due to the doors that collapse with smaller H_{coll}, being such that they do not lead the water to the staircase but instead away from it (see Appendix A)

- When H_{coll} is being increased by 50%, at 2 minutes a clear hindrance in flooding can be noticed. This is the moment at which the water reaches Deck 03 and starts leaking there. The final hindering takes place when the last doors start leaking and all remaining flooding is leaking through closed doors.

Trim

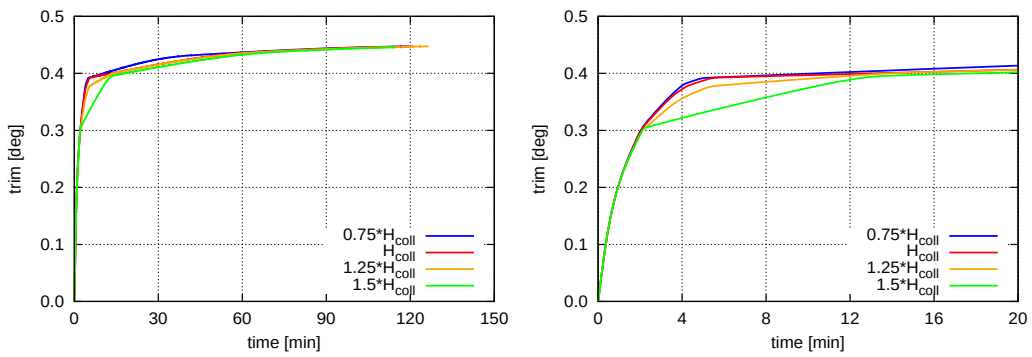

Figure 18: Time history of trim with different collapsing pressure heads

Heel

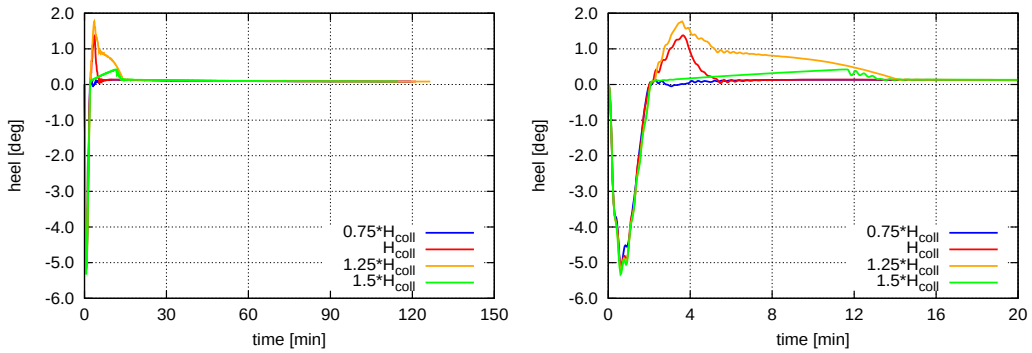

Figure 19: Time history of heel with different collapsing pressure heads

- The effect of varying the collapsing pressure head is negligible at the first peak.

- At the second peak of heeling, the increase of the collapsing pressure head by 25% increases the second heeling, while increasing the collapsing head by 50 % evens out this second peak.
  - H_{coll} +25%
    - At two minutes doors 8. And 10 on Deck 02's port side collapse, but no door on starboard experiences this damage. On the reference case, at the same time with these doors, one starboard door collapses, and thus the second heeling is more moderate.
    - This results in water accumulation to portside. Evening out takes place through leaking through uncollapsed doors on Deck 03.
  - H_{coll} +50%
    - There is no collapsing of any door on Deck 02 at 2 minutes. Therefore there is no major water accumulation resulting in a rapidly increasing heel. There is only very moderate water accumulation to the portside. The increased heel starts evening out when at around 12 minutes door 12 collapses on Deck 02, allowing the water to balance out.
  - H_{coll} -25%
    - On Deck 02, at 2 minutes, doors 7 and 9 on portside and doors 8 and 10 on starboard collapse. This results in the ship maintaining practically zero heeling angle after the transient heel. Thus water is freely flooding on the deck on both sides.

5.4 Effect of the Leakage Modelling

5.4.1 Parameters

The base values for collapsing pressure head (Table 2) are kept constant. Moreover, the full-scale experiments, FLOODSTAND Deliverable D2,1b (*Jakubowski and Bieniek, 2010)*, clearly showed that the leaking starts practically immediately when the doors are below the water level it seems to be justified to assume that H_{leak} = 0 m. Consequently, the main emphasis of the sensitivity analysis is on the modelling of the leakage area ratio.

The guideline values for leakage area ratio (A_{ratio}), Table 2, are used as a reference. In the full-scale tests at CTO some notable difference in the leakage through different A-class hinged doors were observed, *Ruponen and Routi (2011)*. Thus it is considered to be justified to apply significant changes (±50%) for these parameters in the sensitivity analysis.

5.4.2 Results

Floodwater

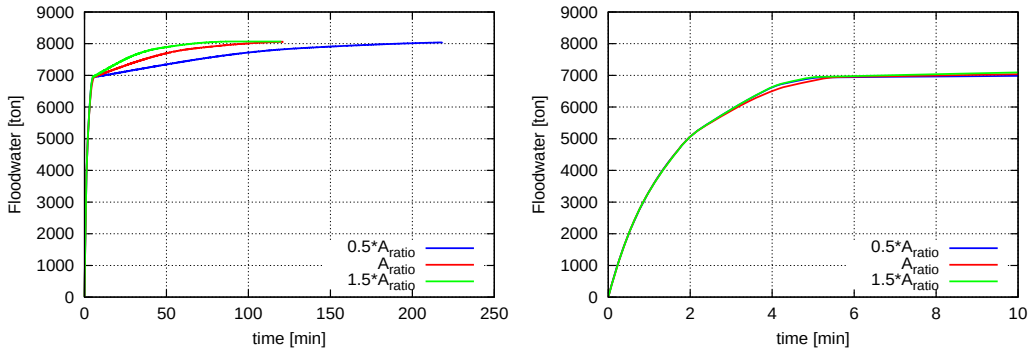

Figure 20: Time history of floodwater volume with different leakage area ratios

- A_{ratio} affects only to the leaking rate through closed doors, and does not apply to collapsed doors.
- In general, there are no great differences concerning the accumulation of floodwater. It is apparent that the flooding time is greater when A_{ratio} is decreased and vice versa.
- At 5 minutes when water reaches Deck 03 a clear decrease in flow rate can be noticed. This is the moment of which onwards all further flooding is leaking through closed doors. This stage is reached in all cases at the same time.
- Mass flow through closed doors is proportional to A_{ratio}.
- Leaking plays a relatively insignificant role compared to flooding through collapsed openings.
    - Before water reaches Deck 03, even quite drastic variation of A_{ratio} does not have much effect on the flow rate.

Trim

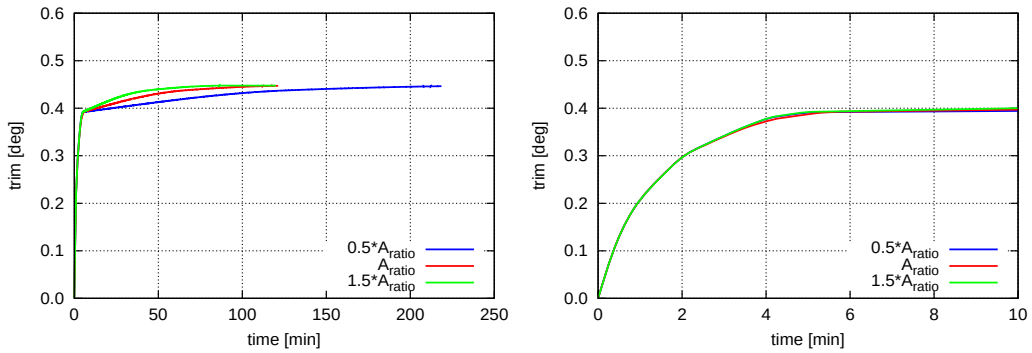

Figure 21: Time history of trim with different leakage area ratios

- The results are practically analogous to the comparison of floodwater volumes.

Heel

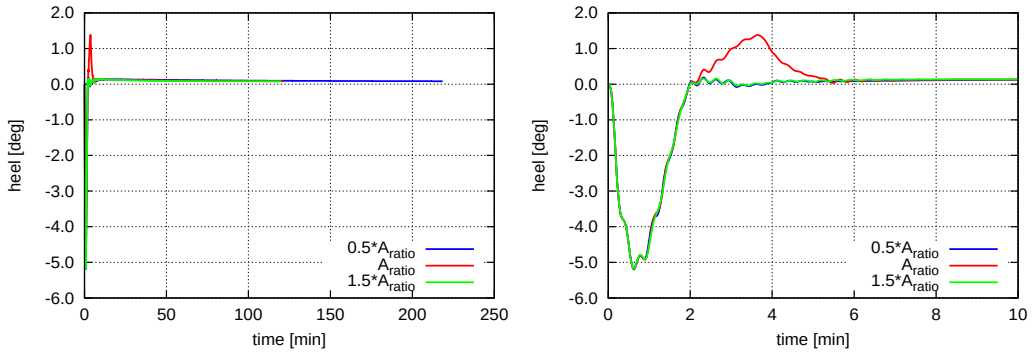

Figure 22: Time history of heel with different leakage area ratios

- The asymmetry in the damaged compartments causes a notable transient heeling in the beginning of flooding.

- With A_{ratio} ±50%, heeling angle is close to zero, when on Deck 02, the opposite doors 9 and 10 collapse at the same time. A moment later doors 7 and 8 collapse similarly. This allows the water to spread evenly on Deck 02. This is the reason for the second peak of heeling to be non-existent and allowing the heel variation to remain noise-like, before reaching a steady angle. What can be concluded is that when collapsing of doors is not affected, the effect of variation in A_{ratio} is very small

5.5 Effects on Flooding Events

Critical factors for the behavior of the ship are the flooding rate as well as the number of collapsing doors and their order of collapse. The nature of the whole flooding process can change, sometimes significantly, when these elements are affected. Varying of collapsing pressure head had a clear effect on the heeling behavior, changing its nature. This was due to the water finding different paths to progress. On the other hand, C_d variation resulted in changed heeling direction and A_{ratio} variation resulted in changes in the occurrence of the second peak of heeling.

There are critical events in this flooding scenario that can be pinpointed:

- When a first door collapses to a space it allows a more rapid water accumulation to that space. Usually this has a noticeable effect on the heel.

- Also, when a space is filled and if this space is in a connection to a staircase for example, that leads to a hindered flooding as well as to flooding progressing to the following deck.

- In this particular flooding scenario the water reaching Deck 02 took place when the heeling angle had returned more or less back to zero. Therefore the first collapsing doors on that deck were very likely to determine the direction of the second heel. If the doors collapsed simultaneously on both sides, this resulted in a nonexistent second heel.

The effects of parameter variation are presented in Table 3 on the next page. The critical events such as the first collapse of doors to Deck 02 or flooding reaching Deck 03 can be easily read on this table. It can be used together with Appendix A to understand the flooding case more thoroughly.

Table 3: Case A - flooding events with different parameters in minutes.

	Ref	C_d		H_{coll}			A_{ratio}	
DECK 01		05	07	-25%	25%	50%	-50%	50%
Door 1								
Starts leaking	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Collapses	0.27	0.33	0.25	0.21	0.35	0.40	0.27	0.40
Door 2								
Starts leaking	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Collapses	0.97	1.15	0.81	0.68	1.15	1.15	0.89	0.97
Door 3								
Starts leaking	0.32	0.33	0.28	0.23	0.37	0.44	0.31	0.40
Collapses	-	-	-	-	-	-	-	-
Door 4								
Starts leaking	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Collapses	0.90	1.07	0.76	0.65	0.97	0.97	0.81	0.44
Door 5								
Starts leaking	0.27	0.33	0.25	0.21	0.35	0.40	0.27	0.37
Collapses	1.20	1.43	1.02	1.07	-	-	1.17	1.18
Door 6								
Starts leaking	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Collapses	0.24	0.28	0.20	0.15	0.31	0.37	0.24	0.27
DECK 02								
Door 7								
Starts leaking	1.37	1.64	1.17	1.35	1.41	1.41	1.36	1.43
Collapses	3.76	2.47	3.23	2.00	-	-	2.06	2.41
Door 8								
Starts leaking	1.37	1.67	1.17	1.38	1.44	1.43	1.38	1.48
Collapses	2.06	4.73	1.77	2.00	2.17	-	2.06	2.41
Door 9								
Starts leaking	1.13	1.35	0.96	1.51	1.15	1.15	1.11	1.01
Stops leaking	1.27	1.51	1.08	-	-	-	1.24	1.41
Continues leaking	1.52	1.82	1.30	-	-	-	1.52	1.97
Collapses	1.96	2.35	1.68	1.90	-	-	1.96	2.18
Door 10								
Starts leaking	1.15	1.38	0.99	1.57	1.18	1.18	1.14	1.15
Stops leaking	1.23	1.47	1.05	-	-	-	1.20	1.34
Continues leaking	1.59	1.90	1.36	-	-	-	1.58	2.12
Collapses	1.96	2.35	1.68	1.90	2.24	-	1.96	2.18
Door 11								
Starts leaking	1.97	2.35	1.68	1.90	1.97	1.97	1.97	2.18
Collapses	2.54	-	2.19	-	-	-	-	-
Door 12								
Starts leaking	1.97	2.35	1.68	1.90	1.49	1.48	1.96	2.18
Collapses	-	3.00	-	2.33	2.85	11.67	2.48	2.67
Door 13								
Starts leaking	2.25	2.64	1.87	2.13	2.59	2.67	2.32	2.55
Collapses	3.13	3.52	2.68	2.72	3.54	-	2.96	9.93
Door 14								
Starts leaking	2.17	2.64	1.87	2.13	2.44	2.55	2.23	2.55
Collapses	2.97	3.71	2.55	2.72	3.37	-	2.96	6.56
Door 15								
Starts leaking	2.17	2.64	1.87	2.13	2.31	2.41	2.23	2.55
Collapses	2.84	4.49	2.43	2.58	3.24	-	2.84	-
Door 16								
Starts leaking	1.23	1.47	1.05	1.86	1.35	1.34	1.20	1.34
Collapses	-	-	-	-	3.54	-	-	-

	Ref	C_d		H_{coll}			A_{ratio}	
DECK 03		05	07	-25%	25%	50%	-50%	50%
Door 17								
Starts leaking	3.67	4.70	3.14	4.76	2.12	2.12	4.83	12.67
Stops leaking	3.79	4.73	3.25	-	2.22	-	-	-
Continues leaking	5.19	153.45	4.45	-	3.80	-	-	-
Collapses	-	-	-	-	-	-	-	-
Door 18								
Starts leaking	3.64	4.58	3.11	4.70	2.12	2.12	4.77	12.08
Stops leaking	3.79	4.80	3.25	-	2.22	-	-	-
Continues leaking	5.14	6.28	4.40	-	3.78	-	-	-
Collapses	-	-	-	-	-	-	-	-
Door 19								
Starts leaking	3.67	4.53	3.14	3.71	2.17	2.18	3.75	10.17
Stops leaking	-	-	-	-	2.27	-	-	-
Continues leaking	-	-	-	-	4.41	-	-	-
Collapses	-	-	-	-	-	-	-	-
Door 20								
Starts leaking	3.62	4.58	3.11	3.71	2.17	2.18	3.75	10.17
Stops leaking	-	-	-	-	2.27	-	-	-
Continues leaking	-	-	-	-	4.14	-	-	-
Collapses	-	-	-	-	-	-	-	-
Door 21								
Starts leaking	4.25	5.06	3.65	4.07	5.37	9.93	4.16	12.00
Collapses	-	-	-	-	-	-	-	-
Door 22								
Starts leaking	4.11	6.20	3.53	4.05	5.02	6.56	4.12	11.87
Collapses	-	-	-	4.97	-	-	-	-
Door 23								
Starts leaking	4.04	4.73	3.47	3.96	4.97	12.67	4.01	11.67
Collapses	-	-	-	-	-	-	-	-
Door 24								
Starts leaking	4.01	4.80	3.45	3.96	4.94	11.87	4.01	11.67
Stops leaking	-	-	-	-	-	12.00	-	-
Continues leaking	-	-	-	-	-	12.08	-	-
Collapses	-	-	-	-	-	-	-	-
Door 25								
Starts leaking	3.98	4.88	3.42	3.96	4.90	10.17	4.01	11.67
Collapses	-	-	-	-	-	-	-	-

6 CASE B – COLD ROOM DOORS

6.1 Damage Case

The main intention of this flooding scenario is to investigate the effects of the sliding cold room door parameters on flooding. Most of the cold rooms are typically located either on the bulkhead deck or directly below it. Thus the expected pressure head of the floodwater is rather small.

Note that in this study the watertight doors at frames #21 and #36 (see Figure 24) had to be kept open, against the regulations and good seamanship, in order to achieve more extensive progressive flooding in this damage case.

The size of the damage in this case is as follows:

- 5.0 m^2 to the workshops on Deck 03
- 5.0 m^2 to the F&B Stores on Deck 03

- 5.0 m^2 to the Central Store on Deck 02
- 5.0 m^2 to the Machinery Spaces on Deck 02

- 2.0 m^2 to the Void Spaces on Deck 01

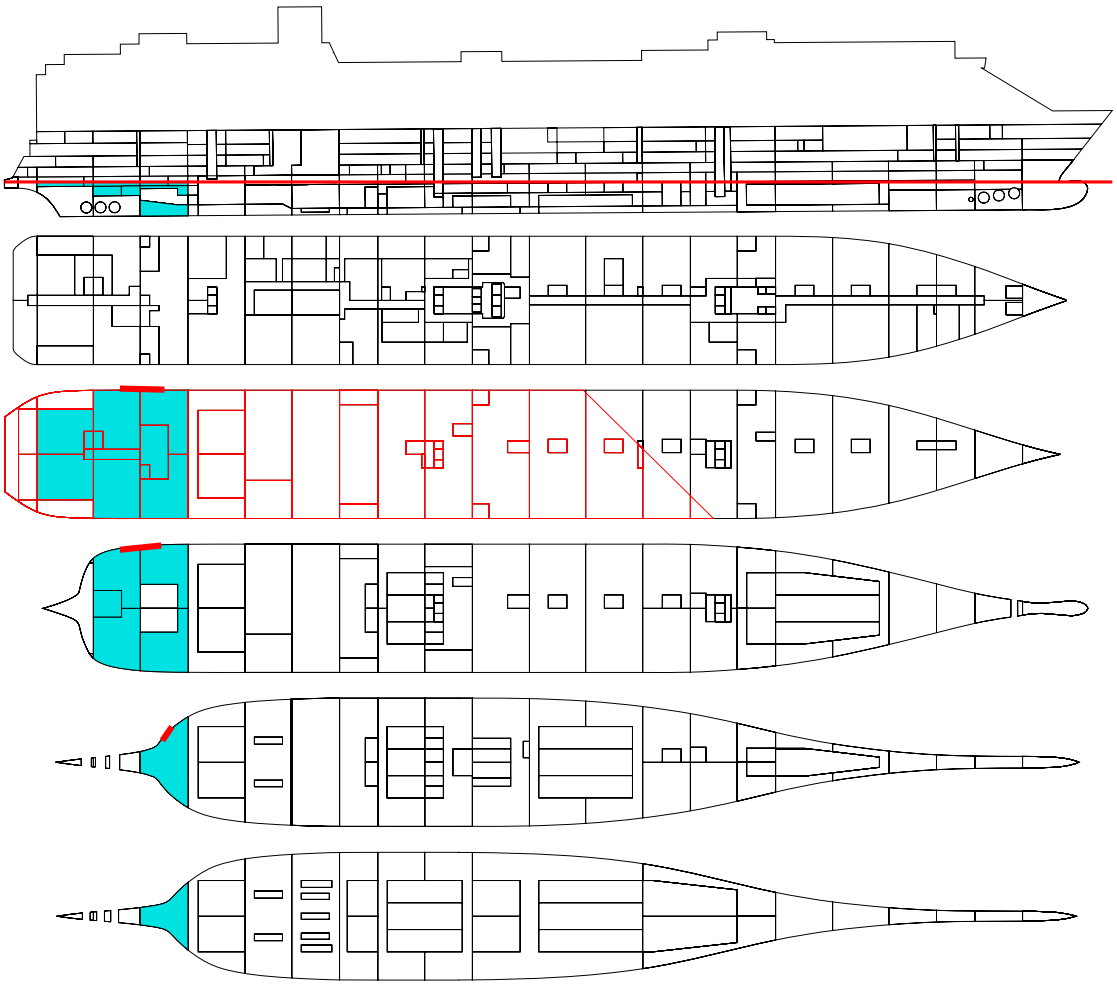

Figure 23: Studied damage scenario for Case B

6.2 Flooded Compartments

The flooded compartments consist of mainly cold stores. In addition there are some other stores, switchboard room, a workshop, corridors and staircases. The detailed general arrangement is presented in Figure 24. The openings and their numbering is presented below in Figure 25, and the progress of the flooding of the reference case in Figure 26.

The water proceeds into the ship through Decks 01, 02 and 03. On Deck 01 water fills the void spaces in the very aft of the deck and in the double bottom (Figure 23). Leaking starts immediately through doors 27 and 29, soon thereafter through door 41 and then through door 36 (Figure 25). It takes longer for the water to balance out on Deck 03 than on Deck 02 since there are two longitudinal bulkheads on the upper deck and only one in the lower deck. Moreover, on Deck 03 the water progresses also further to the aft part of the ship.

