FLOODSTAND-deliverable:

ESTIMATION OF DAMAGE AND FLOODING EXTENT FROM THE FLOOD SENSOR DATA

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Abstract:
Analysis methods for assessing both the damage extent and the flooding extent for progressive flooding are presented. The sensor data is used as the input. Approximate calculations are done by using Bernoulli's equation for flooding rates. The developed method is tested with both a damage scenario from real full-scale flooding tests and detailed flooding simulation results for more extensive damage cases.

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CONTENTS

1 EXECUTIVE SUMMARY

When the hull of a ship is breached due to collision or grounding, floodwater enters the damaged compartments. Open doors and broken pipes may result in progressive flooding to undamaged compartments, thus making the situation more critical. Even within a single watertight compartment, the non-watertight structures can have a notable effect on the flooding progression. Here, the results of WP2 can be directly taken into use.

The flooding prediction consists of two separate tasks: estimation of the breach and calculation of progressive flooding in time-domain. Use of the online data from the water level sensors, ship motions and door statuses, combined with a 3D model of the ship and time-domain flooding simulation tool provides a better and more realistic estimation of both the damage and its consequences during time.

Direct time-domain flooding simulation was found out to be too slow for practical purposes. On the other hand, onboard the damaged ship there are always several uncertainties involved, and thus minimization of the numerical error in the solution of the governing equations is not a key issue. Thus a completely new approach for calculation of progressive flooding has been developed. This method accounts the intermediate phases of the flooding process and provides a rough estimation on the time-to-flood. Leaking and collapsing of non-watertight structures (such as closed fire doors) are taken into account. For the opening parameters the results of WP2 are utilized.

The developed new method for prediction of progressive flooding is tested with two separate case studies. Firstly for flooding of a small fast attack craft, where full-scale measurement data is available, and then for two more extensive flooding scenarios with a modern large passenger ship design (developed in Task 1.1). The simulation results from Task 2.6 with a short time step are used as reference data. In all three test cases the main characteristics of the flooding progression are captured very accurately. This includes the maximum heeling angle and the eventual equilibrium floating position. The results are not time-accurate but the prediction of time-to-flood is somewhat conservative (faster than reality).

Finally, the reliability and accuracy of the prediction results are discussed. The results of Task 3.2 for the effect of waves are used, along with the sensitivity analysis that was performed in Task 2.6. In principle the numerical error due to the simplified calculation of progressive flooding is considered to be much smaller than the uncertainties that are related to the accuracy of modeling the ship and the environmental conditions. Thus the developed calculation method is believed to be an efficient and practical tool for assessing progressive flooding to provide information for decision support.

2 BACKGROUND

Currently, the available tools for damage control onboard the ships are papers showing pre-calculated results of pre-defined damage cases, based on the deterministic rules (e.g. project COMAND, *Ölcer and Majumder, 2006).* These papers and pre-calculated results cannot be applied to any arbitrary damage conditions, which are the most common ones in reality. Recently, *Jasionowski (2011)* has presented a new approach to decision support for ship flooding crisis management, where the vulnerability and probability of capsize are approximated. This approach is based on statistics and stability at the final flooding condition. Thus the intermediate phases and progressive flooding are not taken into account.

The aim of the Task 3.1 was to get a solid basis for development of a reliable tool for flooding control to be used onboard. Currently there are no rules or requirements for such a system. The rules are, however, developing into that direction, but in the beginning, only requiring flooding indicators in dry spaces. The target of this Task was set far beyond: using the real time level sensor information and the state of the art flooding simulation methods, it is possible to predict the behavior of the ship in case of damage.

The calculation results of such a tool can form a solid basis for the decision making, for example, whether to immediately evacuate the ship or is it safe to proceed to the nearest port. This decision is of crucial importance in consideration of the safety of the people onboard, the environment and the ship itself.

The key concept in decision support systems is reliability. In addition any result must be displayed so that it can be easily understood by the crew of the ship, like a simple weather map. It is clear that if the time-domain methods fail to produce better results – meaning more realistic and accurate as well as more understandable – there is hardly any point in using such methods. However, the power and appeal of the direct time-domain methods is that they contain only familiar physical quantities like time, volume and pressure. The set of these everyday physical quantities can make the more complicated and more sophisticated method easier to understand, than the “classic/static” damage stability calculations. Thus an average seaman is likely to find the time domain flooding simulations relatively easy to understand.

This study of breach estimation, using levels sensors, is focused on flooding simulations on passenger vessels in operation. The underlying optimistic belief is, that as long as we can get the initial condition right, predictions from then on is a simple, or at least a straightforward, task.

The problem with getting the initial condition right is simple: how to estimate the breach correctly. This requires the measurement of possible flooding so accurately that the breach properties can be derived from the measurement accurately enough. If we can’t get the initial condition right, the predicted results may not be reliable. The guidelines and requirements for the flooding detection sensors are discussed separately in the Deliverable D3.3.

Any real breach can always be observed afterwards, because the steel hull is permanently deformed. However, flooding is an event; it rises unexpectedly from nowhere and disappears leaving only small clues, like collapsed doors and dislocated equipment, as markers of its path and strength. This work has been carried out to be of maximal usefulness in preparing for the worst situations imaginable.

The prediction of progressive flooding to the undamaged compartments is another problem. In principle this is a rather straight forward task and several simulation methods have been developed at various institutions during the past decade. However, the onboard application requires very fast computations, even in expense of calculation accuracy.

The importance of flooding prediction in decision support is summarized in the following:

> *“The reliability and accuracy of the decision support tools for assessing the consequences of the damage are of utmost importance. The results of the questionnaire for masters indicate that the decision to begin abandonment might be at least partly influenced by the stability software program”* (FLOODSTAND Deliverable D5.1 page 9).

The same report also concludes that:

> *"…generally the ship masters seem to think more of an emphasis should be placed on providing them with information rather than making recommendations to them"*.

This is an important issue. The meaning of a decision support tool is to provide useful information. The master onboard the damaged ship has to do the final decision based on all available facts. This is a kind of dilemma since "black box" approaches should be avoided but at the same time the user interface should be self-explanatory and very simple to use.