Unlike in the flooding Case A, the water does not rise to following decks through staircases, but each deck has their individual damage-hole. There are no spaces below the waterline that extend through more than one deck. Thus, the flooding in this scenario is in some sense “lateral.”

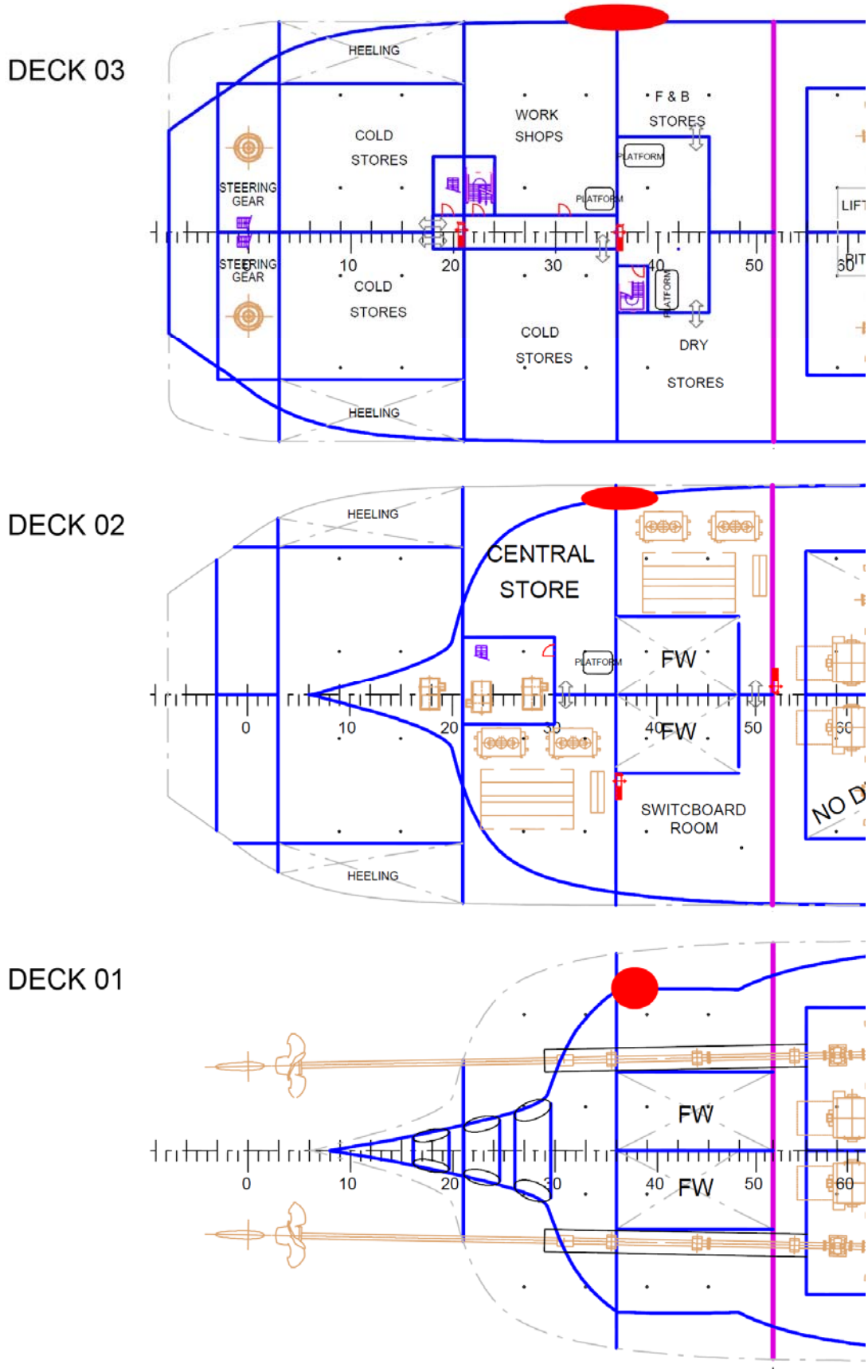

Figure 24: General arrangement of flooded area. The watertight doors at the frames #21 and #36 on Deck 03 are considered to be open. Damage on ship's side marked as red.

Type	Door ID					
A-SLIDING	40	41				
A-HINGED	26	27	32	34	36	39
COLDROOMDOOR	30	31	37			
WT	28	33	38			
OPEN	29	35				

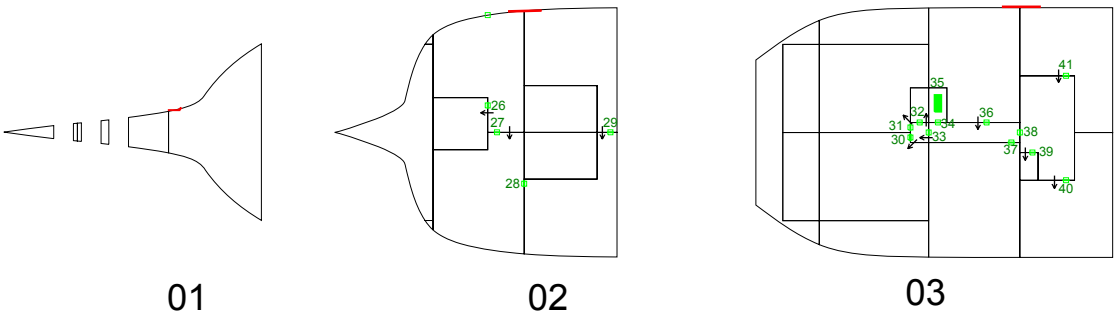

Figure 25: Openings, their types, numbering and apparent flooding directions.

PHASE	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	END
TIME (min)	0.00	0.12	0.13	0.21	0.24	0.34	0.38	0.66	0.71	0.74	0.84	0.99	1.02	1.10	1.22	1.25	1.51	226.65

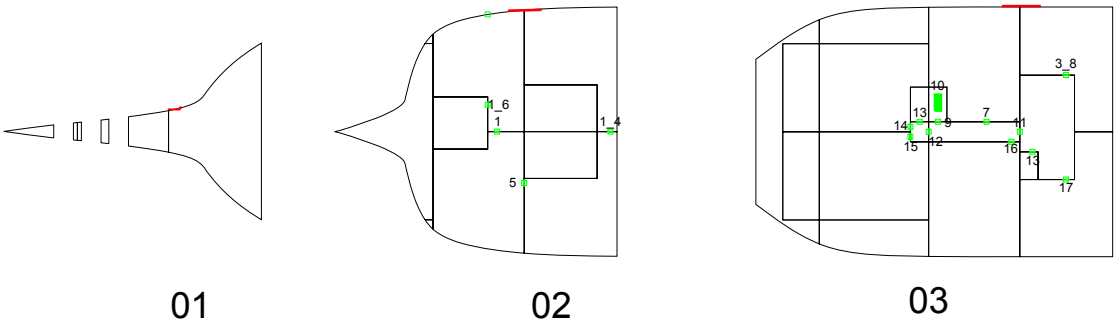

Figure 26: The flooding events in the reference case. A single number expresses the phase at which the door starts to leak. The possible number after an underscore character expresses the phase at which the door collapses. The time at which the events occur are tabulated.

6.3 Effect of the Discharge Coefficient

6.3.1 Parameters

Similarly to the flooding case A, the reference value of discharge coefficient for all openings is C_d = 0.6 and the comparative simulations were performed with C_d = 0.5 and C_d = 0.7, i.e. ±16.7%. Same value is applied to all openings in the 3D model of the ship.

6.3.2 Results

The damage hole is located higher and the volume of the flooded compartments is smaller than in the Flooding Scenario A.

Flooded water

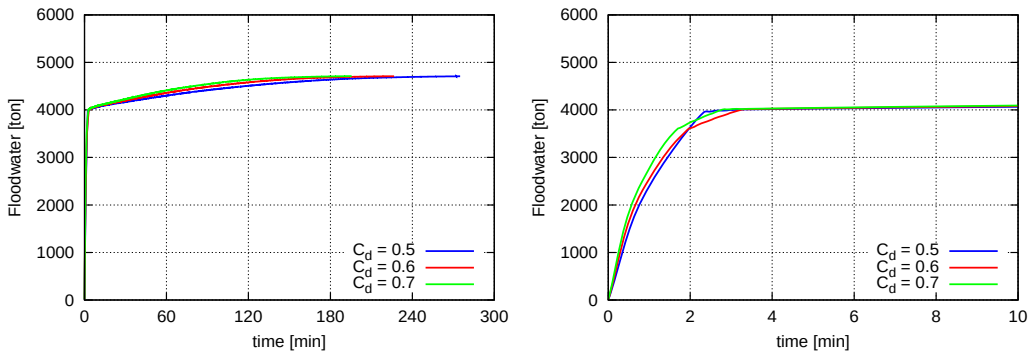

Figure 27: Time histories of floodwater volume with different discharge coefficients

- What can be noticed is that also in this flooding case the increase of the discharge coefficient increases the derivative of flooded water, i.e. faster flooding. And vice versa, decreasing the discharge coefficient hinders the flow, increasing the flooding time.

- Slight differences in the progress of water can be seen before the flooding has reached the stage at which all flooding is leaking through closed doors. With C_d = 0.6 and C_d = 0.7 the hindering is gradual, whereas with C_d = 0.5 it is quite sudden, soon after two minutes of elapsed time.
    - This is due to machinery spaces and switchboard room on deck 02 becoming full at the same time. With higher discharge coefficients these fill up one by one, but with C_d = 0.5 at once because of collapsing of door 27 (which only takes place with the smallest discharge coefficient).

Trim

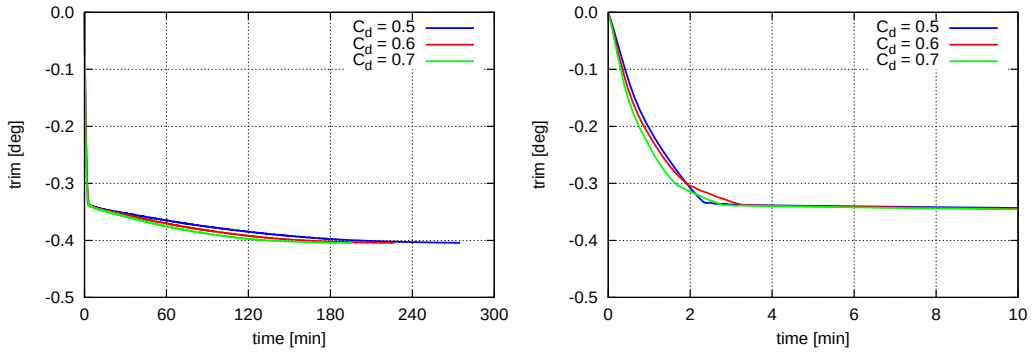

Figure 28: Time histories of trim with different discharge coefficients

Heel

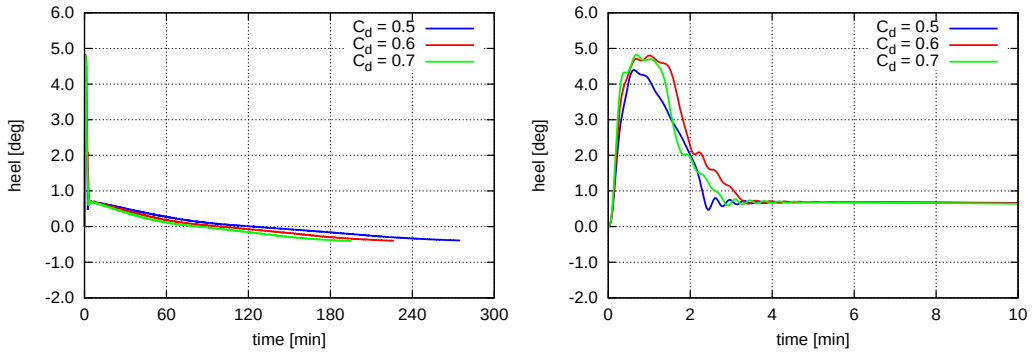

Figure 29: Time histories of heel with different discharge coefficients

- Significant differences do not occur.
- With discharge coefficient C_d = 0.5 the behavior of heeling has slightly different character and also the maximum transient heel is slightly smaller, when compared to the curves with C_d = 0.6 and C_d = 0.7.
    - The main reason for different natured behavior in heel is that also the door 27 collapses when C_d = 0.5, which allows the water to balance out faster on Deck 02, and thus decreases the maximum heel.

6.4 Effect of the Collapsing Pressure Head

6.4.1 Parameters

The guideline values for collapsing pressure heads, Table 2, *Ruponen and Routi (2011)*, are used as a reference. These values are varied by -25%, +25% and +50%, as was done in Case A.

6.4.2 Results

Flooded water

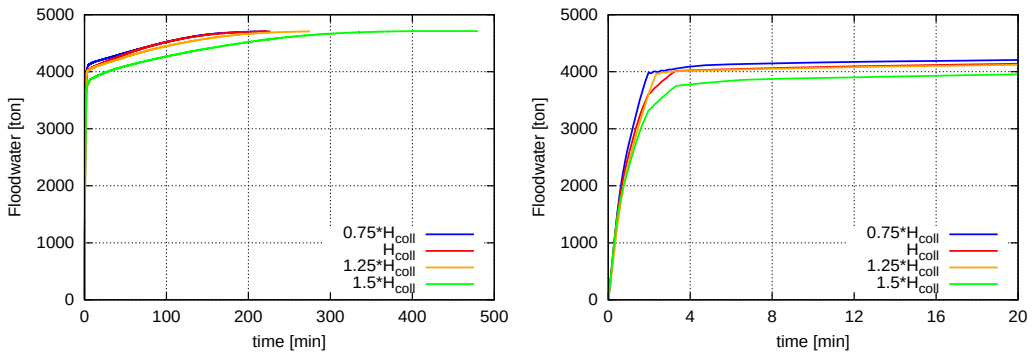

Figure 30: Time histories of floodwater volume with different collapsing pressure heads

- The smaller the H_{coll}, the faster the flooding.
    - This is due to larger number of collapsing doors, allowing the flooding to progress in the beginning through greater effective areas of the openings and thus with greater mass flow (Eq. 1). When the spaces behind the collapsed doors are filled up, the flooding rate decreases and continues with smaller mass flow through closed doors.
- By increasing the collapsing pressure heads of doors, the ship experiences such state where Deck 02 can be filled up, whereas there are still spaces on Deck 03 that the water has not even reached yet. However, this as such, does not have a great effect on the behaviour of the flooded ship.

Trim

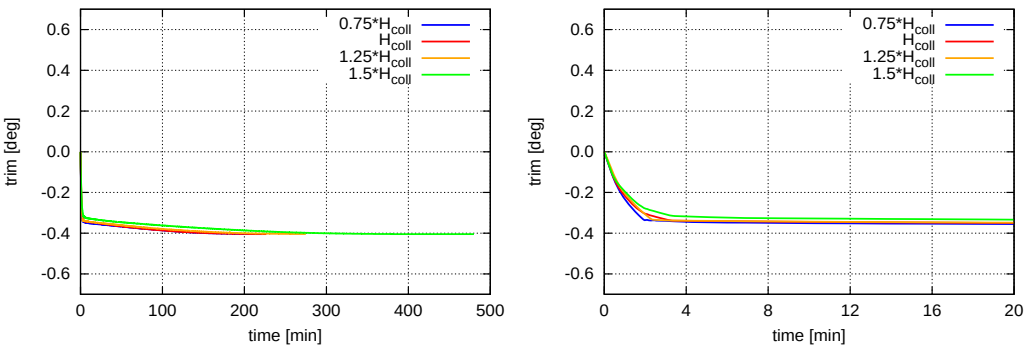

Figure 31: Time histories of trim with different collapsing pressure heads

Heel

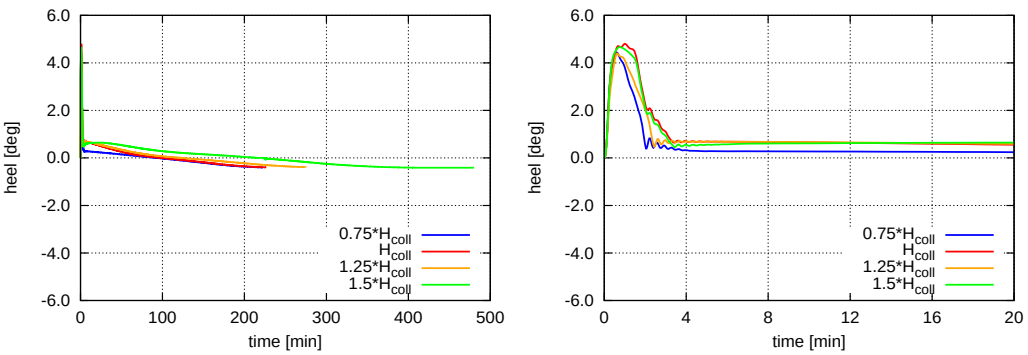

Figure 32: Time histories of heel with different collapsing pressure heads

- All curves have roughly the same nature.

- There are two differences between the reference H_{coll} and the increase by 50%:
  - In the reference case door 26 collapses at 0.34 minutes, whereas with +50% it does not collapse at all. The transverse centre of gravity of the space behind this door is slightly to port side. Therefore when this door is not collapsed, the portion of portside water accumulation is smaller. This results in a slightly smaller maximum heeling angle.
  - Door 41 also collapses in the reference case. The time at which this takes place is 0.66 minutes. When the door collapses, the water flows to the space with greater intensity. This space is in the very middle of the ship in transverse direction. This results that at first the center of gravity is on portside, but soon after does it settle to the centreline. At this point the heel reaches its maximum value in the reference case, remaining there for a moment before starting to decrease.

- There are three more doors that collapse when H_{coll} is decreased by 25%. These are doors 27, 41 and 40. The collapse of all these doors allow the water to accumulate more freely to the middle or opposite side of the ship.
  - Collapsing of doors 27 and 41 allow slightly more rapid decrease of heel from the maximum value, although at the time of collapse the heel is still increasing.
  - The effect of door 40 collapsing at 2 minutes allows the heel to decrease closer to the equilibrium value in a quite early stage of the flooding process.

6.5 Effect of the Leakage Modelling

6.5.1 Parameters

The base values for collapsing pressure heads (Table 2) are kept constant as in the previous Case A. The guideline values for leakage area ratio for different doors can be seen on Table 2. Significant changes of ±50% are applied.

6.5.2 Results

Flooded water

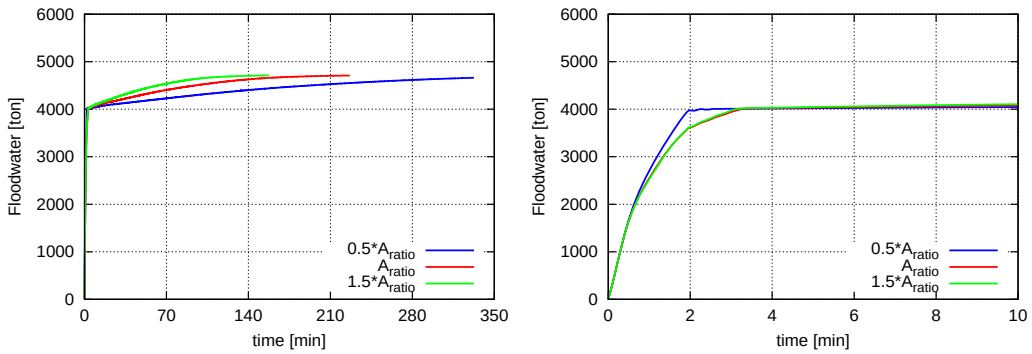

Figure 33: Time histories of floodwater volume with different leakage area ratios

- Sudden drop in the flood rate when A_{ratio} = 0.5 is again due to collapsing of door 27. For this reason the spaces on starboard side on Deck 02 fill simultaneously.
- With the reference values and when A_{ratio} is increased by 50% the door 27 does not collapse and therefore it takes more time for the machinery space to be filled up. This can be seen as a gradual drop in the flooding rate in these cases.
- A_{ratio} affects only the leaking through closed doors. This can be seen after the spaces behind the collapsed doors are filled up. Indirectly A_{ratio} affects also the water accumulation which can result in a collapsing of some doors, if it is decreased, resulting in smaller flow rates and thus increased pressure on the doors.