The calculation performance is a critical issue for any direct analysis tool that is used onboard the ship. The results need to be available very soon after the damage so that they can be used in the decision making. This is the main reason for the need to develop a new calculation method for prediction of progressive flooding, based on the level sensor data.

In this report the developed methods for both the breach detection and estimation of flooding extent due to possible progressive flooding after the damage are explained. The prediction of progressive flooding is tested against both real full-scale measurement data and detailed time-domain flooding simulations.

The demonstration of the developed platform for decision support with the developed calculation method is reported separately within WP7.

3 PROBLEM DEFINITION

3.1 Damage and Flooding Extents

In principle, the interpretation of level sensor data forms two separate tasks that are somewhat different:

1. Estimation of the **damage extent**
    a. What are the damaged rooms/compartments?
    b. What is the size and location of the damage?

2. Estimation of the **flooding extent**
    a. What are the rooms that can possible be flooded through various connections (open doors, collapsing of non-watertight structures)?
    b. How long does the flooding of these rooms take?

Most notably, only the flooding extent is usually time dependent. In a very long time span, even a small leaking rate through a closed door can result in notable progressive flooding. However, active counter actions, such as pumping or building barriers, as in the flooding of the *MONARCH OF THE SEAS*, Figure 1, *Maritime Investigator & USCG (2003),* may solve this problem in practice.

Open (or leaking) doors can result in very extensive flooding extent even through the damage extent is limited to a single watertight compartment, as in the case of *STENA NAUTICA*, *Swedish Accident Investigation Board (2005).*

Moreover, the real accidents (e.g. the grounding of the *SALLY ALBATROSS* in 1994, *Ministry of Justice, Finland, 1996*) have demonstrated that floodwater can find unpredicted routes. Thus based on the level sensor data the flooding rates can be assessed and combining this to the information on the door status data, the flooding extent at the given time frame can be estimated with rough time-domain simulation.

Figure 1: Welded plate across stairwell put in place to limit the chance of progressive flooding on the *MONARCH OF THE SEAS*, credit: *Maritime Investigator & USCG (2003)*.

The main problem in the estimation of the damage extent is to distinguish internal progressive flooding from the direct inflow through the damage. Thus the measurement data from the very beginning of the flooding process is the most valuable. If the breach is initially only partly immersed, the changes in the ship’s floating position can cause unpredictable effects on the flooding rates.

In case of large damages, the damage size is irrelevant since the damage rooms are filled up with water in a very short time. Thereafter, they can be considered as “**open to sea”**. This means that in stability calculations these rooms are treated as lost buoyancy, whereas the progressive flooding in time-domain is treated as added (moving) weight.

3.2 Initial Condition

Another basic requirement for reliable assessment of both the damage extent and the flooding extent is to know the initial condition before the damage. This includes:

- Floating position (draft, trim and heeling)
- Loading condition:
  - tank level information (all liquid loads)
  - center of gravity (metacentric height)
- Status of the doors:
  - Watertight doors
  - “Semi-watertight” doors (typically used on the bulkhead deck)
  - A-class fire doors

In addition, information on the current sea state and course of the ship may be needed in order to assess the reliability of any simplified simulation results. It should be noted that high waves (when compared to the size of the ship) can cause a “pumping effect” that results in additional flooding. Thus e.g. rooms on the bulkhead deck may be flooded due to waves even through the deck itself is not immersed (in respect to the still sea level).

In the following, it is assumed that the ships floating position and loading condition are known accurately enough. Additionally, the sea state is considered to be moderate so that the waves have only a minimal effect on the flooding process.

3.3 Effect of the Changing Floating Position

The vertical location of a breach can have a significant influence on the simulation results. Therefore the changes in floating position need to be considered. As a result of the flooding, the ship’s floating position will change. The change in the floating position will affect the flooding rate, because the immersion of the breach will increase (or decrease) by some amount ΔH_{imm}. The situation is illustrated in Figure 2.

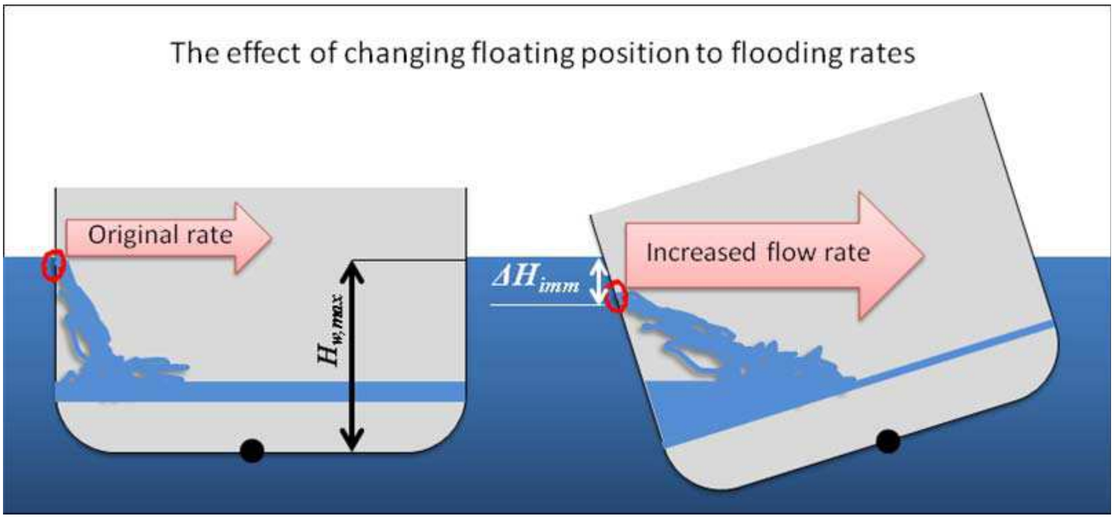

Figure 2: The effect of changing floating position on the flooding rate through the breach

The dynamic roll motion that may be caused by the waves or large transient flooding can also result in notable changes in the floating position of the ship. However, based on the studies in Task 3.2, it seems that the averaged heel angle corresponds well with the assumption of quasi-static motions, especially in a moderate sea state, *Manderbacka (2011)*. The previous research, such as *Papanikolaou et al. (2003)* and *van't Veer et al. (2004)* also support this conclusion.