Trim

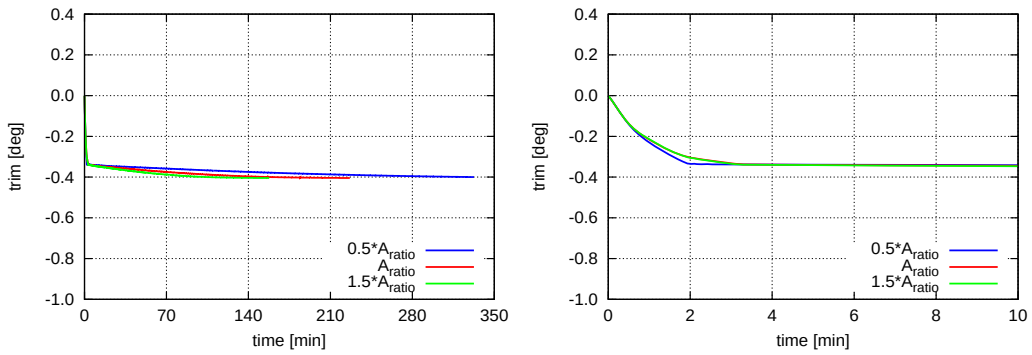

Figure 34: Time histories of trim with different leakage area ratios

Heel

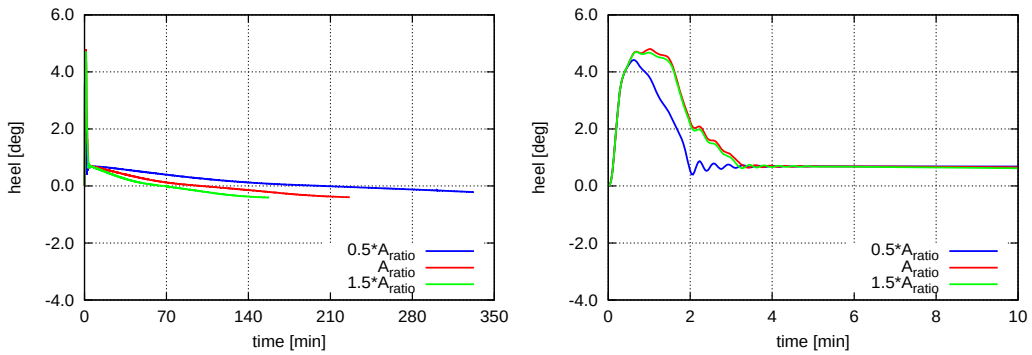

Figure 35: Time histories of heel with different leakage area ratios

- The maximum heeling angle is slightly smaller when A_{ratio} is decreased by 50%. This is also explained by the collapsing of door 27. This collapse takes place at 0.37 minutes, just before a notable difference in the heeling angle can be seen.

- It seems in the light of this small sample that if varying A_{ratio} does not affect to the collapsing of doors, the effect of this variation on heeling angle is very small.

6.6 Effects on the Flooding Events

The Flooding Case Scenario B being, as mentioned above, is kind of“lateral”, meaning that mose of the flooding takes place along the decks and not vertically. This results in the ship having only one peak in heeling which takes place always to the same side. The variation of the transient, maximum heel is slightly greater than in case A. The center of gravity of the flooded spaces in Case B is higher than in Case A. This results in a smaller effective pressure head, less of collapsing doors and thus in a longer flooding time.

The critical events of this Flooding Scenario B aren’t as apparent as in Case A. Rather, what seems to be critical is the amount of collapsing doors, whether their effect is immediate or not. This applies to the heel as well as to the floodwater accumulation and flood rate.

The flooding events with different parameters can be seen on Table 4, and their effects can be studied more closely with the Appendix B.

Table 4. . Case B - flooding events with different parameters.

	Ref	C_d		H_{coll}			A_{ratio}	
DECK 02		05	07	-25%	25%	50%	-50%	50%
Door 26								
Starts leaking	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Collapses	0.34	0.41	0.30	0.27	0.36	-	0.34	0.35
Door 27								
Starts leaking	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Collapses	-	0.43	-	0.37	-	-	0.37	-
Door 28								
Starts leaking	0.24	0.29	0.18	0.13	0.32	0.38	0.20	0.25
Collapses	-	-	-	-	-	-	-	-
Door 29								
Starts leaking	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Collapses	0.21	0.26	0.15	0.12	0.30	0.36	0.20	0.22
DECK 03								
Door 30								
Starts leaking	1.22	1.52	1.07	1.04	1.74	2.03	1.15	1.37
Collapses	-	-	-	-	-	-	-	-
Door 31								
Starts leaking	1.10	1.38	0.96	0.93	1.47	1.78	1.03	1.22
Collapses	-	-	-	-	-	-	-	-
Door 32								
Starts leaking	1.02	1.31	0.90	0.86	1.30	1.62	0.97	1.15
Collapses	-	-	-	-	-	-	-	-
Door 33								
Starts leaking	0.99	1.25	0.87	0.82	1.22	1.51	0.92	1.07
Collapses	-	-	-	-	-	-	-	-
Door 34								
Starts leaking	0.71	0.82	0.51	0.62	0.71	0.71	0.77	0.66
Collapses	-	-	-	-	-	-	-	-
Door 35								
Starts leaking	0.74	0.96	0.63	0.75	0.75	5.70	0.80	0.74
Collapses	-	-	-	-	-	-	-	-
Door 36								
Starts leaking	0.38	0.43	0.35	0.37	0.39	0.38	0.37	0.38
Collapses	-	-	-	-	-	-	-	-
Door 37								
Starts leaking	1.25	1.52	1.10	1.04	2.30	2.92	1.15	1.40
Collapses	-	-	-	-	-	-	-	-
Door 38								
Starts leaking	0.84	1.13	0.76	0.66	1.69	2.44	0.77	1.07
Collapses	-	-	-	-	-	-	-	-
Door 39								
Starts leaking	1.02	1.28	0.90	0.82	2.93	3.06	0.92	1.22
Collapses	-	-	-	-	-	-	-	-
Door 40								
Starts leaking	1.51	1.54	1.30	1.12	3.69	4.76	1.18	1.57
Collapses	-	-	-	2.03	-	-	-	-
Door 41								
Starts leaking	0.13	0.18	0.15	0.13	0.13	0.13	0.13	0.13
Collapses	0.66	0.97	0.61	0.42	-	-	0.60	0.92

7 CASE C – EXTENSIVE FLOODING

7.1 Damage Case

In principle, this is a slightly more extensive version of the Case A. The damage extends to two other watertight compartments. The additional damaged rooms are voids around tanks, and thus the transient heeling angle in the beginning of the flooding process is significantly larger than in the Case A. Eventually cross-flooding between the voids equalizes the ship and the heeling in the final equilibrium is small.

The idea is to study the possible effects of larger heeling as the case comparable to the Case A.

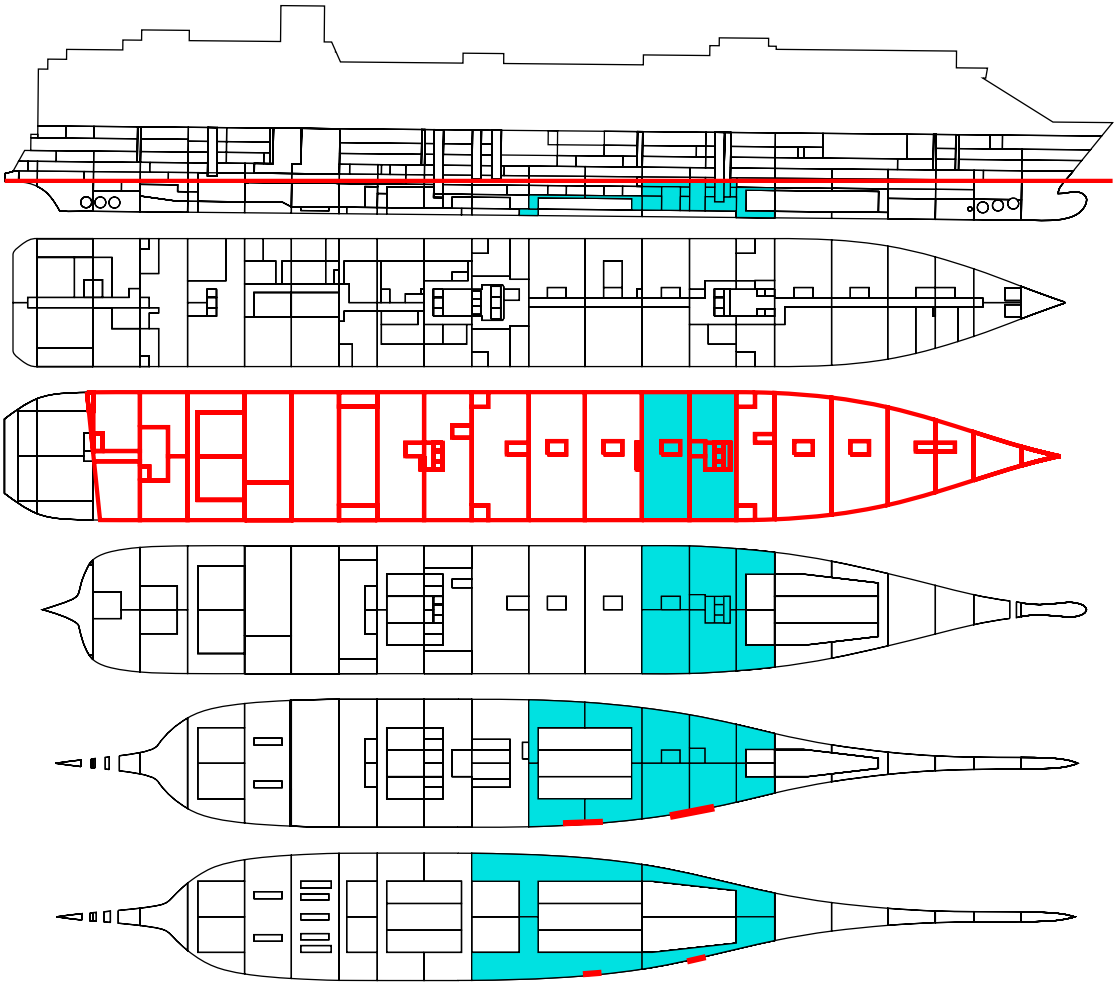

Figure 36: Studied damage scenario for Case C

The damage openings to the fore part are identical to the Case A:

- 5.0 m^2 to the double bottom
- 2.0 m^2 to the store on Deck 01
- 3.0 m^2 to the laundry on Deck 01

In addition, there is a damage hole at frame #183 to the voids. The total size of this additional damage hole is 12.0 m^2 (4.0 m^2 to each damaged void).

7.2 Results

7.2.1 Effect of the Discharge Coefficients

Floodwater

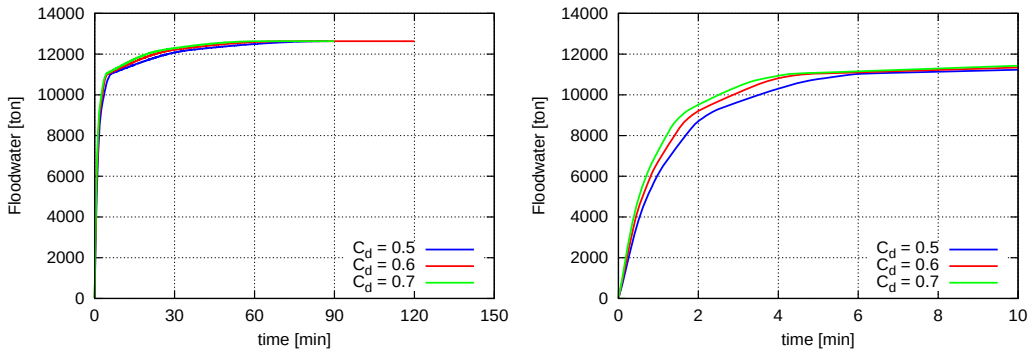

Figure 37: Time histories of floodwater volume with different discharge coefficients

- The flooding is very similar to the Case A, only the amount of floodwater is greater.

Trim

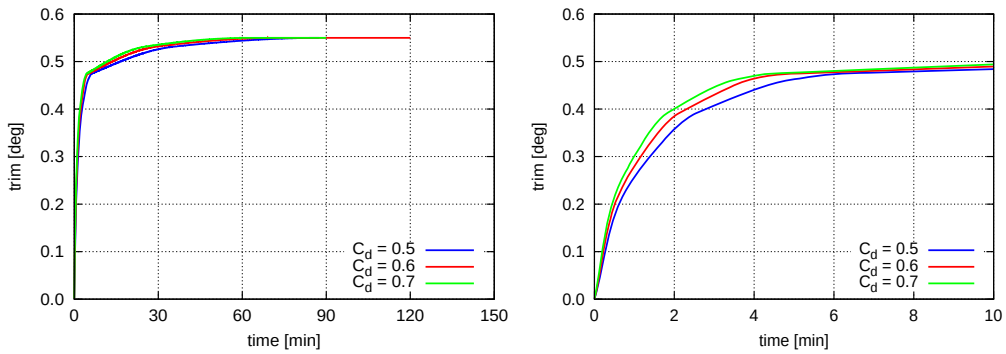

Figure 38: Time histories of trim with different discharge coefficients

Heel

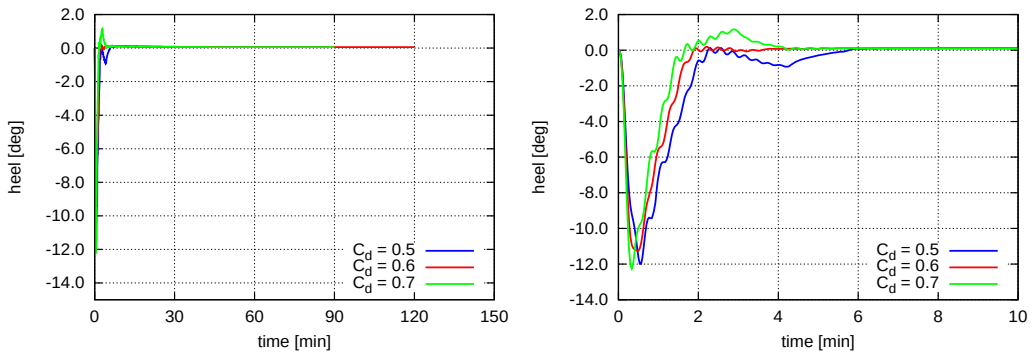

Figure 39: Time histories of heel with different discharge coefficients

- The behaviour is analogous to Case A with C_d = 0.5 and C_d = 0.7 when compared to the reference case with C_d = 0.6.

- The transient heeling angle is significantly larger than in Case A due to more extensive damage and asymmetric flooding.
    - As in Case A the maximum heeling is practically independent on the applied discharge coefficient.

- On the reference case when C_d = 0.6 at 2 minutes on Deck 02, doors from staircases to the Deck 02 collapse simultaneously on port and starboard side. This results in the ship maintaining almost a zero heeling angle after the transient heel.

7.2.2 Effect of the Collapsing Pressure Head

Floodwater

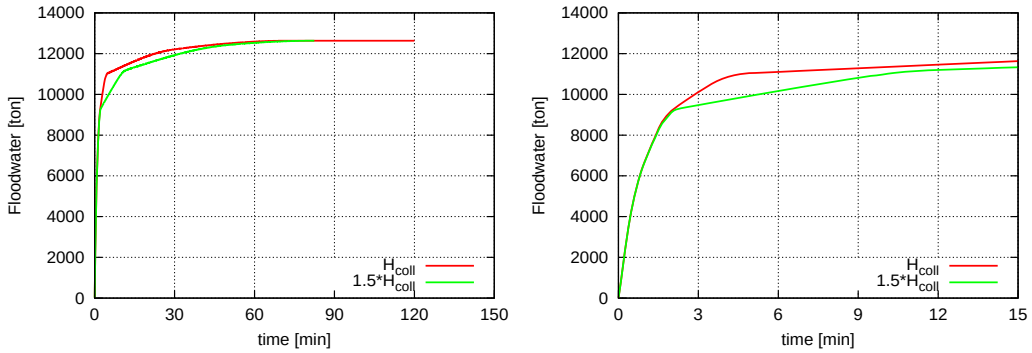

Figure 40: Time histories of floodwater volume with different collapsing pressure heads

- The higher the H_{coll}, the more does it hinder the flowing, as in Case A. This is a result of smaller amount of collapsing doors, which results in smaller effective area of openings and thus smaller mass flow.

- The two clear hindrances are that can be noticed in both curves are times at which the water reaches Deck 03, and a time at which all flooding is leaking through closed doors. These events take place earlier when H_{coll} is increased by 50% for two reasons:
    - There are less of collapsing doors, therefore faster rising to Deck 03
    - The less of doors collapse, the more are there doors to leak.

Trim

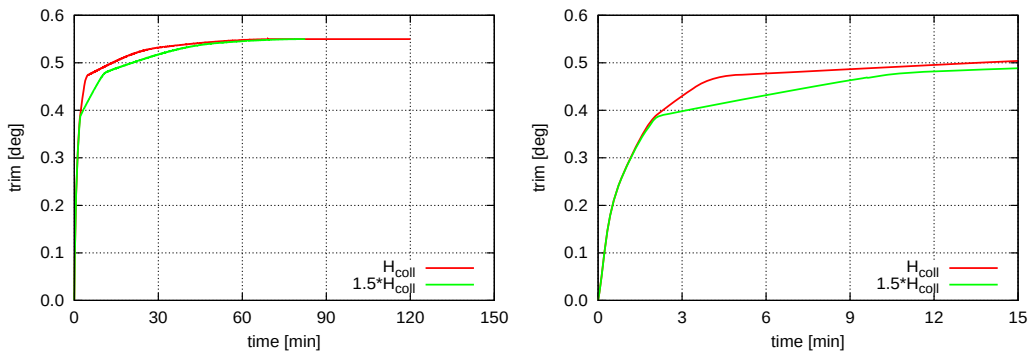

Figure 41: Time histories of trim with different collapsing pressure heads

Heel

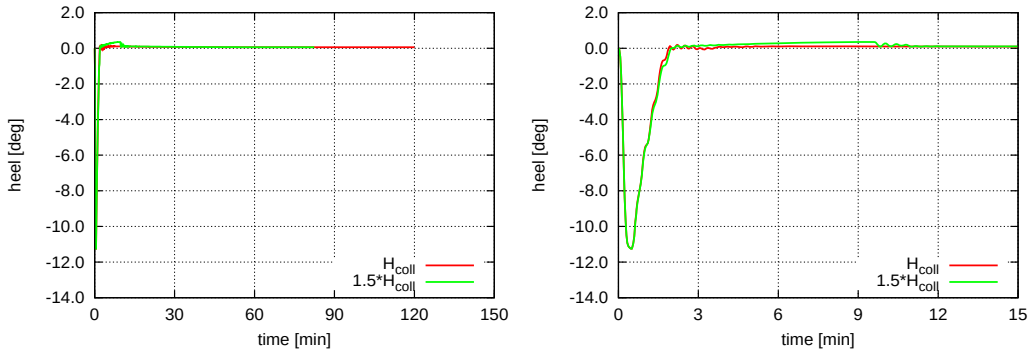

Figure 42: Time histories of heel with different collapsing pressure heads

- The effect of varying the collapsing pressure head is negligible at the first peak.
- With H_{coll} +50%, like in Case A, there is no collapsing of any door on Deck 02 at around 2 minutes. Therefore there is only very moderate water accumulation to the portside. The increased heel starts evening out at around 10 minutes

7.3 Effect on the Flooding Events

As mentioned above, Case C follows the behaviour of Case A quite analogously. The only difference is the much larger transient heeling in the beginning of flooding. The reason for such behaviour is very clear in the light of previous results in this report. The collapsing order of the doors 7, 8, 9 and 10 on Deck 02 is critical. Without any parameter variation in this Case C, those doors on that deck collapse simultaneously resulting in a non-existent second heel.

Even with this extensive damage and asymmetric flooding the maximum transient heeling angle is only 12°. The simulations were done with the dynamic roll motion calculation. Thus the direct stability analysis (GZ curve) at the time of the maximum heel angle is not possible. However, considering that the heeling is much less than the typical criterion of capsizing for steady heeling of 20° it may be concluded that there is no risk of capsizing.

Based on this study, it seems that the applied opening parameters do not have a significant effect on the maximum transient heeling angle in the beginning of the flooding.

8 CROSS-FLOODING DUCTS

8.1 Background

Previously known as the Resolution A.266 (VIII), the regulation has been recently updated, *IMO (2007)*. However, the basic concept and equations have remained the same. Most notably, the effect of counter air pressure was included in the rule. This needs to be taken into account if the area of the air pipes is less than 10 % of the effective area of the cross-flooding ducts.

The resolution allows four alternative methods for assessing the equalization time:

- Simplified formula
- Computational fluid dynamics (CFD)
- Time-domain flooding simulation
- Model tests

CFD tools can be used in two different ways: either only for evaluation of the effective discharge coefficient of the duct or for calculation of the cross-flooding time. In the latter case the CFD solver should be coupled with the simulation of the ship motions during the flooding.

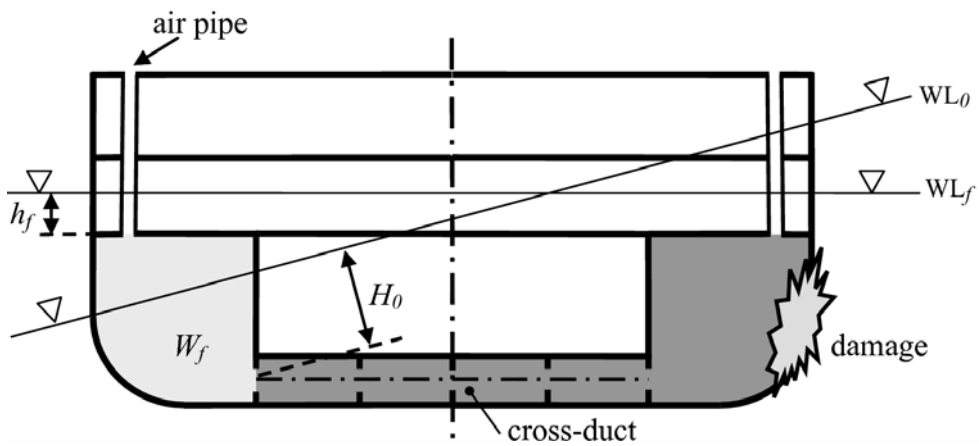

Figure 43: Definitions for cross-flooding, the dark shaded area is considered to be instantly flooded.