The first prediction of breach size and location is normally done right after the damage. Thus the possible transient heeling angle can be large and it may also have a notable effect on the flow rate through the breach. Naturally, the changes in the floating position usually slow down after the transient flooding. In collision damages the effect of the striking ship is likely more influential right after the damage creation. However, it is favourable to base the breach detection on the measurement data from the first phases of flooding, where there is likely not so much progressive flooding (see section 3.5).

3.4 Partially Immersed Breaches

The partially immersed breach is a serious problem in flooding prediction because of two separate reasons:

- First of all, it is close to the waterline, and thus even a small flooding rate may correspond to a rather large opening. Therefore it may have a significant influence on the simulation results. In other words, flooding results are very sensitive to breaches near the waterline.

- The other reason is that, if the breach is very close to the waterline, how can we tell if part of it is actually "hiding" above the waterline? The answer is that it is impossible! No measurement can ever detect something, which has no measureable effect. As long as nothing changes, the area which is above the waterline remains undetected, because there is no effect from it. Only, if the ship heels or trims, or the draft changes, the area may become immersed and detectable. This effect should always be included in the estimate of reliability of the simulation results.

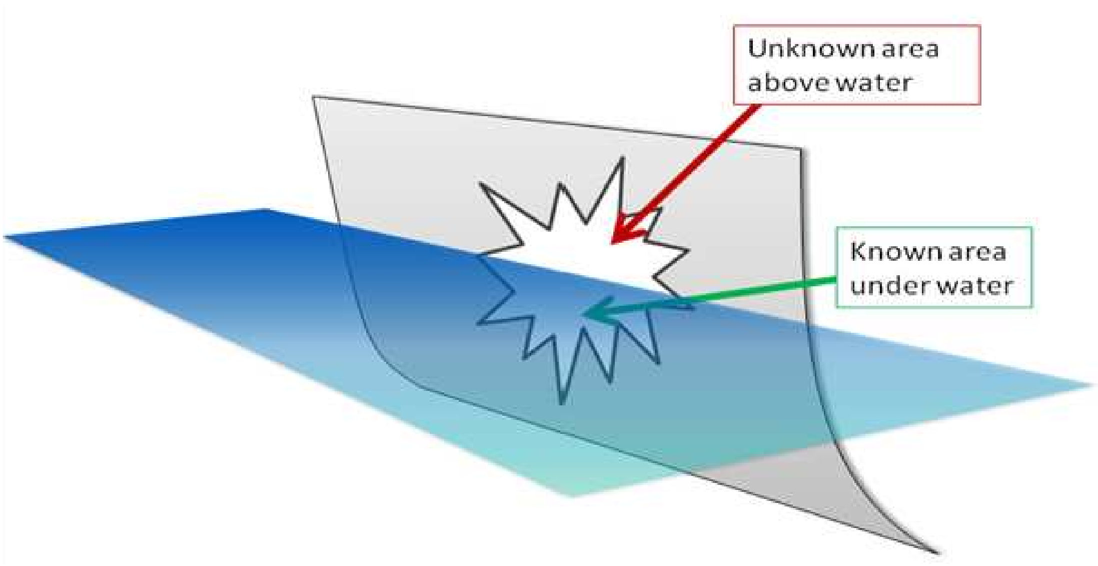

Figure 3: Unknown breach area above waterline

An additional difficulty that is related to breaches near the waterline is that a possible increase or decrease in the flooding rate may be mistakenly interpreted as a breach with a wrong vertical location. However, this should not be serious, because the "mistake" works both ways for small openings. We will simply end up with an opening that is estimated to be closer to the waterline, having more or less the same flooding characteristics, as long as the breach does not rise above the waterline in simulations or in reality. In general, this problem is not considered to be so significant if the breach is large and the damaged rooms can be considered to be "open to sea", i.e. the water level in the room is practically immediately equal to the sea level.

3.5 Flooding through Rooms without Detection

If we want to find out where the breach is and what its size is and so on, the flow of floodwater past the detection sensor is a serious problem. This issue should be addressed in any guidelines for flooding detection (see Deliverable D3.3). An example of a "worst case" scenario is considered here:

The hull is breached near the waterline and water flows from the breach to other rooms inside the vessel. A flooding sensor is installed near a wall slightly above the deck level. The room which is primarily flooding is connected to a stairway, which leads to lower decks. The fire door to the staircase happens to be open and the flood water flows directly from the sea to the staircase and downwards. The scenario is illustrated in Figure 4.

Because the size of the fire door opening may be much bigger than the breach, the flood water does not rise in the primarily flooded room and the sensor stays dry. Then on the tween-deck, the fire door leading out from the staircase is closed, and the flood water progresses even further down, finally reaching the tank top, where the flood water starts to accumulate. Eventually flooding is detected in the lowest room and the flooding rate is calculated based on this sensor data.

Now based on the sensor data, we would like to know, what is the size of the breach? The flood water was first detected on a lower deck, because the water flowed past the sensors higher up. We now assume that the room, where the sensors first detected water, is the primarily flooded one and has a breach. If we define a hole to the JHA (joint hull surface) of the room on the tank top, we get a certain breach size. However in the example, the breach was in reality much closer to the sea level and thus also some water got trapped along the way in the staircase. So not only is the flooding rate slightly off, but also the vertical location of the breach is completely wrong! The breach may in fact be ten times larger, and if one were to simulate the flooding with this falsely detected breach size and location, like in this case, the prediction would be highly unreliable.