8.2 Arrangement and Damage Scenario

A comprehensive case study was performed in order to assess the effect of different methods for determination of the discharge coefficients on the cross-flooding time. The Sample Ship Design A was used. A two-compartment damage scenario was selected to represent a situation with large heeling due to the asymmetric distribution of the floodwater. The flooding on the upper decks is assumed to be instantaneous. As a result, the initial heeling angle before the cross-flooding is 5.2°. The damage scenario is illustrated in Figure 44.

The empty tanks in the double bottom are connected by two parallel 18 m long cross-ducts with two manholes in the girders. This is the longest duct design (Case C6) that has been tested in model-scale 1:3, *Stening (2010), Stening et al. (2011)*. Since the web frame in the middle of the tested duct did not have a notable effect on the discharge coefficient, the results of the model tests are assumed to be applicable also to parallel ducts.

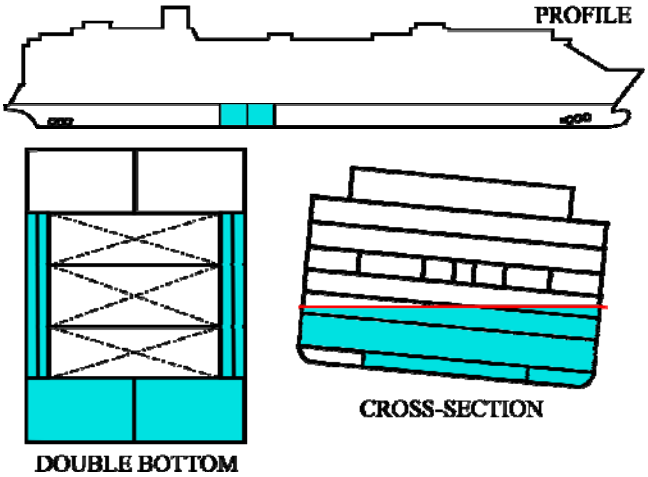

Figure 44: Case study for cross-flooding calculation

The tanks are ventilated through air pipes (Case 1 in chapter 5), containing two 90° double mitre bends and free outlet to the atmosphere without any valve or an air cap. The area of the air pipe is 4.9% of the total area of the cross-flooding openings. Consequently, according to MSC.245(83) the air compressibility needs to be accounted.

8.3 Calculations

Calculations for the cross-flooding time were performed with the NAPA software, using both the time-domain flooding simulation feature (*Ruponen, 2007*) and the simplified method of MSC.245(83). In the simulation the actual air compression inside the tanks was calculated. The applied time step was 0.1 s. In the simplified approach the effective discharge coefficient of the cross-duct was modified, based on the pressure losses in the air pipe. Comparative calculations were also performed with the assumption of full ventilation in the tanks.

The applied discharge coefficients for the cross-ducts and the air pipes are presented in Table 5. First the regression equation for this type of duct (*Pittaluga and Giannini, 2006*) is used to calculate the pressure loss coefficient for each space between two adjacent girders:

$$k_i = 0.0424 L_i^{\,3} - 0.3593 L_i^{\,2} + 1.1401 L_i - 0.356, \quad 1 \le L_i \le 4\,, \tag{6}$$

where L_i is the distance between two adjacent girders in meters. In this case L_i = 3.0 m.

The second approach uses the following equation for accounting pressure losses in successive openings:

$$\sum k = k_1 + \sum_{i=2}^{N} k_i \cdot \frac{S_1^2}{S_i^2}\,, \tag{7}$$

where S_i is the area of the opening i. Thus the pressure losses, weighted by the square of the relative area, are summed. This is a very simple approach and it does not take into account any effects from the stiffeners. In this study rough estimation of C_d = 0.6 for each manhole. Consequently, the pressure loss coefficient for each girder is k_i = 1.778.

With both methods, the outlet (k_i = 1) is accounted in the calculation of the discharge coefficient. In the third approach the experimental result from the model test (*Stening et al., 2011*) is used.

Table 5: Discharge coefficients for the cross-duct and air pipe.

Item	Calculation method	C_d
Cross-duct	MSC.245(83), *Pittaluga and Giannini (2006)*	0.382
Cross-duct	Subsequent manholes, Eq. (7)	0.273
Cross-duct	Model tests, *Stening et al. (2011)*	0.287
Air pipe	CFD, Deliverable D.2.4b	0.580
Air pipe	MSC.245(83)	0.533

The air compression effect in the simplified method was taken into account according to the Eq. (9). The applied reference density of air in atmospheric pressure is 1.177 kg/m^3 and water density is 1025 kg/m^3. The resulting additional pressure-loss coefficient is presented in Fig. 19 as a function of the air pipe discharge coefficient.

8.4 Results

The cross-flooding times, calculated by using the simple calculation method of MSC.245(83), are presented in Table 6. The corresponding results of time-domain flooding simulations are given in Table 7. The regression Eq. (6) over-estimates the discharge coefficient by 39%, when compared to the measured value. Consequently, the calculated cross-flooding time is about 25% faster.

Air compression in the tank clearly delays the cross-flooding time by 6% .. 11%. Although the difference in the applied C_d for the air pipes is notable (about 9%), the effect on the time is much smaller (less than 2%). This suggests that the simplified approach for accounting the pressure losses in the air pipes might be accurate enough for many practical applications.

The simplified method for calculation of the cross-flooding time provides very similar results to the time-domain flooding simulation. The maximum difference is only about 2%. The maximum simulated overpressure in the tanks is about 10 kPa. Eventually the whole tank is filled up and thus the air pressure does not decrease back to the atmospheric pressure. The volume of floodwater in this tank increases almost linearly. This partly explains the good correlation between the simplified method and time-domain simulation.

Table 6: Cross-flooding times [s] with the simple calculation method, MSC.245(83)

Calculation method for cross-duct C_d:	full ventilation	C_d for air pipes:	
		MSC.245(83)	CFD
MSC.245(83), *Pittaluga and Giannini (2006)*	46.0	51.1	50.3
MSC.245(83), Eq. (7)	64.4	68.1	67.6
Model test, *Stening et al. (2011)*	61.2	65.1	64.6

Table 7: Cross-flooding times [s] with the time-domain flooding simulation.

Calculation method for cross-duct C_d:	full ventilation	C_d for air pipes:	
		MSC.245(83)	CFD
MSC.245(83), *Pittaluga and Giannini (2006)*	46.4	52.1	51.1
MSC.245(83), Eq. (7)	64.8	68.6	67.9
Model test, *Stening et al. (2011)*	61.7	65.7	65.0

9 CONCLUSIONS

Systematic variations of input parameters for simulation of progressive flooding in a damaged passenger ship have been performed. Some minor modifications to the Sample Ship Design A of the FLOODSTAND project were necessary in order to increase the asymmetry of flooding during the intermediate phases. In general, SOLAS2009 damage stability regulation tends to drive towards designs with as few longitudinal bulkheads as possible. Thus the flooding cases are mainly symmetric. The target of this study was to carry out research on the effects of opening parameters on the flooding process and indirectly also to the survivability of the ship. Thus it was considered to be necessary to add some longitudinal bulkheads in order to achieve larger heel angles in the beginning of the flooding.

In the presented studies, no parameter variation whatsoever seemed to have any significant effect on the maximum transient heel. No change to this conclusion was justified even with the extensive and asymmetric flooding in the Case C. On the other hand, the applied parameters had notable effects on the time-to-flood and on the progress of flooding and the heeling after the transient phase. For example, variation of discharge coefficient affected directly the flooding time and indirectly the collapses of doors. An interesting result in the light of heel was in Case A when the heeling after the transient peak took a different direction with a lower discharge coefficient, C_d = 0.5 (in comparison to the reference value 0.6).

Variation of critical pressure head for collapse had the most apparent effect on the way the flooding progressed. In this way it affected the nature of the heeling behaviour, but it also had an effect on the flooding rate and thus on the time-to-flood.

Leakage area modelling had a clear effect on the time-to-flood. This effect became apparent after the early flooding phases when most of the flooding was based on leaking through closed doors. If the variation of A_{ratio} did not have an effect on the collapse of doors, the consequent effects especially on heel were almost non-existent.

These sensitivity studies created some thoughts on the order of door collapses with time. If two closed doors with an equal nominal collapse pressure head lead out of a single flooded room, it might still be possible, due to the standard deviation of the ultimate strength, that one of them will collapse before the other. Basically, such doors, when exposed to the same water pressure, should collapse simultaneously. However, it might still be useful to consider other alternatives, with their probabilities, too. In numerical simulations this would only necessitate the implementation of a model for the relevant probability distribution(s) and additional flooding calculations (based on Monte Carlo simulations) as feasible. Such calculations would shed more light on the possible outcomes of the flooding and also on their probabilities.

In a flooding case, where most of the flooding is leaking through closed doors, such as the Case B, the applied leakage area ratios have a significant effect on the time-to-flood. E.g. underestimation by 50% can lead to up to 50% overestimation in the time-to-flood, Figure 33 on page 29. However, the effects on the behaviour of flooding (e.g. order of flooded compartments) were minimal. Thus the conservative approach is to use slightly too large leakage area ratios in order to avoid the over-estimation of time-to-flood.

Based on the presented studies, it seems to be well justified to use the industry standard discharge coefficient 0.6 for all openings, except the pipes and cross-flooding devices. Based on the CFD and model tests in Tasks 2.3 and 2.4 of the FLOODSTAND project, this value is very realistic. In addition, small variations (0.5 or 0.7) had only small effects on time-to-flood and the flooding characteristics.

Based on this study, it seems that the applied opening parameters do not have a significant effect on the maximum transient heeling angle in the beginning of the flooding.

The simplified formula for calculation of cross-flooding time, MSC.245(83) provides very similar results as detailed time-domain flooding simulation. However, the effective discharge coefficient for the duct should be determined with Eq. (7) or with CFD since the use of the regression Eq. (6) results in significantly too fast cross-flooding times.

As a final conclusion, it must be noted that the real flooding of a ship always contains several uncertainties. It is practically impossible to model all possible routes that the floodwater can progress. The opening parameters cannot either be modelled accurately. Instead, the flooding simulation results should be treated as indicative since they are always based on a number of simplifications and approximations. However, the simulation results provide a reasonable estimation on the time-to-flood and valuable information on the flooding process, especially during the intermediate phases. Furthermore, it is noteworthy that flooding simulation with sophisticated CFD tools, even if combined with FEM solutions for leaking and collapsing structures, would not provide any more realistic or accurate results since it is still impossible to model every detail that has effect on the flooding.

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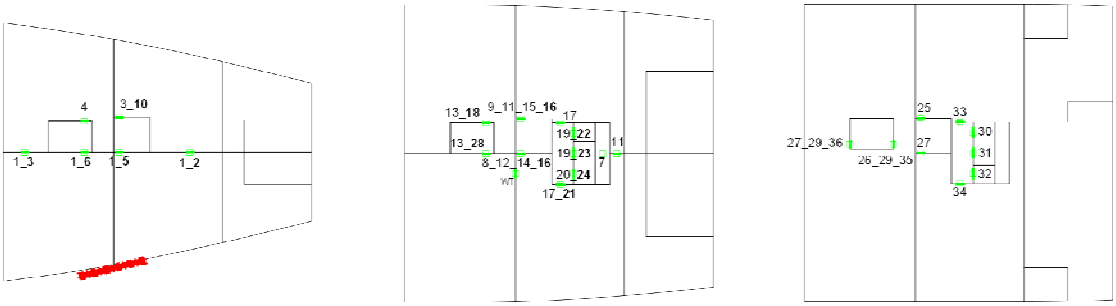
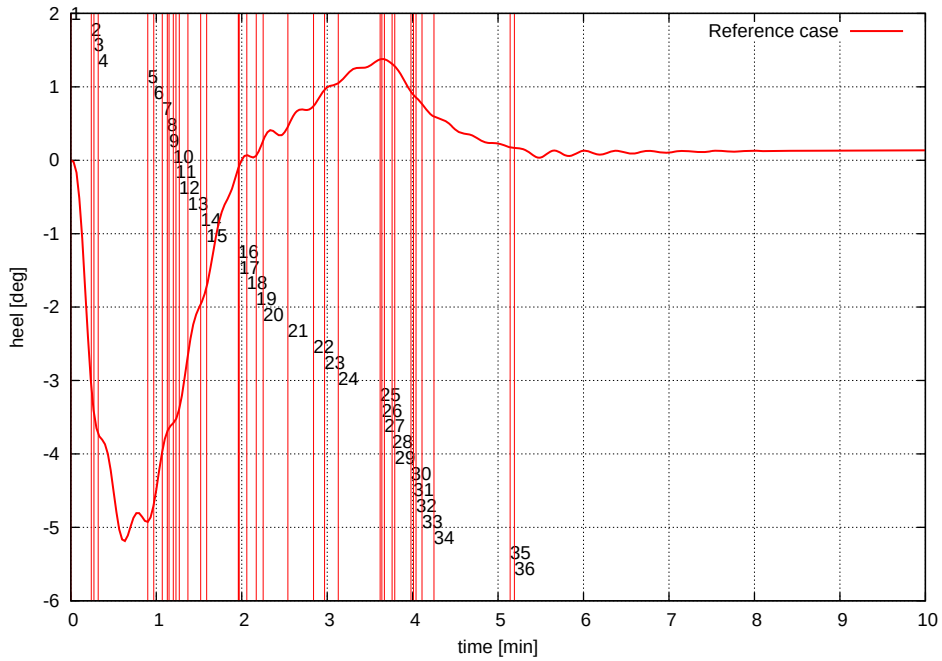
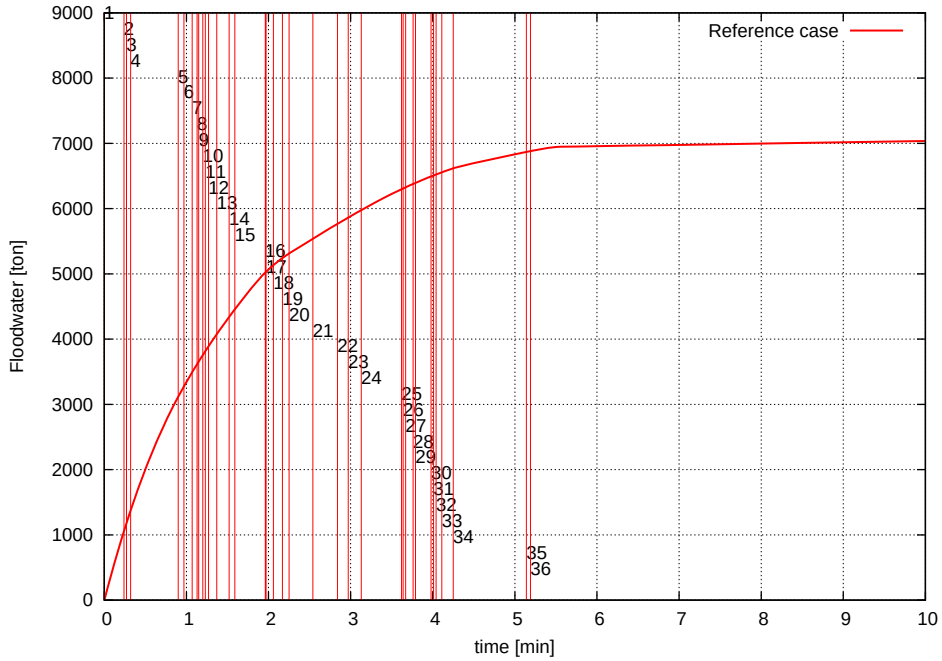
APPENDIX A: Flooding Events for Case A

Reference Case







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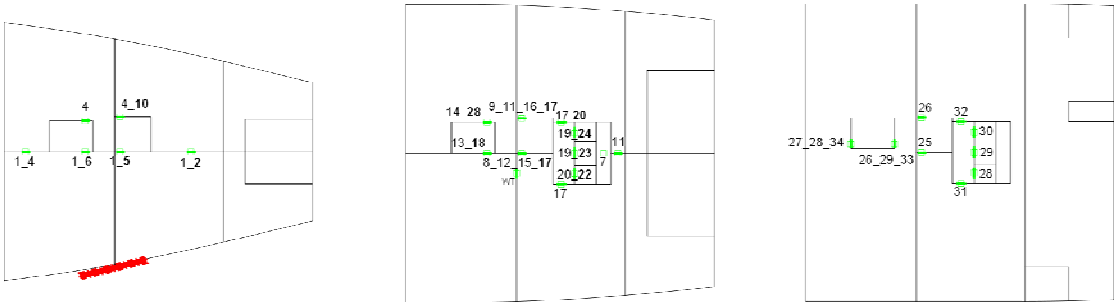
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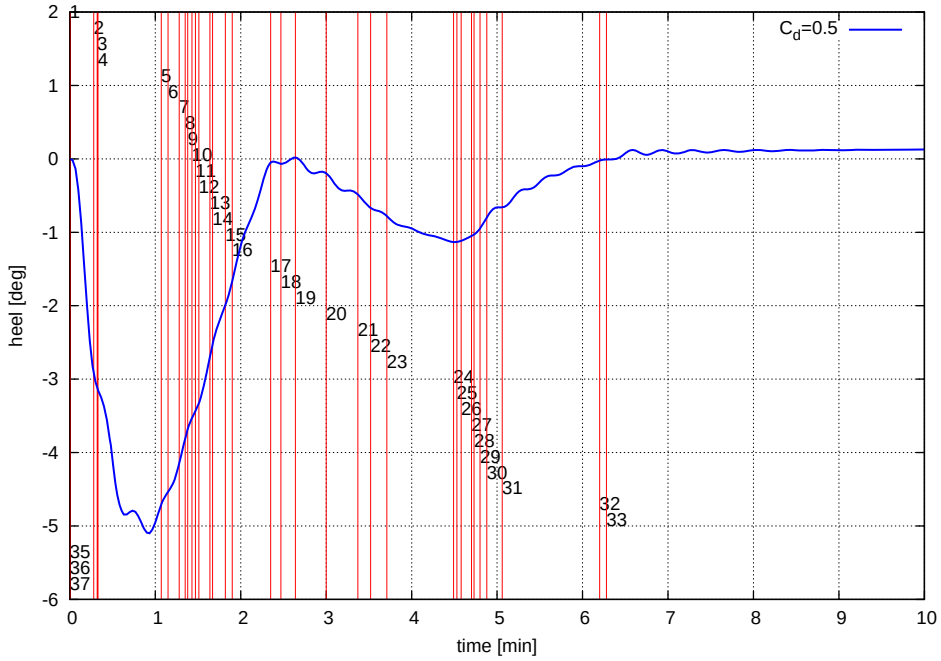
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time [min]
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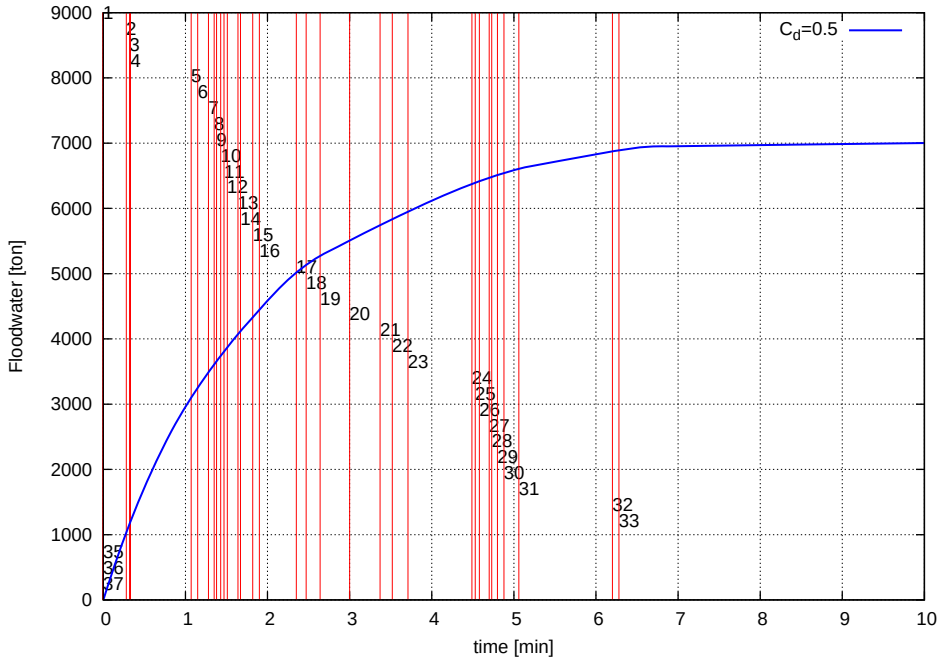
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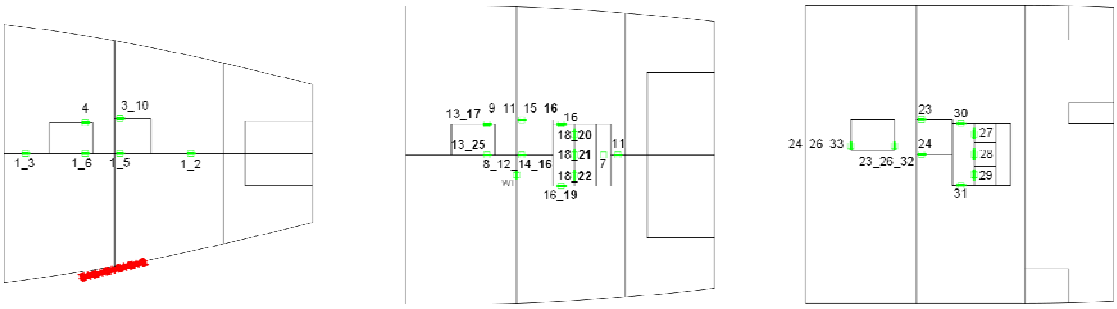
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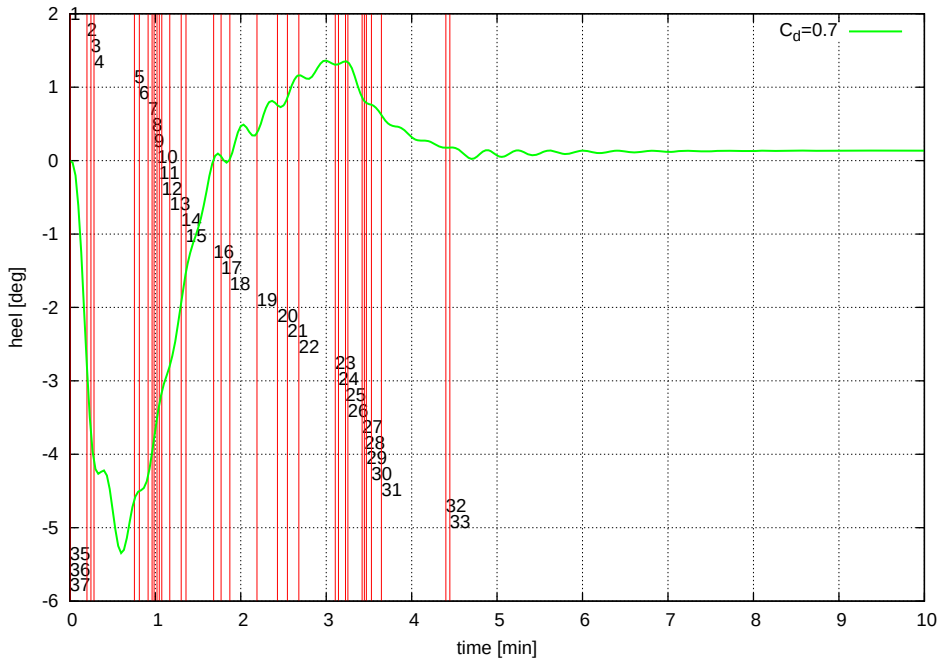
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time [min]
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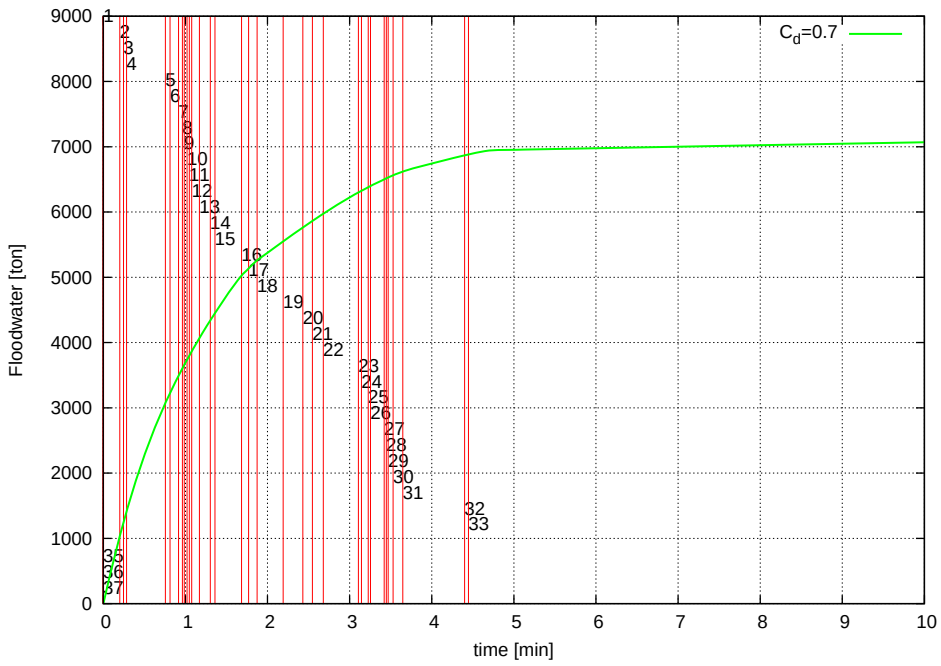
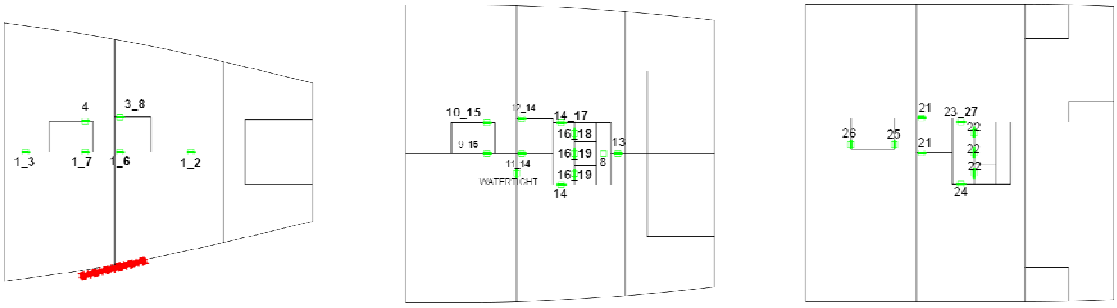