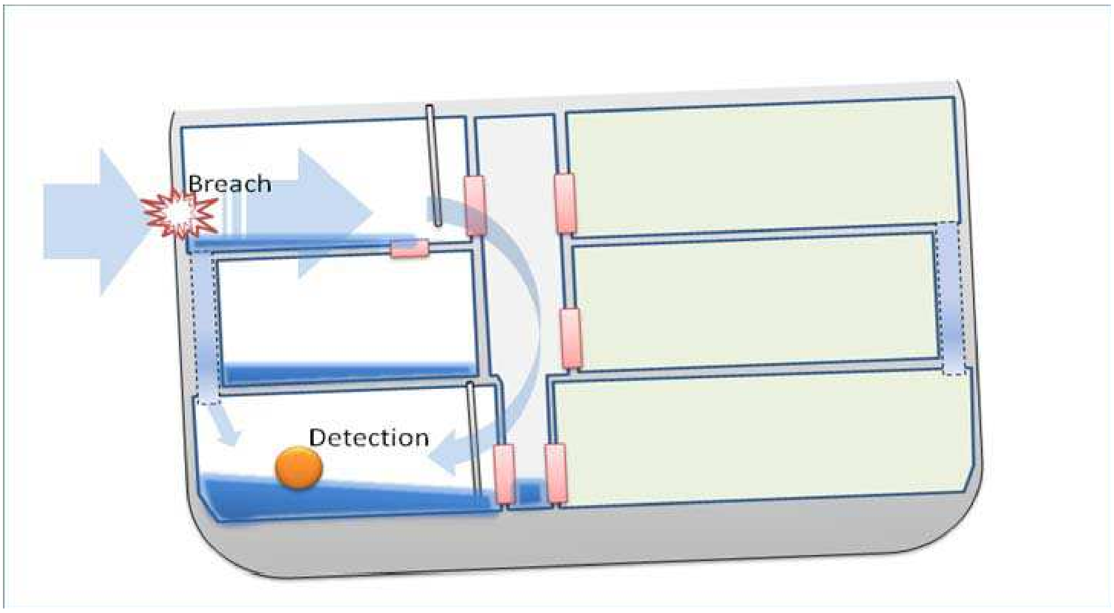

Figure 4: False detection due to "crawling flow"

Another variation of the same problem would be that the flood water flows downwards from a down flooding duct or hatch. This would have the same consequences as mentioned earlier. To avoid such problematic cases, any down flooding ducts or hatches ought to have some flooding detection sensors as well[1].

The flow of flood water past detection is a real measurement problem, which can be solved only by dense sensor arrangements. Like a steel structure, the arrangement has to be strong in places where the greatest risk of failure exists. Flooding simulations can be used in finding the weak places and improving the sensor arrangement designs.

Guidelines for flooding detection sensors and their locations in different compartments have been developed within Task 3.3, and will be reported in the Deliverable D3.3. Proper sensor arrangement should decrease the probability of such case where the real source of flooding cannot be detected.

[1] The analysis and recommendations for flooding detection sensors are reported in the deliverable D3.3.

4 ESTIMATION OF THE DAMAGE EXTENT

4.1 Background

The size and location of the damage is not usually known, at least accurately. Instead, the consequences, i.e. flooding, can be detected by sensors. Consequently, both the size and location of the breach (damage extent) has to be estimated on the basis of this indirect measurement data. The developed methods and approaches for this problem are presented in the following.

4.2 Assessment of Flow Rates

The flooding rate is usually measured or calculated from changes in the indirectly measured volume, and the volume is usually calculated from the measured level in a tank or room. The level can be measured with a radar system or pressure sensor(s). The following analysis will, in general, be applicable to all types of level sensors, but some special attention is focused on pressure sensors.

The measured pressure is converted to level with the following equation:

$$H(t) = \frac{P(t) - P_{REF}}{\rho g} + H_{REF} \tag{1}$$

where $H(t)$ is the height of liquid level from reference height and $P(t)$ the observed pressure as a function of time t. The flood water density ρ is assumed to remain constant. P_{REF} is the reference pressure (atmospheric or other) and H_{REF} is the reference height of the sensor. Consequently the relative error in level measurement equals inversely the error of the measured density.

Measured level can easily be converted into volume V with tank tables or a 3D model like a NAPA-model of a ship. Trim angle θ (can be converted from trim in meters) and heel angle ϕ can be included in the conversion and throughout this text the conversion from level to volume for a room is assumed to be a function of only these variables:

$$V(t) = f\left(t, H(t), \phi(t), \theta(t)\right) \tag{2}$$

It should be noted that the measured trim and heel angles may contain some phase difference, relative to the time of the level measurement, which must be compensated in the timing.

Any internal structures, such as equipment and B-class boundaries, inside the flooded volume or changes in permeability as a function of water height are disregarded, i.e. it is assumed that the permeability is evenly distributed in all rooms.

Based on equation (2), it is possible to estimate the net flow rate to the room:

$$\dot{V} \approx \frac{V\left(t + \frac{\Delta t}{2}\right) - V\left(t - \frac{\Delta t}{2}\right)}{\Delta t} \tag{3}$$

where Δt is the time between the measurements.

Naturally, a higher order differential could be used but since Δt is normally short (typically 10s), the first order approximation is considered to be good enough.

4.3 Inverse Method for Breach Detection

The first idea for assessing the breach and the damage extent was to apply time-domain flooding simulation tool and an inverse method for finding the breach size and location that result in the best match with the measurements from the flood level sensors. The principal idea and the results of the first case study on applying this method are presented by *Penttilä and Ruponen (2010)*. In the following, only a brief introduction is presented:

> *If the hull of a ship is breached below the waterline, the floodwater starts to flood in. The flooding is always deterministic and usually non-reversible. All water levels inside the flooded rooms have dependency on time. The ship's floating position is also a function of time. Whatever happens is considered to be the consequence of the breach and the breach only. Depending on the breach(es), the flooding forms a recognizable pattern. The problem is to find the right breach, or the right parameters, that result in a simulated flooding matching with the observations. The parameters are the breach properties, like the number of breaches, the location of each breach and their corresponding sizes and also the ship's initial stability and so on.*
>
> *Detecting or calculating the breach properties indirectly from level measurement qualifies as an inversion problem. Inversion problems typically have more than one solution. The degrees-of-freedom can however be great, due to the fact that we might not always have the possibility to measure the flood water in the rooms, which are primarily flooded. If the number of different possibilities can be limited, so that every combination can be calculated within a reasonable time, the breach can be estimated by what is in this work called "best-fit pattern matching". For each possible breach, the resulting flooding is calculated†, and the "best-fit" breach is a set of parameters that produce simulation results, that are the closest match to observed values. We can see if they match, for instance, by calculating the mean variance between the two values. The mean variance between the real and simulated values also gives us a tool to estimate the error in the predicted simulation results.*

The inverse method for breach detection provided very good results in the initial study. However, the method requires a lot of short simulations and thus the performance was not very good. Consequently, a somewhat simplified approach was developed. This is described in the following.

4.4 Simplified Approach

4.4.1 Principles

The first alerts from the flooding detection system will give indication on the damage extent. The later alerts are more likely caused by progressive flooding.

The breaches are divided into two categories that are treated with different methods. These are described in the following.

4.4.2 Large Damage

If the flooding rate to a room is very large or the water level in the room reaches the external sea level rapidly the room is considered to be "**open to sea**". This means that when the floating position of the ship (heel, trim and draft) change due to the flooding, the water level in the damaged room will still be equal to the sea level since the breach is so large that water can freely flow through it. The situation is illustrated in Figure 5.

In this case there is no need to model the breach and the whole damaged room is simply reduced from the buoyancy of the hull and the so-called "**lost buoyancy**" method is used, whereas normally the progressive flooding is treated with the added mass method.

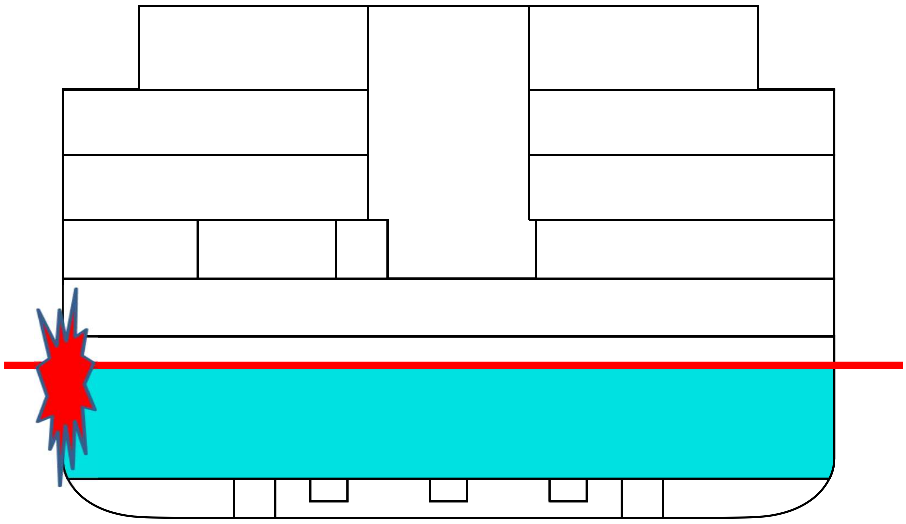

Figure 5: Large damage is considered as lost buoyancy, i.e. the damaged room is reduced from the buoyant hull

4.4.3 Small Breaches

In the simplified approach to flooding predictions, each primarily flooded room has a separate breach. This means that each room is considered to have a direct connection to sea and the simulated results are then the same as somebody could somehow connect these rooms with some pipe through the hull to the sea. This is of course not the case but the approximation works fairly well.

The simplified approach is based on the following assumptions:

- all flood water is always detected and measured
- each initially flooded room has separate breach
- breach sizes can be calculated from flooding rates
- floating position of the vessel is static
    - initial flooding rates correspond to breach sizes
    - The exact location of the breach has no effect on progressive flooding

Each individual breach can be modelled as a "line opening", extending from deck to deck or as a "point opening". This is illustrated in Figure 6. Modelling of the breach as a "line opening" avoids the problems related to the vertical location of the breach (described in sections 3.3 and 3.4). In practice, using the "line openings" as approximations to the real breach geometry is like telling the computer: *"I do not know where exactly the breach is, or what shape it is, but run flooding prediction assuming that the breach is anywhere on the hull, but calculate the flooding rates as average of all possibilities"*. Thus in general, the use of "line openings" is considered to be a conservative approximation, with respect to changes in heeling angles.

For rooms which are not connected to the hull surface, a simple point opening in the middle of the room (lowest point) is used instead of line opening on the hull.

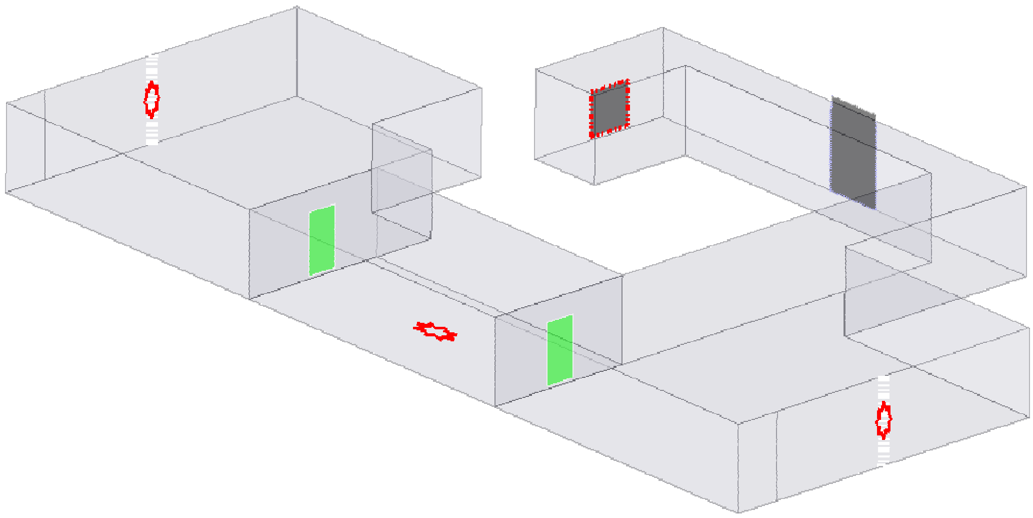

Figure 6: Simplified breach modelling: two "line opening" breaches on the hull and one "point opening" in the centreline

The breach size of each room is calculated separately, based on the measured flooding rate. Each room is treated separately and currently there is no global analysis. The flooding rate to the damaged room is calculated from the level sensor data by using the equations (2) and (3). If the flooding rates of all breaches are added together, the sum is the same as the total measured flooding rate. In this sense the simplification is valid but will increase inaccuracy in the results if the floating position of the ship significantly changes over time.