Floodwater [ton]
time [min]
Cd=0.7

0.75·H_{coll}



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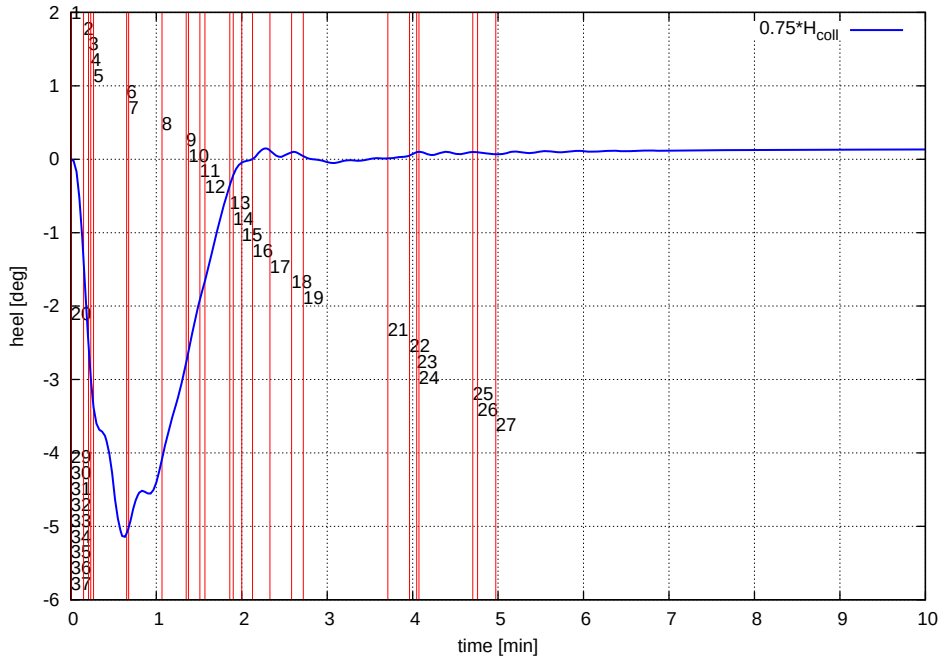

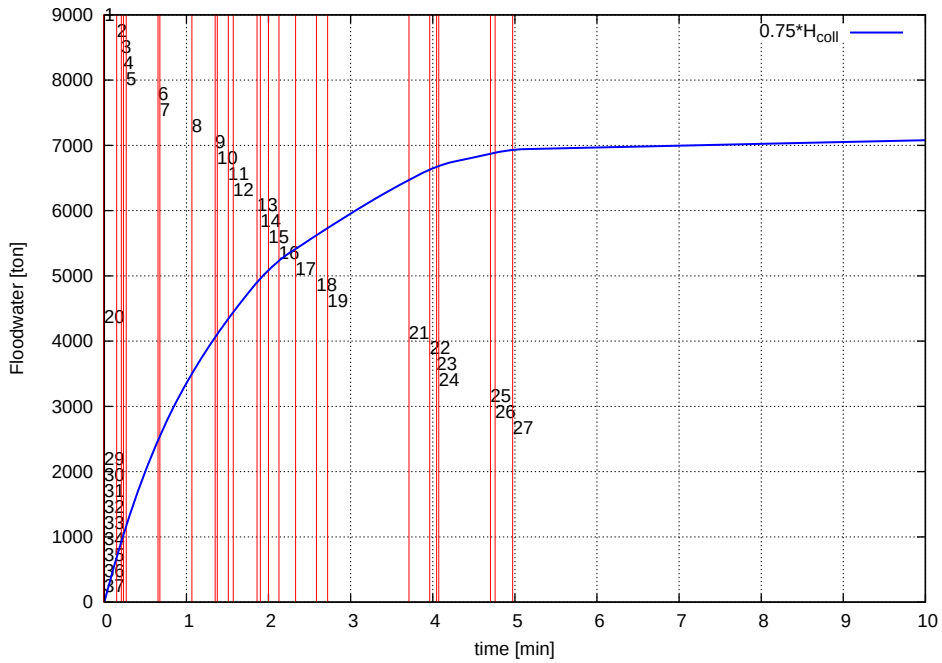

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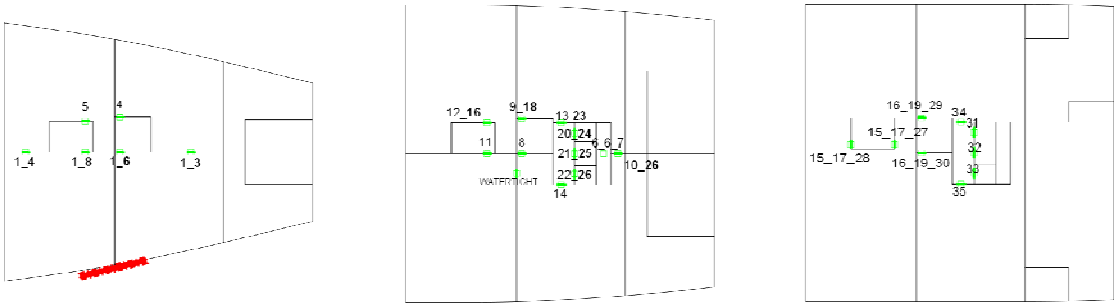
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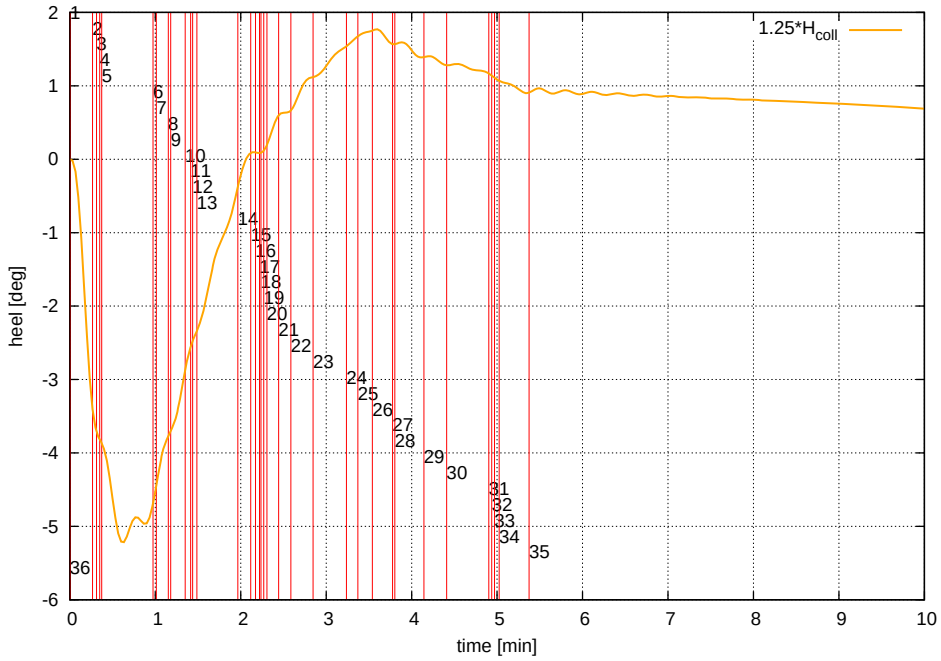
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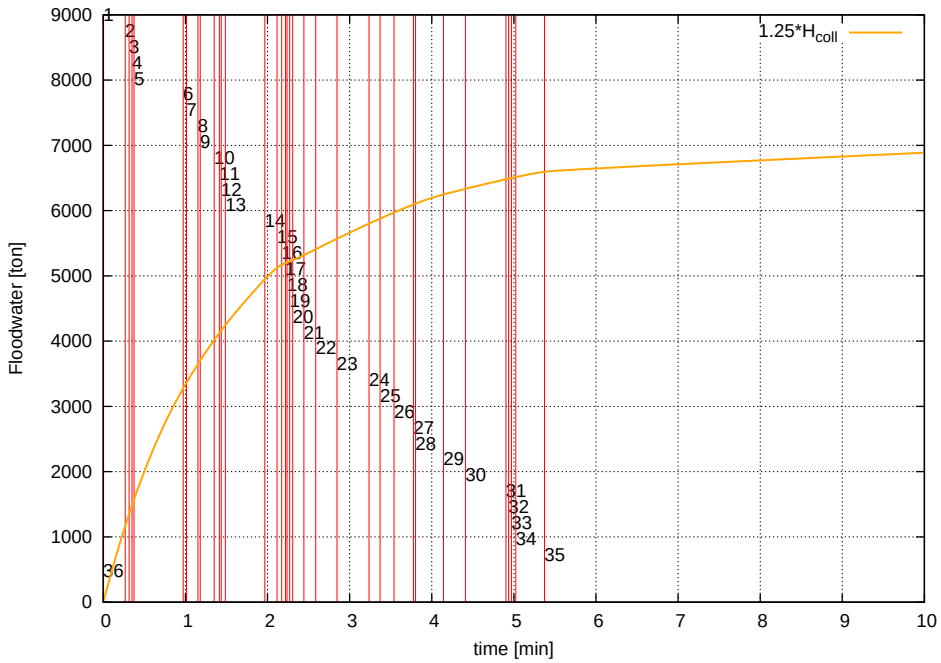
heel [deg]
time [min]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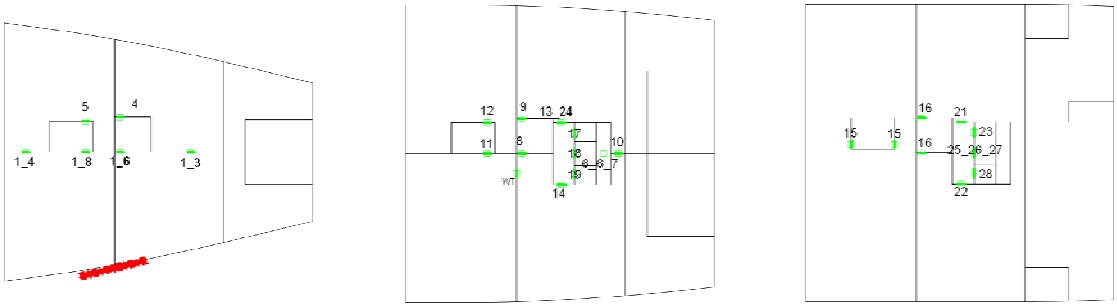
time [min]

1.5·H_{coll}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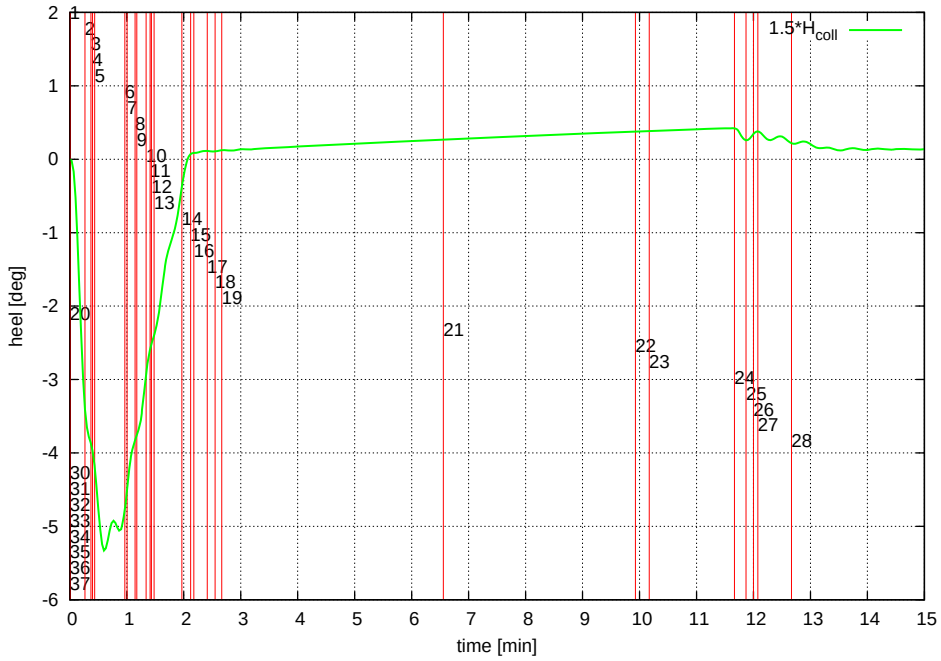
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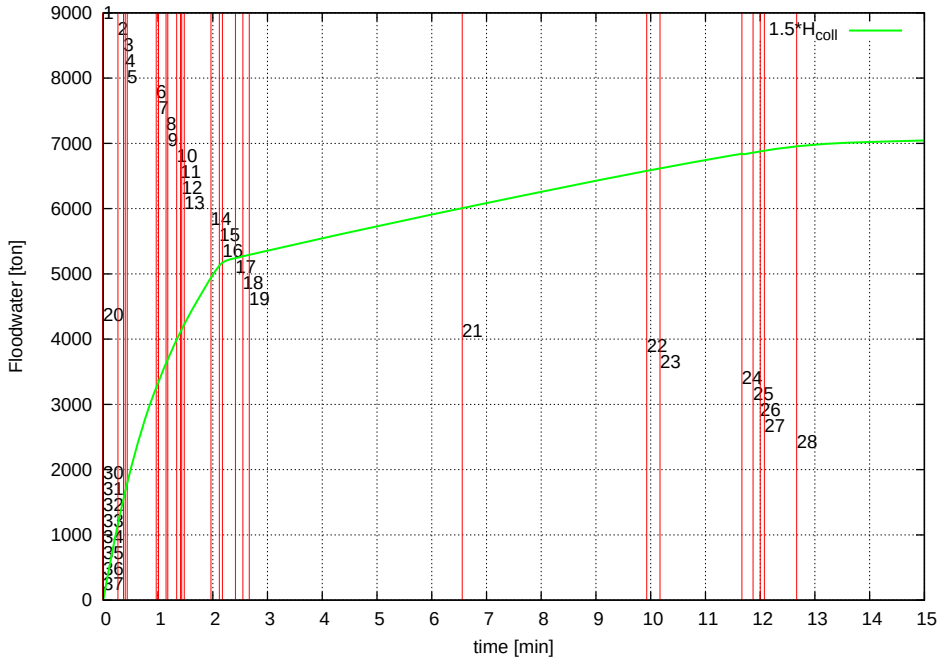
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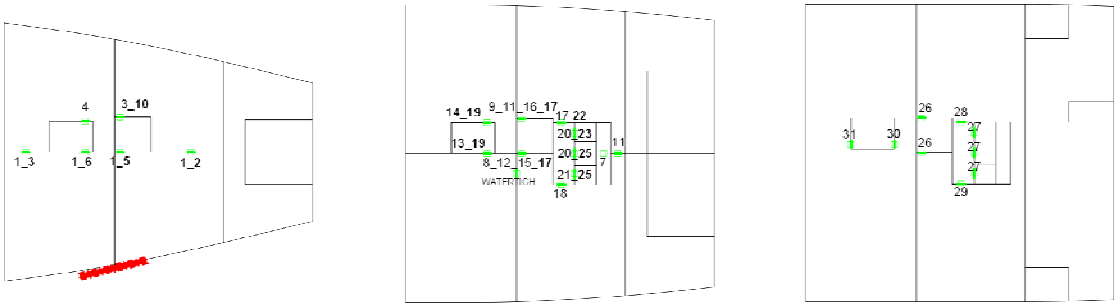
Floodwater [ton]
time [min]