The main problem with the simplified approach is that it derives the breach size directly from the flooding rate. The errors in calculated flooding rate are likely to be much larger than the errors in measurement of water levels, and these errors are directly proportional to the timing errors in the predictions. The simplified approach is not accurate, but considering the accuracy and reliability of the available input data, it is believed to be reasonable estimation for practical applications.

The simplified approach contains also some other problems. It does not take into account the possibility that all measured flood water may be from a single origin (i.e. progressive flooding) and therefore if there are more than one room flooding, the calculated breach sizes are not correct.

The simplified approach also requires that each room has a flooding detector. This is rarely the case and simplified approach has not a mechanism to take into account the possibility of undetected flooding. Also a room can have more flooding detectors than one, but the simplified approach is unable to utilize the information of several sensors effectively, and will only consider the average of all measurements.

4.5 Flow Rates through Openings and Total Flooding Rate

One essential difficulty is the flow rate through openings and the filling rate of a room. We have been describing flooding rate as a "property" of a room, when in fact it is a "property" of the liquid flowing through the openings.

A room may have several openings, each with a set of specific flow rates, and the room then has consequently a certain total flooding rate, which is the sum of all the rates from individual flooding openings. When the water level in a room is measured, we are only measuring the total amount, and not the parts. Thus we are unable to distinguish from the total amount which opening is flooding faster than others, or whether one opening has a very high inflow rate and another one a correspondingly high outflow rate.

The sum of all flow rates may be relatively small, but individual flows could be much larger. It should be noted however, that the flow of water is not arbitrary and that there may be other ways of calculating the individual flow rates. Much in the same way as the single room flooding from several openings, the ship's hull may be breached more widely at several frames, and the flood water from different origins mixes in the rooms where water level is measured, and naturally there is no way of separating the origins of the flows after that. But even though we might not be able to measure the flooding rate to a room, it is however always possible to calculate the total flooding rate in the ship, that is, if water does not "disappear"[2] from the sensors.

[2] Water may get trapped in smaller rooms and between internal structures

5 ESTIMATION OF THE FLOODING EXTENT

5.1 Calculation Method

5.1.1 Background

The flooding extent can be calculated in time-domain with dedicated simulation methods, such as NAPA Flooding Simulation tool, *Ruponen (2007)*. However, due to rather long computation times this approach is not optimal for onboard decision support tools. Consequently, a simplified, yet reasonably accurate, approach for the calculation of progressive flooding has been developed. The principle idea of this method is explained in the following.

5.1.2 Governing Equations

Conservation of Momentum

Similarly to time-accurate flooding simulation, e.g. *Ruponen (2007)*, the calculation of flow velocities is based on the application of Bernoulli's equation. For a streamline from point A that is in the middle of a flooded room to point B in the opening, Bernoulli's equation is:

$$\int_A^B \frac{dp}{\rho} + \frac{1}{2}\left(u_B^2 - u_A^2\right) + g\left(h_B - h_A\right) = 0 \tag{4}$$

where p is air pressure ρ is density, u is flow velocity, g is acceleration due to gravity and h is height from the reference level. The equation applies for inviscous and irrotational flow. For water flow the density is constant and the equation (4) reduces to:

$$p_B - p_A + \frac{1}{2}\rho\left(u_B^2 - u_A^2\right) + \rho g\left(h_B - h_A\right) = 0 \tag{5}$$

It is assumed that the flow velocity is negligible in the center of the room ($u_A = 0$). The pressure losses in the openings are taken into account by applying semi-empirical discharge coefficients (C_d). Furthermore, in this case the air pressure is assumed to be constant. Consequently, the volumetric flow rate through a small opening is:

$$Q = \mathrm{sign}\left(H_{eff}\right) \cdot C_d \cdot A_{eff} \sqrt{2g\left|H_{eff}\right|} \tag{6}$$

where C_d is the discharge coefficient (assumed to be 0.6 by default), A_{eff} is the effective area of the opening and H_{eff} is the effective pressure head.

For large openings, integration over the submerged area of the opening is needed. Since this new method for assessing progressive flooding for decision support is intended to be only approximate, also the integration can be simplified. Basically, this is done simply by calculating the submerged area of the opening. Consequently, the resulting water flows can be somewhat too large for partially submerged openings. However, this results in a conservative approach.

Conservation of Mass

In addition, at each time step the conservation of mass must be satisfied in each flooded room. The equation of continuity is:

$$\int_\Omega \frac{\partial \rho}{\partial t} d\Omega + \int_S \rho \mathbf{v} \cdot d\mathbf{S} = 0 \tag{7}$$

where ρ is density, $\mathbf{v}$ is the velocity vector and $\mathbf{S}$ is the surface that bounds the control volume Ω. For water flow the density is constant, resulting in:

$$\rho\int_S \mathbf{v}\cdot d\mathbf{S} = 0 \tag{8}$$

In practice this means that for each flooded compartment:

$$\frac{dV_w}{dt} = \sum_{i=1}^{n} Q_i \tag{9}$$

where V_w is the volume of water in the compartment and Q_i is the volumetric flow through an opening i that is connected to the flooded compartment.

5.1.3 Further Assumptions

Ship Motions

The ship motions are considered to be quasi-static. In principle this means that at each time step a static floating position of the ship is calculated based on the distribution of floodwater in the compartments. It is also possible to calculate the full stability curve at each time step[3]. The stability curve can also be calculated after the flooding prediction for any moment in time, e.g. for the time when the heeling angle reaches the maximum value. For these calculations the floodwater is treated as added weight and only the open-to-sea compartments are treated as lost buoyancy.

In addition it is assumed that the sea is calm. This simplification allows purely deterministic approach. On the other hand the increased flooding due to waves is disregarded. However, based on the HARDER statistics over 90% of the collision damages occur in a sea state, where significant wave height is less than 2.0 m, *Tagg and Tuzcu (2003)*. For certain operational areas, such as the Mediterranean, the probability of damage in practically calm sea is even more likely, *Spanos and Papanikolaou (2011)*. Thus for a large passenger ship with dense internal subdivision[4], the effect of waves on the flooding process can be considered as minimal.

The presented calculation method is based on the assumption that the water levels inside the flooded compartments are lower or equal to the sea level, and the water levels are in descending in the direction of the water flows. In practice this contains the assumption that the ship motions are slow. This simplification complies with the previously presented assumptions of small waves. Also flooding typically increases roll damping.