0.5·A_{ratio}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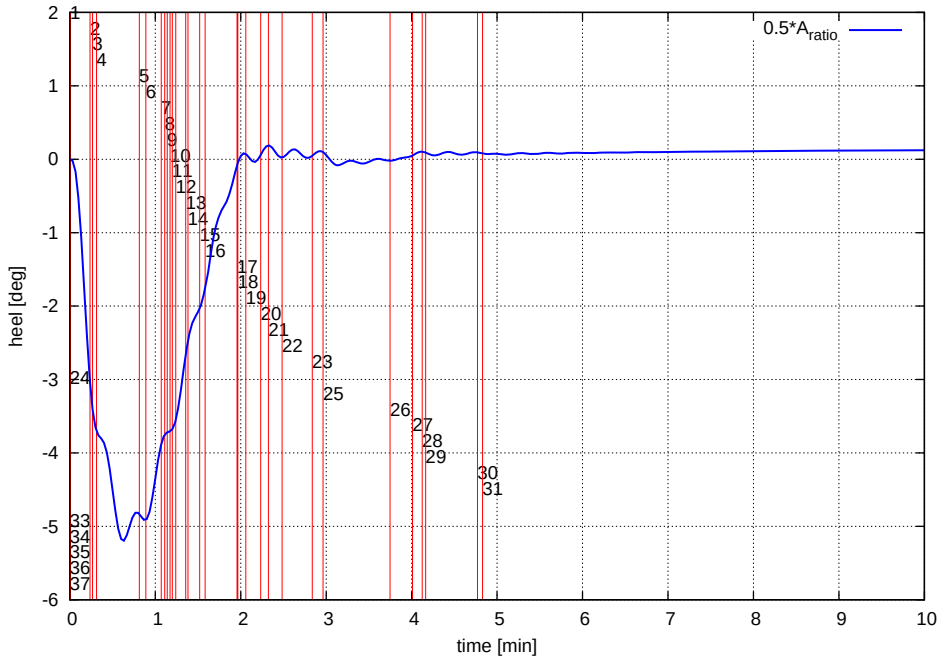
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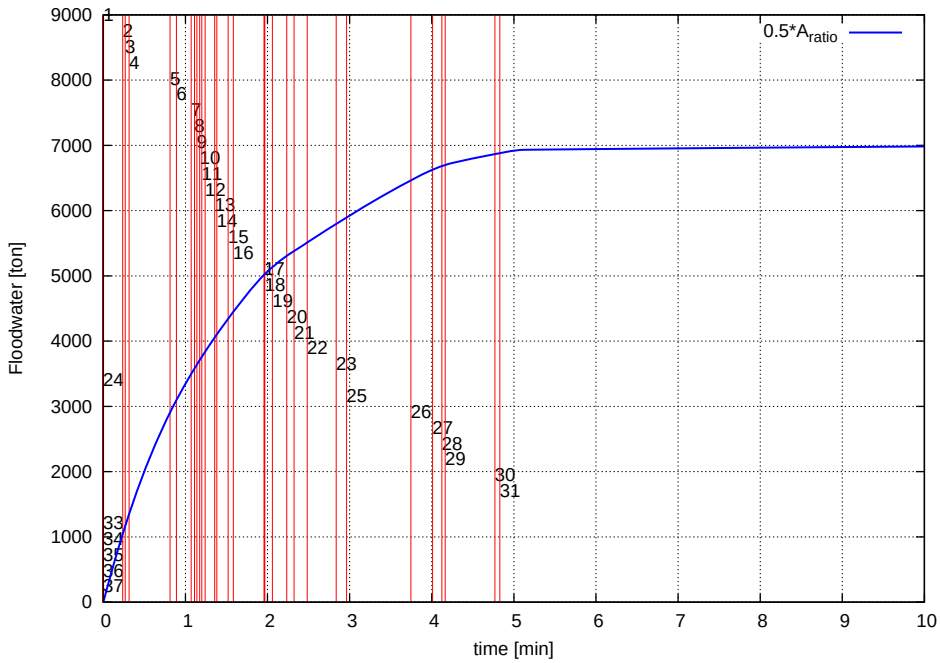
time [min]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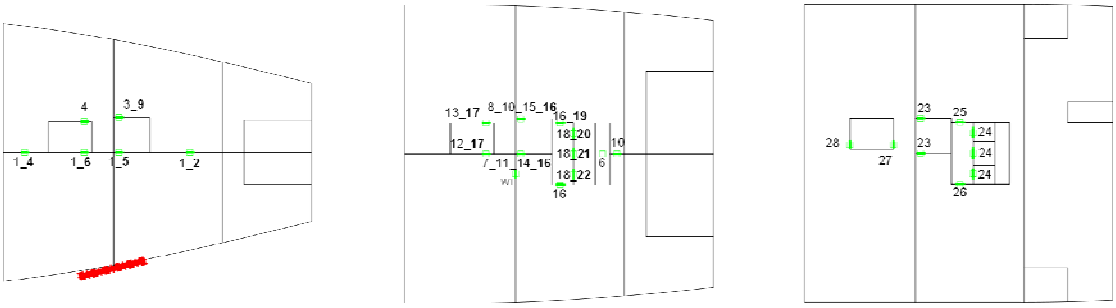
Floodwater [ton]
time [min]

1.5·A_{ratio}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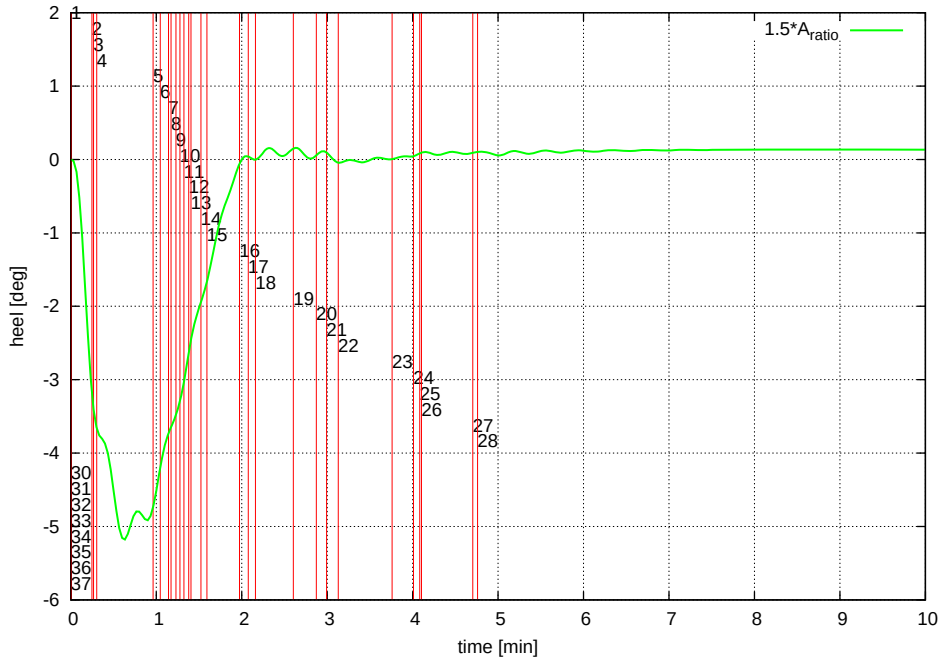
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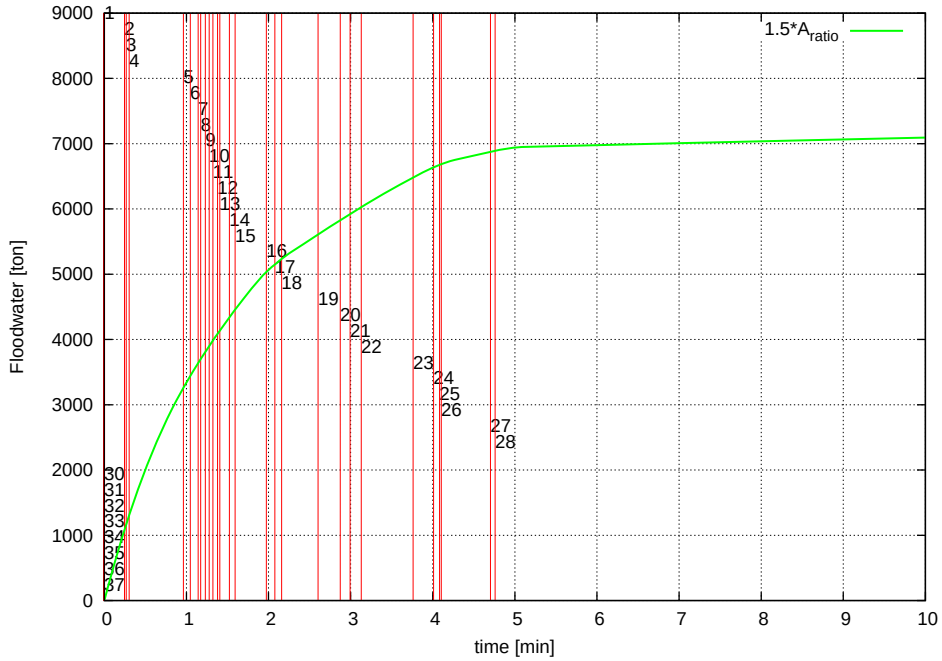
heel [deg]
time [min]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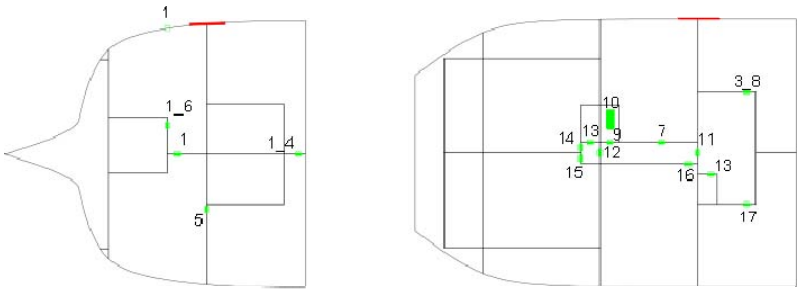
Floodwater [ton]
time [min]

APPENDIX B: Flooding Events for Case B

Reference Case



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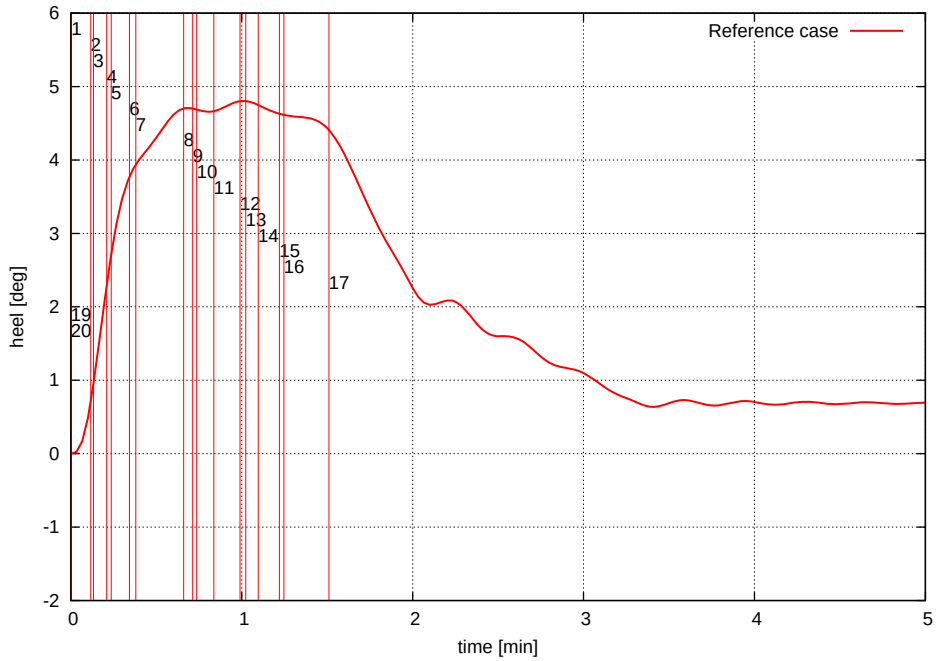

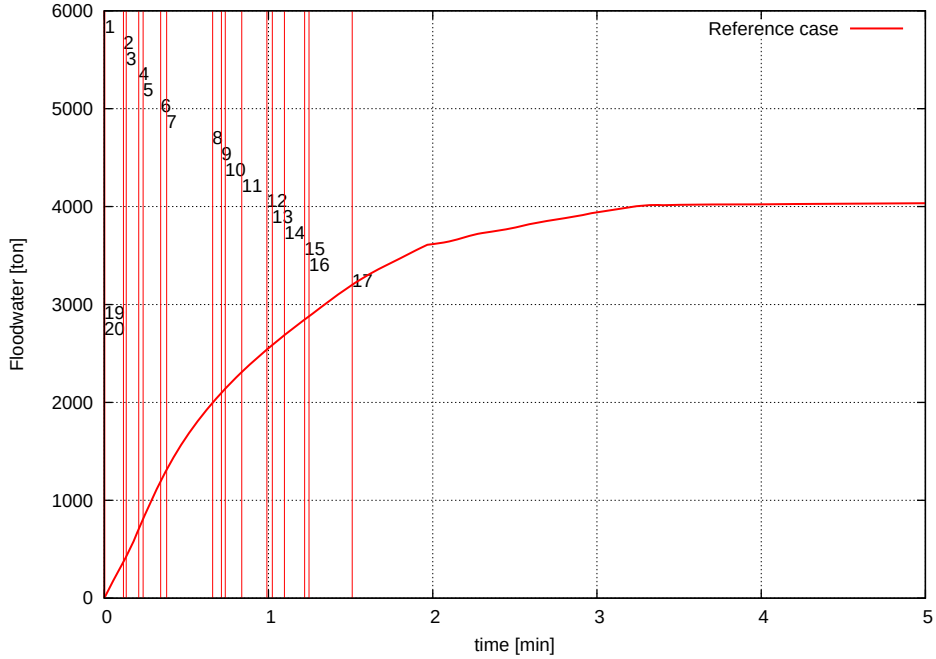

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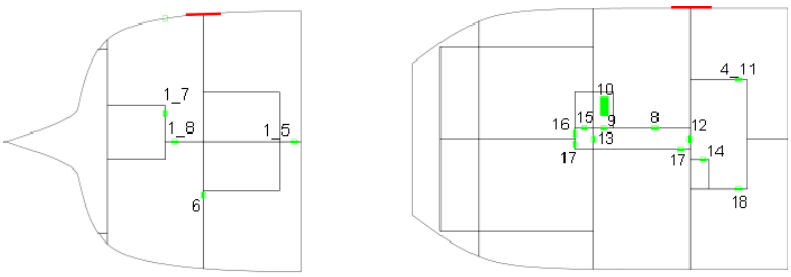

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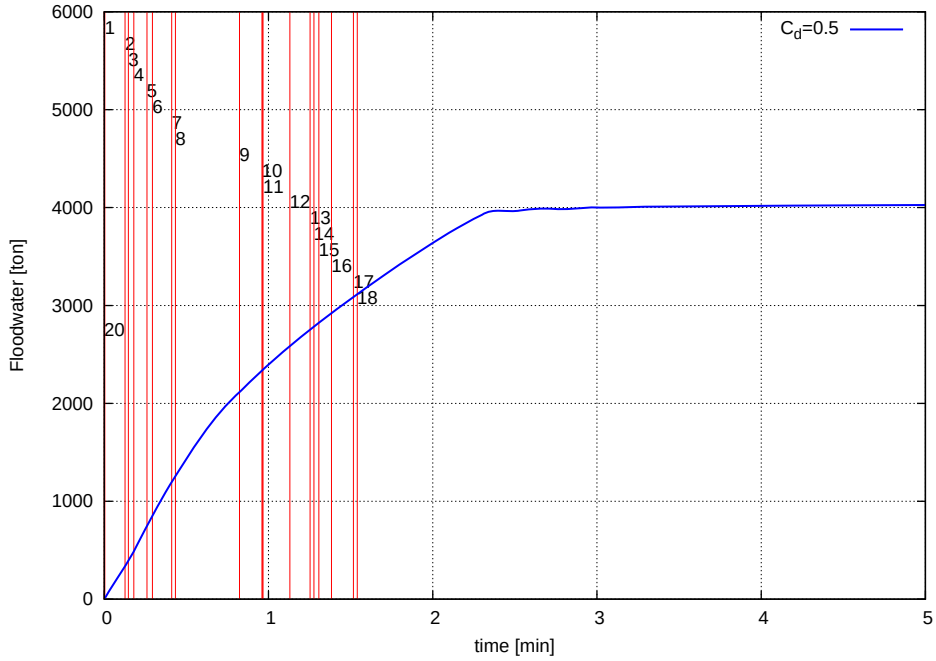

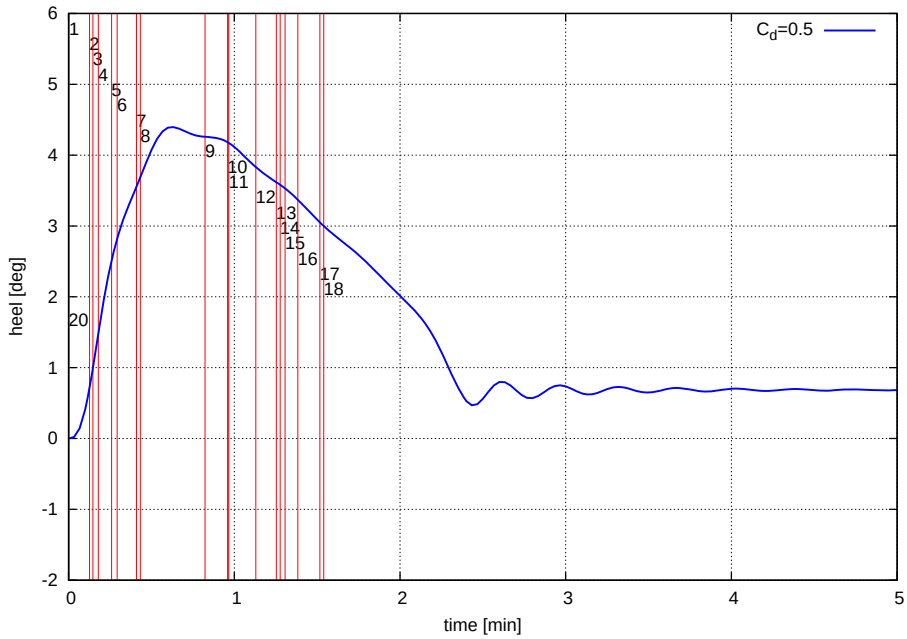

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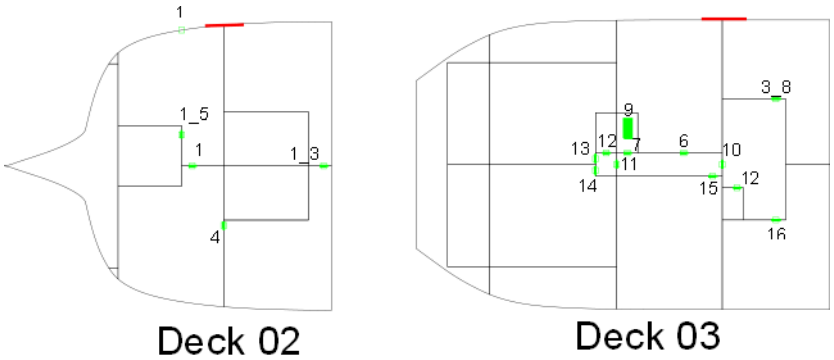
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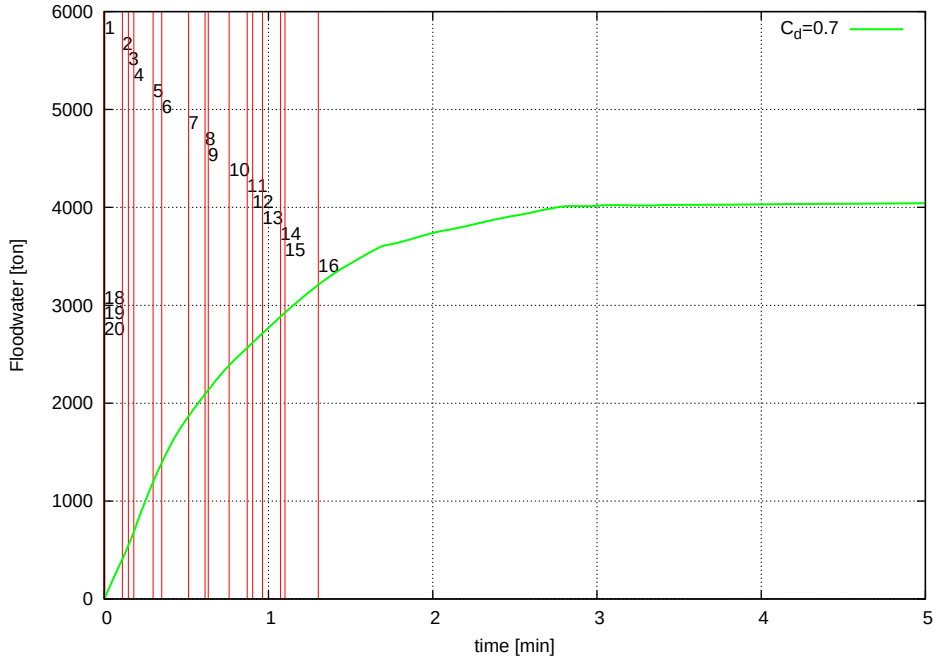
Floodwater [ton]
time [min]
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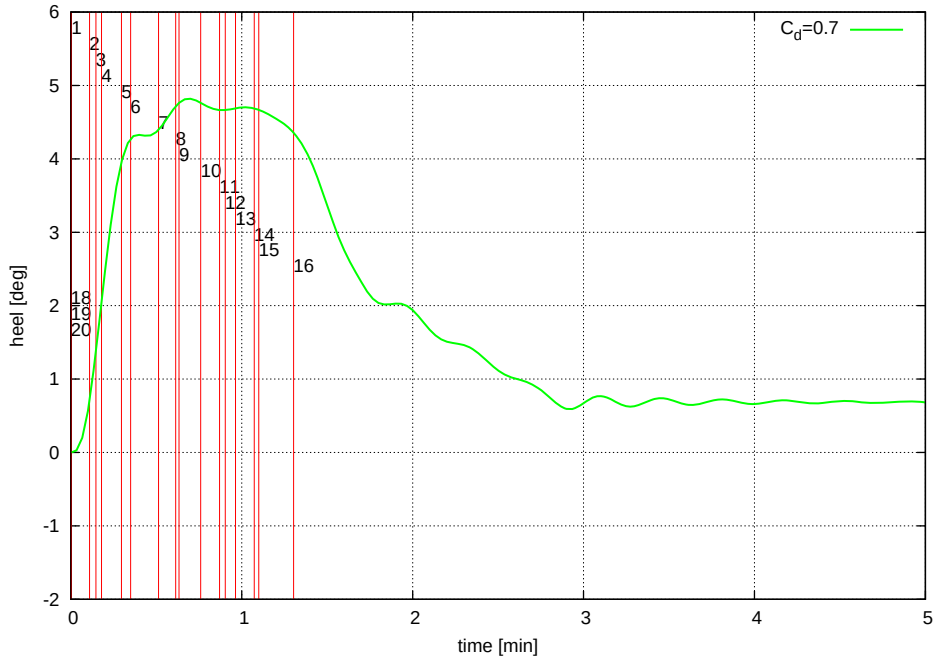
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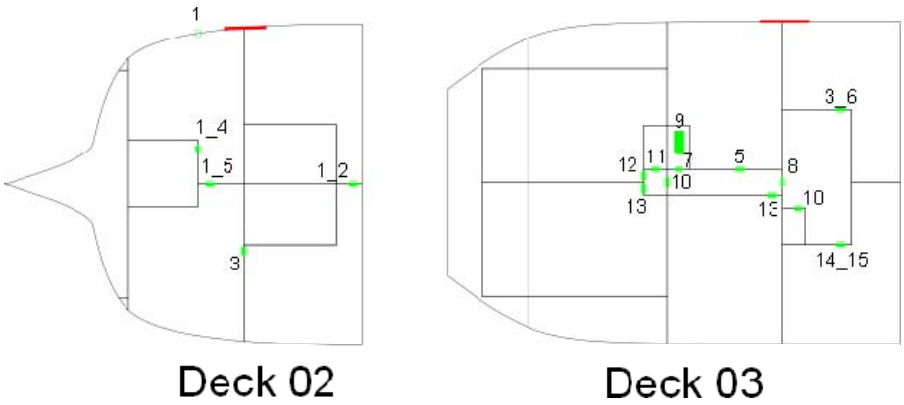
time [min]
C_d=0.7