Naturally the aforementioned assumption of descending water levels applies only to rooms that are connected to the sea through openings that are at least partially submerged. During the flooding progression water may be trapped in a room as the floating position changes and eventually the level of this trapped water may be above the sea level.

Sloshing

The developed method is mainly intended for passenger ships that have a dense internal non-watertight subdivision within the watertight compartments. Thus it is considered to be justified to assume that all water levels remain horizontal throughout the flooding process.

Air Compression

Compression of air in tanks can have a notable effect on flooding. This effect can be calculated with flooding simulation, *Ruponen (2007)*, but all ventilation pipes etc. need to be modelled. Considering

[3] E.g. for calculation of the s-factor
[4] No large open spaces like a vehicle deck on ro-ro ferries

that the prediction of progressive flooding onboard the ship is simplified and approximate method, it is justified to assume that all flooded rooms are fully ventilated.

Ventilation level is normally significant only in tanks and the assumption of full ventilation can result in too fast flooding. However, this should affect only in the first minutes of flooding.

5.1.4 Chain of Flooded Compartments

Progressive flooding forms chain(s) of flooded compartments. The principle idea is to keep track on these chains or routes. These are illustrated in Figure 7. The starting point for each chain is the sea or a damaged compartment that is considered to be open-to-sea.

The mass balance in the flooded compartments is solved compartment by compartment, in a reverse order. Thus the calculation is started from the compartment that was flooded last in the chain. This is continued and finally the damaged compartments are solved. Thus the calculation is “sucking water from the sea” instead of the traditional approach, where floodwater is pushed from the sea to the compartments. This inverse order has been found out to significantly stabilize the solution of the governing equations.

Water levels in the flooded compartments must remain descending along the chain of flooded compartments, starting from the sea level. This is a valid limitation since the ship motions are assumed to be slow. This approach stabilizes the calculation in many cases, especially when there are large openings and the effective pressure heads are small. However, it should be noted that the flooding chains may be broken if a flooding opening becomes non-immersed.

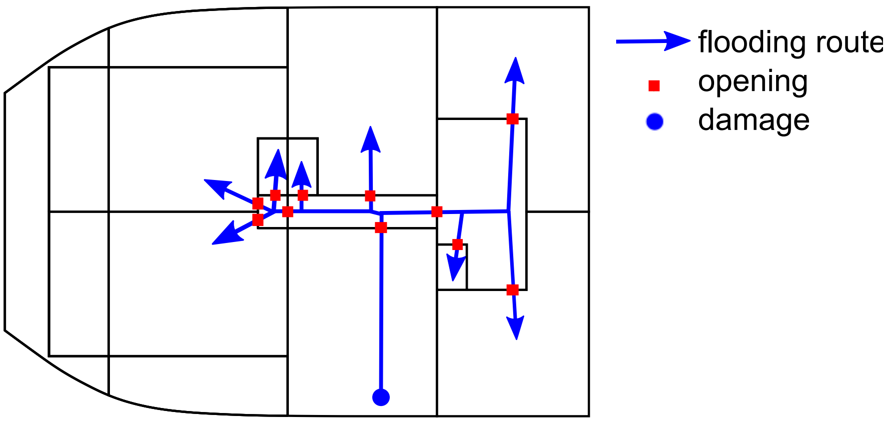

Figure 7: Chains of flooded compartments

5.1.5 Calculations for a Flooded Room

Let us first consider the flow through a single opening between two flooded compartments. The situation is illustrated in Figure 8. For simplicity, it is assumed that $h_1 > h_2$. Based on Bernoulli’s equation (6), the volumetric flow rate through the opening is:

$$Q = C_d A \sqrt{2g(h_1 - h_2)} \tag{10}$$

On the other hand, the flow rate can also be calculated as the time derivatives of the water volumes (when only a single opening is considered):

$$Q = -\frac{\partial V_1}{\partial t} = -\frac{\partial V_1}{\partial h_1}\frac{\partial h_1}{\partial t} = -S_1 \dot{h}_1 \tag{11}$$

or

$$Q = \frac{\partial V_2}{\partial t} = \frac{\partial V_2}{\partial h_2}\frac{\partial h_2}{\partial t} = S_2 \dot{h}_2 \tag{12}$$

where *S* is the free surface area in the flooded compartment (assumed to be constant within time step).

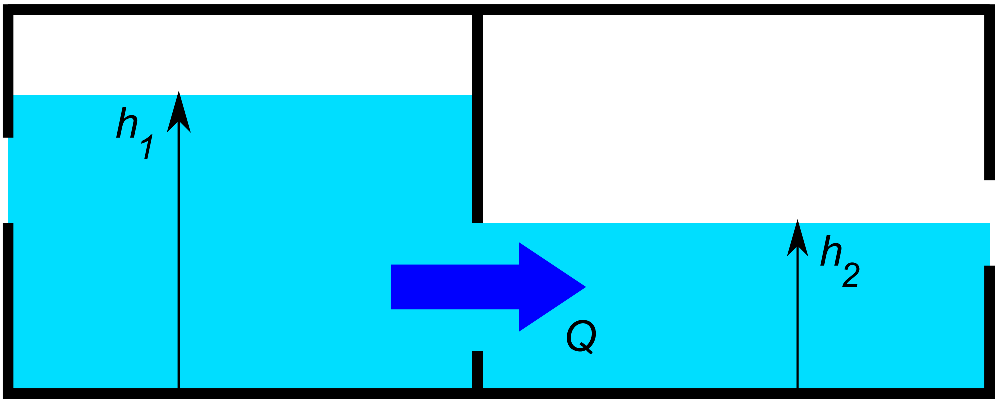

Figure 8: Water flow through an opening

The following notation is used in order to simplify the equations:

$$C_F = C_d A \sqrt{2g} \tag{13}$$

Also the effects of leakage and partially submerged opening can be taken into account by modifying this (dimensional) coefficient. This is presented in section 5.1.6.