0.75·H_{coll}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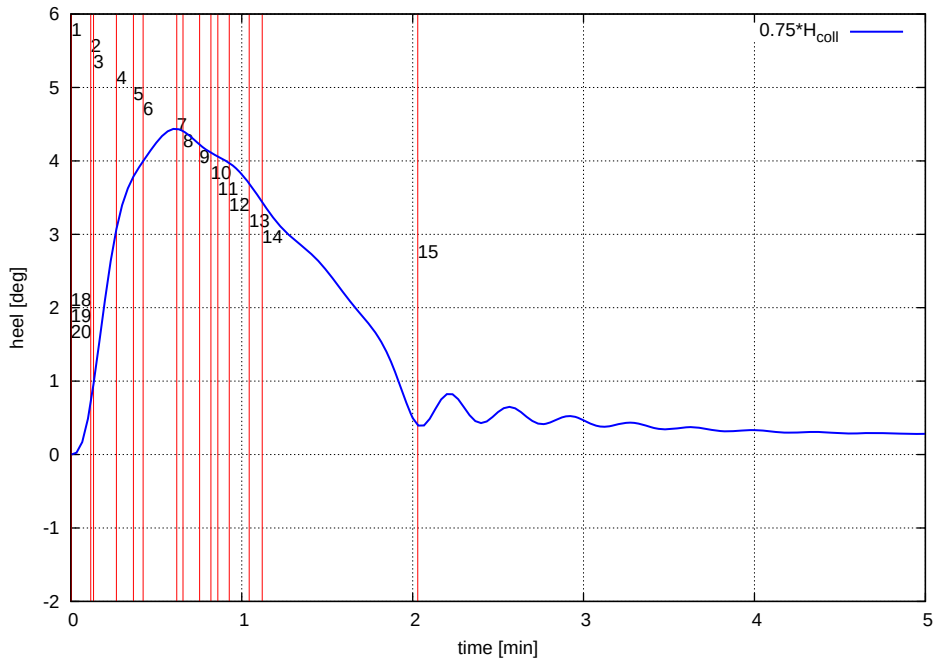
0.75*H_coll
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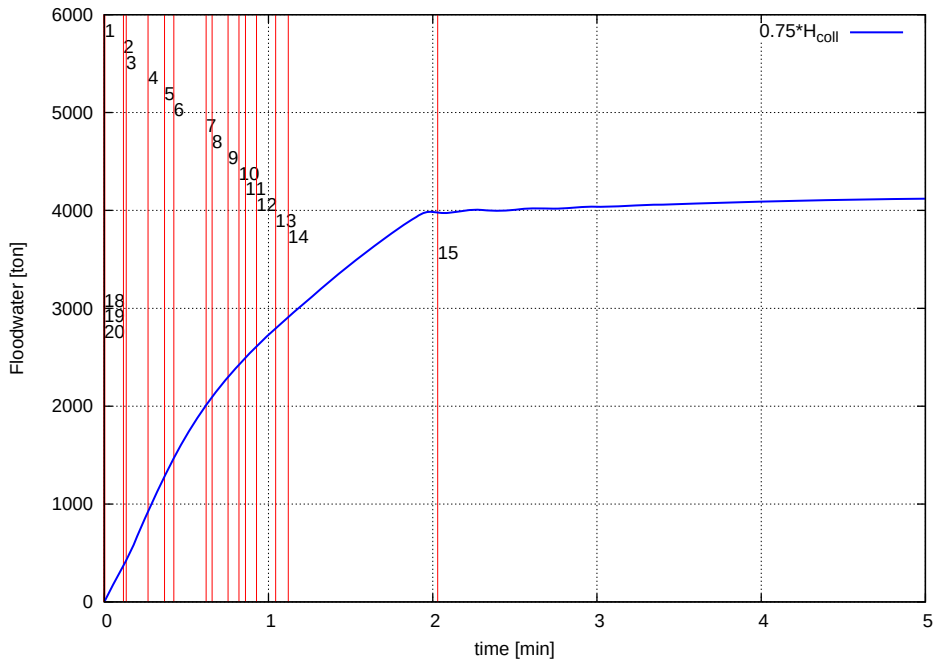
time [min]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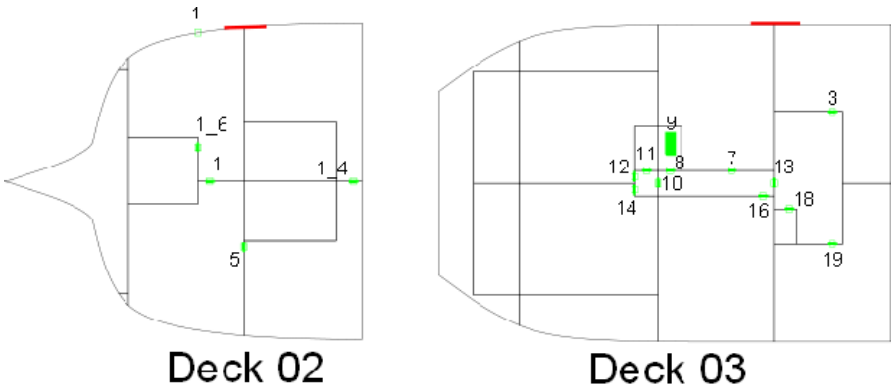
Floodwater [ton]
time [min]

1.25·H_{coll}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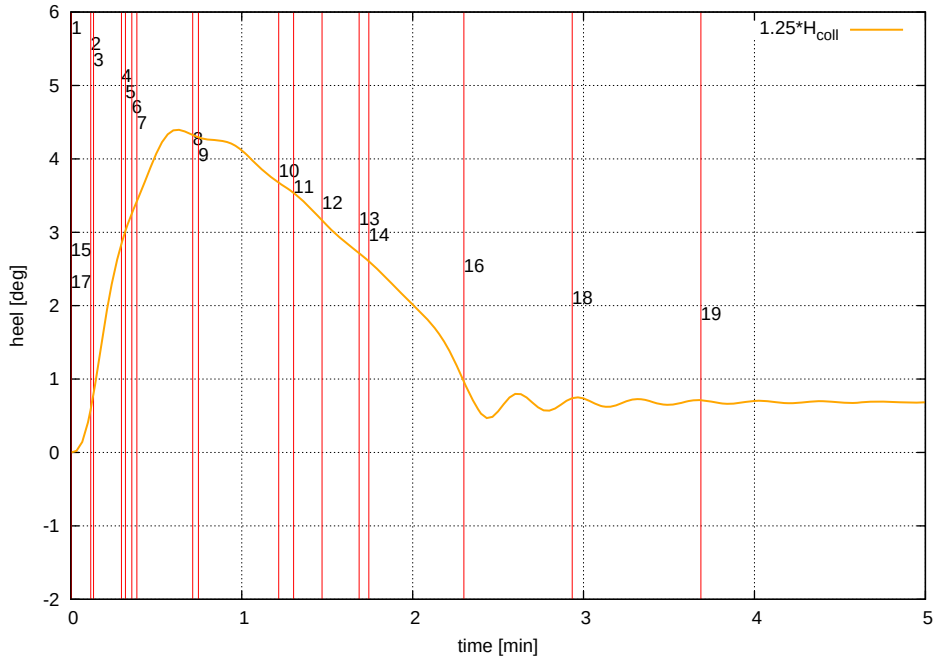
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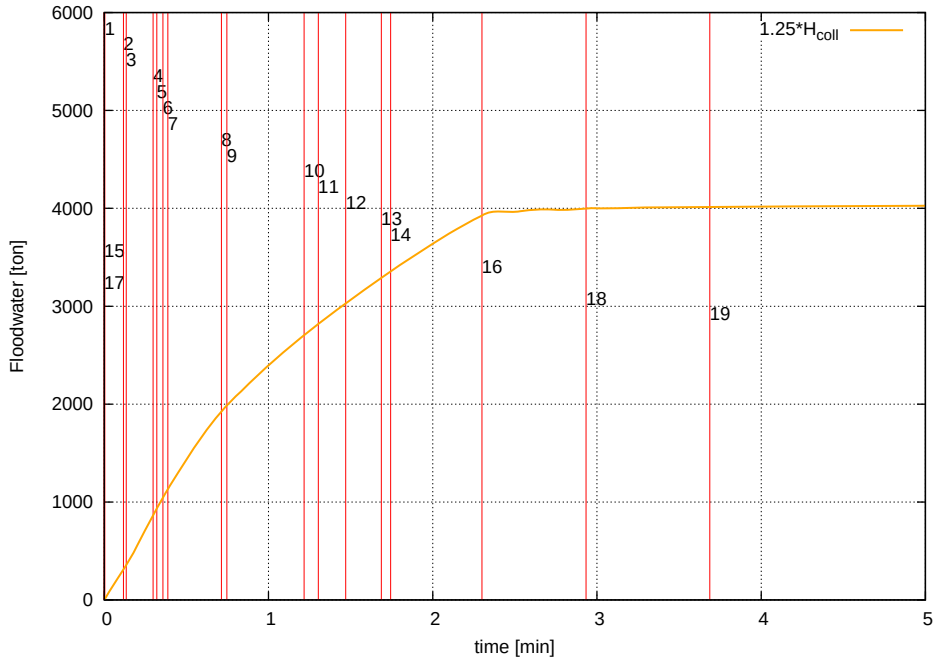
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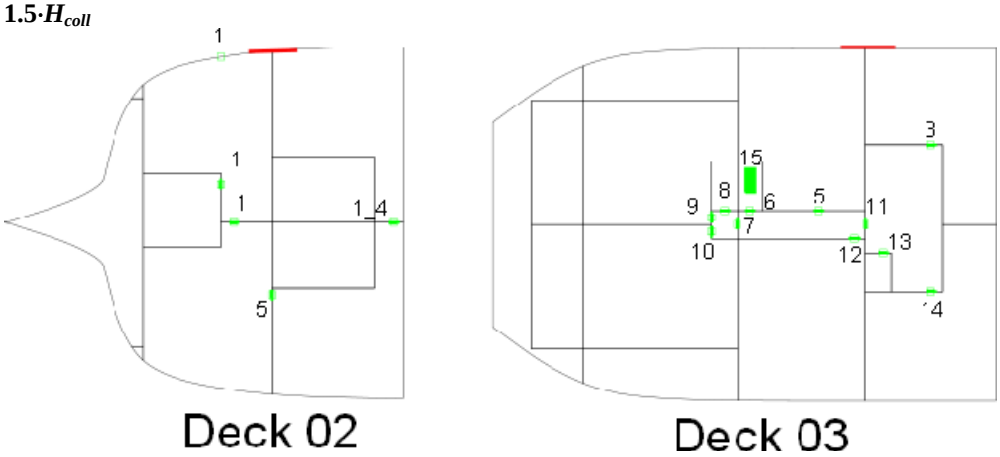
Floodwater [ton]
time [min]

1.5·H_{coll}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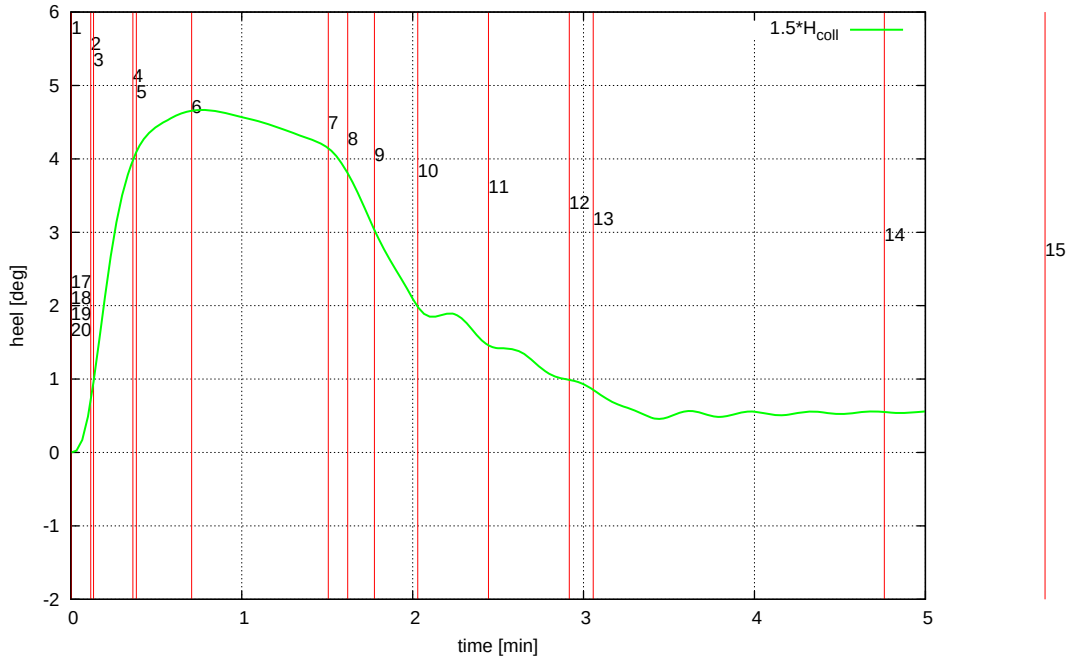
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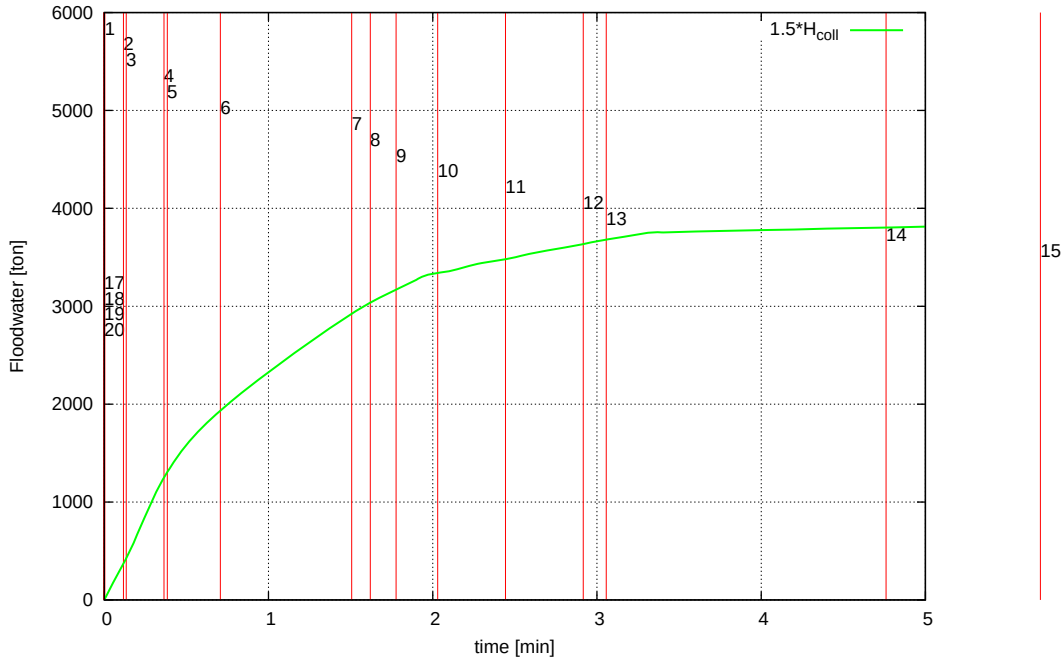
heel [deg]
time [min]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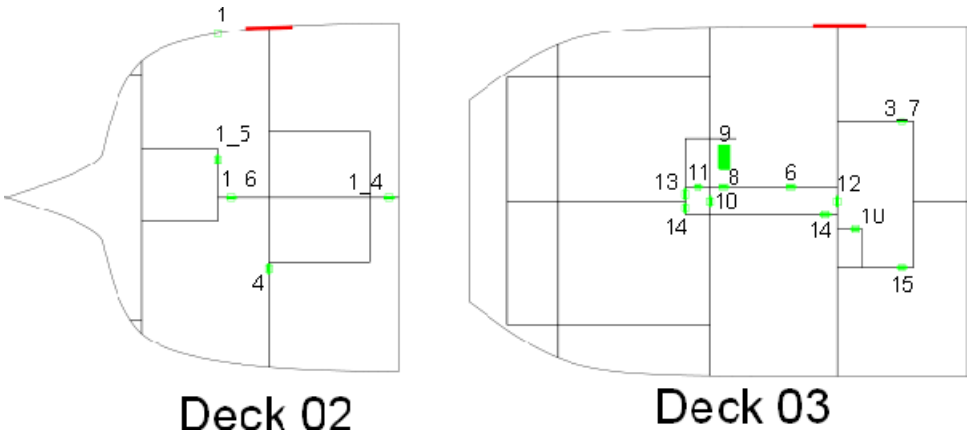
Floodwater [ton]
time [min]

0.5·A_{ratio}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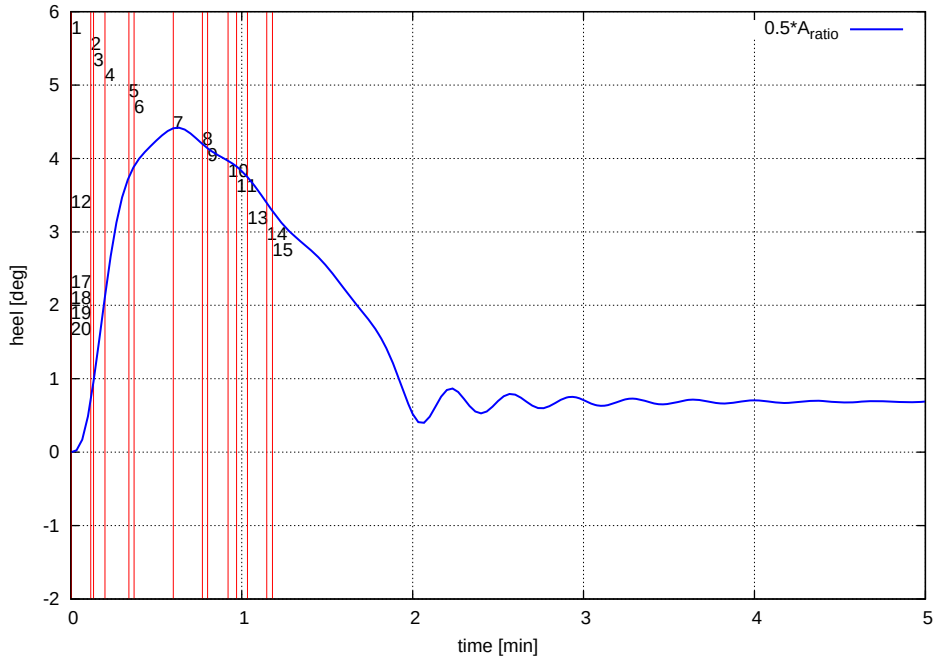
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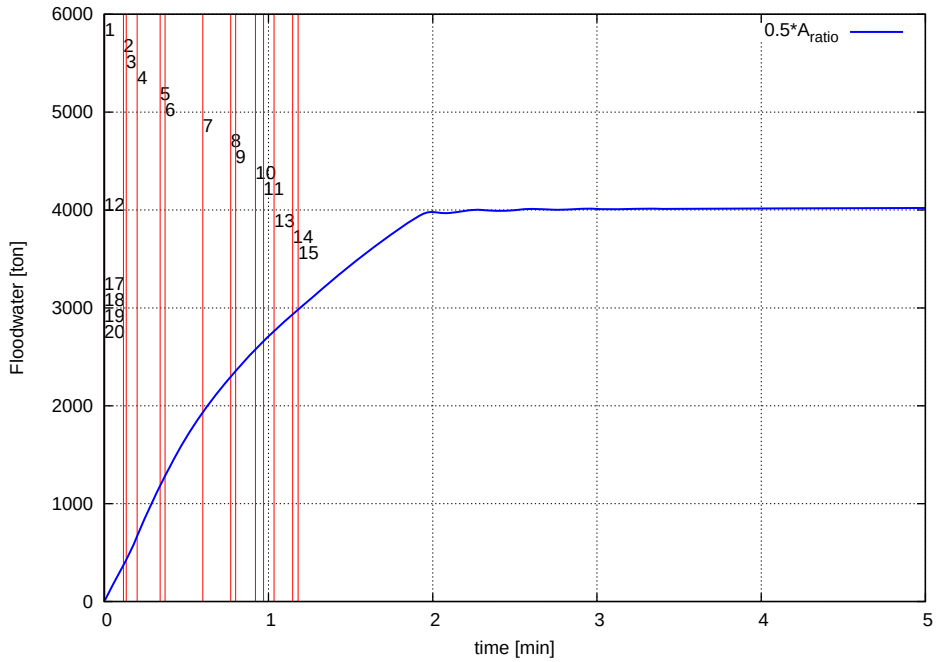
time [min]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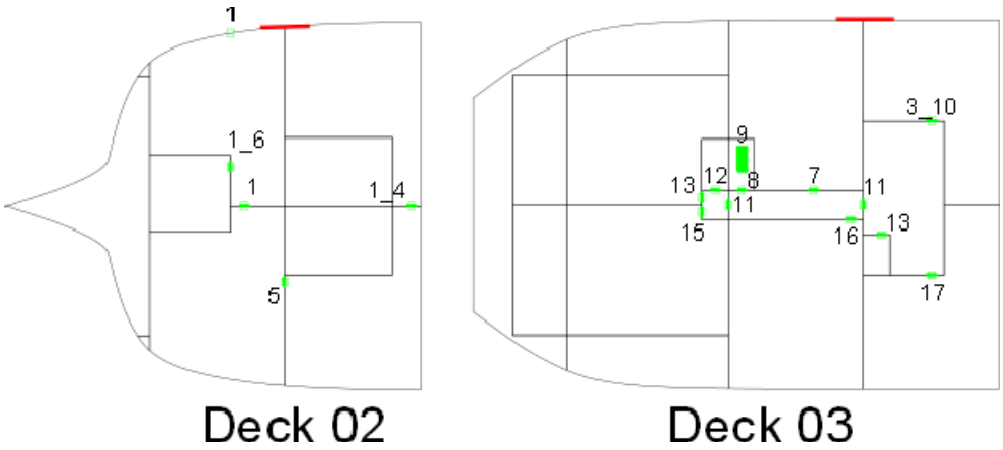
Floodwater [ton]
time [min]

1.5·A_{ratio}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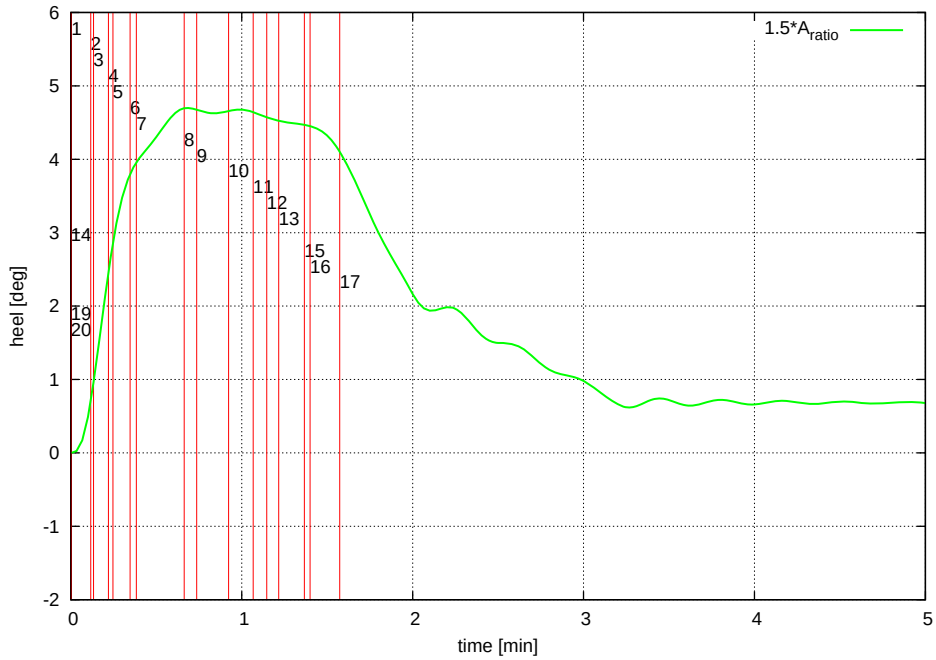
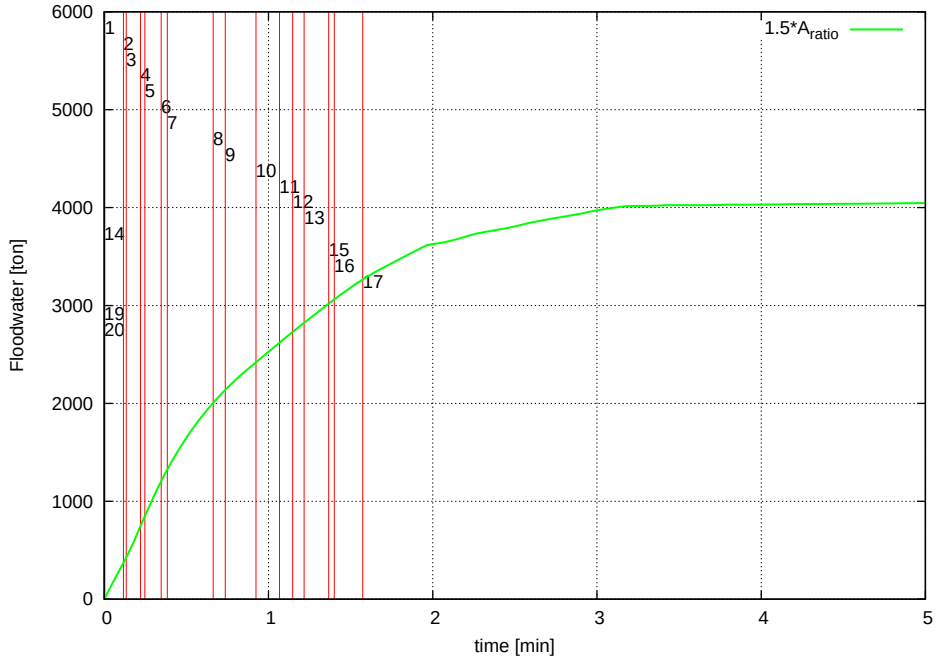

1.5*A_ratio
heel [deg]
time [min]


1.5*A_ratio
Floodwater [ton]
time [min]

APPENDIX C: Definitions for Internal Openings

The reference values and connections for all the internal openings of the case study ship are presented in the following table, as defined in the NAPA software. The quantity WRCOEF represents the discharge coefficient.

ID	OTYPE	CONN	DES	WRCOEF	HCOLL	HLEAK	ARATIO
CROSS-R140001_1	OPEN	R140001P,R140001S	CROSS-FLOODING OPENING	0.6			1
CROSS-R140001_2	OPEN	R140001P,R140001S	CROSS-FLOODING OPENING	0.6			1
D.A.01_COLDROOM-R010401	COLDROOMDOOR	R010403,R010401	COLD ROOM SLIDING DOOR, W=1100	0.6 0.6	3.5 3.5	0.0 0.0	'0.01*HEFF' '0.01*HEFF'
D.A.01_COLDROOM-R010402	COLDROOMDOOR	R010403,R010402	COLD ROOM SLIDING DOOR, W=1100	0.6 0.6	3.5 3.5	0.0 0.0	'0.01*HEFF' '0.01*HEFF'
D.A.01_CORRIDOR-R010403	OPEN	R010403,R020403	SERVICE CORRIDOR CONNECTION	0.6 0.6	0.0 0.0	0.0 0.0	1
D.A.01_HATCH-R010403_1	HATCH	R010301,R010403	HATCH TO STEERING GEAR ROOM	0.6 0.6	2.5 2.5	0.0 0.0	0.05
D.A.01_HATCH-R010403_2	HATCH	R010302,R010403	HATCH TO STEERING GEAR ROOM	0.6 0.6	2.5 2.5	0.0 0.0	0.05
D.A.02_COLDROOM-R020301	COLDROOMDOOR	R020302,R020301	COLD ROOM SLIDING DOOR, W=1100	0.6 0.6	3.5 3.5	0.0 0.0	'0.01*HEFF' '0.01*HEFF'
D.A.02_COLDROOM-R020303	COLDROOMDOOR	R020302,R020303	COLD ROOM SLIDING DOOR, W=1100	0.6 0.6	3.5 3.5	0.0 0.0	'0.01*HEFF' '0.01*HEFF'
D.A.02_COLDROOM-R020401	COLDROOMDOOR	R020403,R020401	COLD ROOM SLIDING DOOR, W=1100	0.6 0.6	3.5 3.5	0.0 0.0	'0.01*HEFF' '0.01*HEFF'
D.A.02_COLDROOM-R020404	COLDROOMDOOR	R020403,R020404	COLD ROOM SLIDING DOOR, W=1100	0.6 0.6	3.5 3.5	0.0 0.0	'0.01*HEFF' '0.01*HEFF'
D.A.02_CORRIDOR-R020403	OPEN	R020403,R030403	SERVICE CORRIDOR CONNECTION	0.6 0.6	0.0 0.0	0.0 0.0	1
D.A.02_PREPROOM-R020402	A-HINGED	R020403,R020402	A-CLASS FIRE DOOR, W=950	0.6 0.6	2.5 2.5	0.0 0.0	'0.02*HEFF' '0.03*HEFF'
D.A.02_STAIR-R020STAIRS	A-HINGED	R020302,R020STAIRS	A-CLASS FIRE DOOR TO STAIRCASE, W=950	0.6 0.6	2.5 2.5	0.0 0.0	'0.02*HEFF' '0.03*HEFF'
D.A.02_STAIRS-R020411	A-HINGED	R020403,R020STAIRS	A-CLASS FIRE DOOR TO STAIRCASE, W=950	0.6 0.6	2.5 2.5	0.0 0.0	'0.02*HEFF' '0.03*HEFF'
D.A.03_COLDROOM-R030303	COLDROOMDOOR	R030302,R030303	COLD ROOM SLIDING DOOR, W=1100	0.6 0.6	3.5 3.5	0.0 0.0	'0.01*HEFF' '0.01*HEFF'
D.A.03_COLDROOM-R030401	COLDROOMDOOR	R030403,R030401	COLD ROOM SLIDING DOOR, W=1100	0.6 0.6	3.5 3.5	0.0 0.0	'0.01*HEFF' '0.01*HEFF'
D.A.03_COLDROOM-R030405	COLDROOMDOOR	R030403,R030405	COLD ROOM SLIDING DOOR, W=1100	0.6 0.6	3.5 3.5	0.0 0.0	'0.01*HEFF' '0.01*HEFF'
D.A.03_ELSUBST-R030404	A-HINGED	R030403,R030404	A-CLASS FIRE DOOR, W=950	0.6 0.6	2.5 2.5	0.0 0.0	'0.02*HEFF' '0.03*HEFF'
D.A.03_PREPROOM-R030402	A-HINGED	R030403,R030402	A-CLASS FIRE DOOR, W=950	0.6 0.6	2.5 2.5	0.0 0.0	'0.02*HEFF' '0.03*HEFF'
D.A.03_STAIR-R030STAIRS	A-HINGED	R030302,R030STAIRS	A-CLASS FIRE DOOR TO STAIRCASE, W=950	0.6 0.6	2.5 2.5	0.0 0.0	'0.02*HEFF' '0.03*HEFF'
D.A.03_STAIRS-R030411	A-HINGED	R030403,R030STAIRS	A-CLASS FIRE DOOR TO STAIRCASE, W=950	0.6 0.6	2.5 2.5	0.0 0.0	'0.02*HEFF' '0.03*HEFF'
D.A.03_STAIRS-THRUSTER	OPEN	R030203,R030STAIRS	STAIRWAY OPENING IN DECK 3	0.6 0.6	0.0 0.0	0.0 0.0	1
D.A.03_STORE-R030201	A-HINGED	R030202,R030201	A-CLASS FIRE DOOR, W=950	0.6 0.6	2.5 2.5	0.0 0.0	'0.02*HEFF' '0.03*HEFF'
D.A.03_THRUSTER-R030203	A-HINGED	R030201,R030203	A-CLASS FIRE DOOR, W=950	0.6 0.6	2.5 2.5	0.0 0.0	'0.02*HEFF' '0.03*HEFF'
D.A.03_WORKSHOP-R030301	A-HINGED	R030302,R030301	A-CLASS FIRE DOOR, W=950	0.6 0.6	2.5 2.5	0.0 0.0	'0.02*HEFF' '0.03*HEFF'
D.A.03_WT-DOOR-R020302	WT	R030302,R020302	WT-DOOR IN SERVICE CORRIDOR	0.6 0.6	15	10	'0.001*HEFF' '0.001*HEFF'
D.A.03_WT-DOOR-R030202	WT	R030202,R040202	WT-DOOR IN PROP MACHINE ROOM, W=1000	0.6 0.6	15	10	'0.001*HEFF' '0.001*HEFF'
D.A.04_DRYSTORE-R040403	A-SLIDING	R040302,R040303	STORE SLIDING DOOR, W=1100	0.6 0.6	1.0 1.0	0.0 0.0	0.025 0.025
D.A.04_FBSTORES-R040301	A-SLIDING	R040302,R040301	STORE SLIDING DOOR, W=1100	0.6 0.6	1.0 1.0	0.0 0.0	0.025 0.025
D.A.04_STAIRS-R040311	A-HINGED	R040302,R040311	A-CLASS FIRE DOOR TO STAIRCASE, W=950	0.6 0.6	2.5 2.5	0.0 0.0	'0.02*HEFF' '0.03*HEFF'
D.A.04_SWBOARD-R040202	OPEN	R040201,R040202	PASSAGE BETWEEN ROOMS	0.6 0.6	0.0 0.0	0.0 0.0	1
D.A.04_WT-DOOR-R040302	WT	R030302,R040302	WT-DOOR IN SERVICE CORRIDOR, W=1000	0.6 0.6	15	10	'0.001*HEFF' '0.001*HEFF'
D.A.14_D1_CL_DOOR	A-SLIDING	R140101P,R140101S	A-CLASS SLIDING DOOR AT CL	0.6 0.6	1.0 1.0	0.0 0.0	0.025 0.025
D.A.14_STAIRS-R140101_1	A-HINGED	R140101S,R140STAIRS	A-CLASS FIRE DOOR TO STAIRCASE, W=950	0.6 0.6	2.5 2.5	0.0 0.0	'0.02*HEFF' '0.03*HEFF'
D.A.14_STAIRS-R140101_2	A-HINGED	R140101P,R140STAIRS	A-CLASS FIRE DOOR TO STAIRCASE, W=950	0.6 0.6	2.5 2.5	0.0 0.0	'0.02*HEFF' '0.03*HEFF'
D.A.14_STAIRS-R140201	A-HINGED	R140201,R140STAIRS	A-CLASS FIRE DOOR TO STAIRCASE, W=950	0.6 0.6	2.5 2.5	0.0 0.0	'0.02*HEFF' '0.03*HEFF'
D.A.14_STAIRS-R140203	A-HINGED	R140203,R140STAIRS	A-CLASS FIRE DOOR TO STAIRCASE, W=950	0.6 0.6	2.5 2.5	0.0 0.0	'0.02*HEFF' '0.03*HEFF'
D.A.14_STAIRS-R140301_1	A-HINGED	R140301,R140STAIRS	A-CLASS FIRE DOOR TO STAIRCASE, W=950	0.6 0.6	2.5 2.5	0.0 0.0	'0.02*HEFF' '0.03*HEFF'
D.A.14_STAIRS-R140301_2	A-HINGED	R140301,R140STAIRS	A-CLASS FIRE DOOR TO STAIRCASE, W=950	0.6 0.6	2.5 2.5	0.0 0.0	'0.02*HEFF' '0.03*HEFF'
D.A.15_ACVENT-R160401	OPEN	AC160401,R150101S	OPENING TO VENTILATION SHAFT	0.6 0.6	0.0 0.0	0.0 0.0	1
D.A.15_D1_CL_DOOR	A-SLIDING	R150101P,R150101S	A-CLASS SLIDING DOOR AT CL	0.6 0.6	1.0 1.0	0.0 0.0	0.025 0.025
D.A.15_D2_CL_DOOR	A-SLIDING	R150201P,R150201S	A-CLASS SLIDING DOOR AT CL	0.6 0.6	1.0 1.0	0.0 0.0	0.025 0.025
D.A.15_LLOBBY-R150211_1	A-SLIDING	R150211,R150201P	SLIDING DOOR TO LIFT LOBBY, W=1100	0.6 0.6	1.0 1.0	0.0 0.0	0.025 0.025
D.A.15_LLOBBY-R150211_2	A-SLIDING	R150211,R150201S	SLIDING DOOR TO LIFT LOBBY, W=1100	0.6 0.6	1.0 1.0	0.0 0.0	0.025 0.025
D.A.15_LLOBBY-R150311_1	A-SLIDING	R150311,R150301	SLIDING DOOR TO LIFT LOBBY, W=1100	0.6 0.6	1.0 1.0	0.0 0.0	0.025 0.025
D.A.15_LLOBBY-R150311_2	A-SLIDING	R150311,R150301	SLIDING DOOR TO LIFT LOBBY, W=1100	0.6 0.6	1.0 1.0	0.0 0.0	0.025 0.025
D.A.15_SLIFT_D2-SL10	LIFT	R150211,SL10	SERVICE LIFT DOOR, W=1300	0.6 0.6	1.5 1.5	0.0 0.0	0.03
D.A.15_SLIFT_D2-SL7	LIFT	R150211,SL7	SERVICE LIFT DOOR, W=1300	0.6 0.6	1.5 1.5	0.0 0.0	0.03
D.A.15_SLIFT_D2-SL9	LIFT	R150211,SL9	SERVICE LIFT DOOR, W=1300	0.6 0.6	1.5 1.5	0.0 0.0	0.03
D.A.15_SLIFT_D3-SL10	LIFT	R150311,SL10	SERVICE LIFT DOOR, W=1300	0.6 0.6	1.5 1.5	0.0 0.0	0.03
D.A.15_SLIFT_D3-SL7	LIFT	R150311,SL7	SERVICE LIFT DOOR, W=1300	0.6 0.6	1.5 1.5	0.0 0.0	0.03
D.A.15_SLIFT_D3-SL9	LIFT	R150311,SL9	SERVICE LIFT DOOR, W=1300	0.6 0.6	1.5 1.5	0.0 0.0	0.03
D.A.15_STAIRS-R150101_1	A-HINGED	R150STAIRS,R150101S	A-CLASS FIRE DOOR TO STAIRCASE, W=950	0.6 0.6	2.5 2.5	0.0 0.0	'0.02*HEFF' '0.03*HEFF'
D.A.15_STAIRS-R150101_2	A-HINGED	R150STAIRS,R150101P	A-CLASS FIRE DOOR TO STAIRCASE, W=950	0.6 0.6	2.5 2.5	0.0 0.0	'0.02*HEFF' '0.03*HEFF'
D.A.15_STAIRS-R150201_1	A-HINGED	R150201S,R150STAIRS	A-CLASS FIRE DOOR TO STAIRCASE, W=950	0.6 0.6	2.5 2.5	0.0 0.0	'0.02*HEFF' '0.03*HEFF'
D.A.15_STAIRS-R150201_2	A-HINGED	R150201P,R150STAIRS	A-CLASS FIRE DOOR TO STAIRCASE, W=950	0.6 0.6	2.5 2.5	0.0 0.0	'0.02*HEFF' '0.03*HEFF'
D.A.15_STAIRS-R150301_1	A-HINGED	R150301,R150STAIRS	A-CLASS FIRE DOOR TO STAIRCASE, W=950	0.6 0.6	2.5 2.5	0.0 0.0	'0.02*HEFF' '0.03*HEFF'
D.A.15_STAIRS-R150301_2	A-HINGED	R150301,R150STAIRS	A-CLASS FIRE DOOR TO STAIRCASE, W=950	0.6 0.6	2.5 2.5	0.0 0.0	'0.02*HEFF' '0.03*HEFF'
D.A.15_WT-DOOR-R150201	WT	R150201,R140203	WT-DOOR BETWEEN UN.STORE AND IRONING, W=1000	0.6 0.6	15	10	'0.001*HEFF' '0.001*HEFF'

APPENDIX D: General Arrangement and Room Names