By combining the equations (11) and (12) and taking into account Bernoulli's equation (10), the time derivative of the pressure head ($h_1 - h_2$) is:

$$\begin{aligned} \dot{h}_1 - \dot{h}_2 &= -Q\left(\frac{1}{S_1} - \frac{1}{S_2}\right) \\ &= -C_F \sqrt{h_1(t) - h_2(t)}\left(\frac{1}{S_1} - \frac{1}{S_2}\right) \end{aligned} \tag{14}$$

Thus the following differential equation is obtained:

$$\frac{\dot{h}_1 - \dot{h}_2}{\sqrt{h_1(t) - h_2(t)}} = -C_F\left(\frac{1}{S_1} - \frac{1}{S_2}\right) \tag{15}$$

Integration of this results in:

$$\sqrt{h_1(t) - h_2(t)} = -\frac{1}{2} C_F \left(\frac{1}{S_1} - \frac{1}{S_2}\right) t + \sqrt{h_1(0) - h_2(0)} \tag{16}$$

It should be noted that based on the notation (13), the equation (10) for the volumetric flow through the opening is:

$$Q = C_F \sqrt{h_1(t) - h_2(t)} \tag{17}$$

Consequently, the volume of water that flows through the opening during a time step Δt is obtained by integration:

$$\begin{aligned}\Delta V &= \int_0^{\Delta t} C_F \sqrt{h_1(t) - h_2(t)}\,dt \\ &= C_F \left[\sqrt{h_1 - h_2}\,\Delta t - \frac{1}{4} C_F \left(\frac{1}{S_1} - \frac{1}{S_2} \right) \Delta t^2 \right]\end{aligned} \tag{18}$$

Furthermore, the effective pressure head $h_1(t) - h_2(t)$ cannot be negative since the flow direction cannot change during the time step. Consequently, the time step Δt has to be limited to:

$$\Delta t = \min \left[\Delta t_0, \frac{2\sqrt{h_1 - h_2}}{C_F \left(\frac{1}{S_1} - \frac{1}{S_2} \right)} \right] \tag{19}$$

where Δt_0 is the initial time step. This situation is illustrated in Figure 9. The limitation is necessary for numerical stability but usually it is needed only in the beginning of the flooding process, when the flow rates are large or sometimes when a closed door collapses.

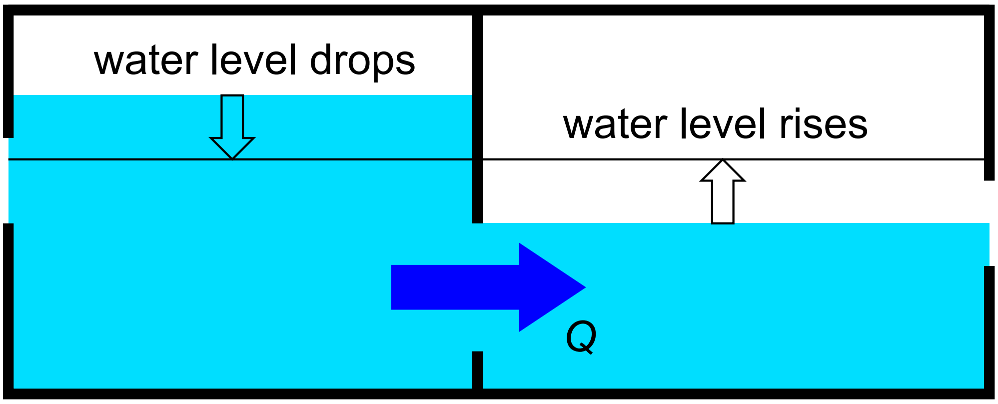

Figure 9: Adjustment of time step due to fast flooding

The inflow from the sea is treated similarly but the water level area for the sea is $S_{sea} = \infty$. Otherwise the same equations can be applied.

The same treatment is done to all openings that are connected to the flooded room. The procedure is illustrated in Figure 10 and the workflow is shown Figure 11.

The requirement that floodwater levels are in descending order in the chains of flooded compartments also somewhat limits the applicability of the prediction tool to cases, where the ship motions (especially rolling) is not too significant.

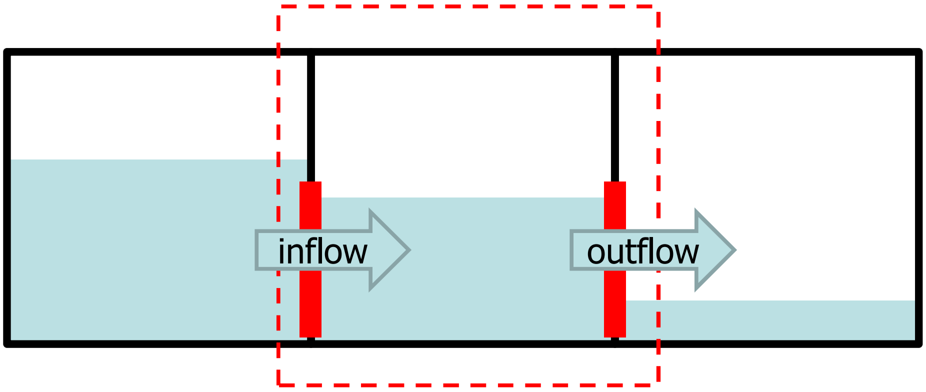

Figure 10: Principle idea of solving progressive flooding in the highlighted compartment

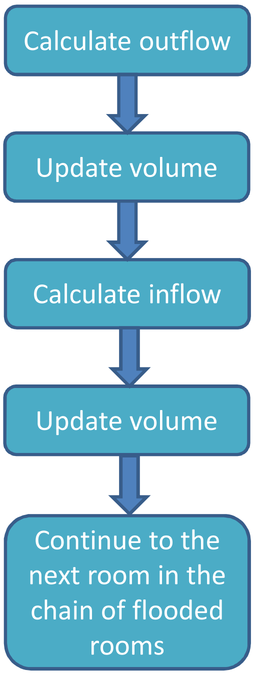

Figure 11: Process for solving progressive flooding for one compartment

5.1.6 Leaking and Collapsing Structures

Closed non-watertight doors, such as A-class fire doors and cold room doors will start to leak even under moderate water pressure. If the pressure increases the door will eventually collapse. This process is illustrated in Figure 12. Structural failure of a closed door is irreversible, meaning that the leakage area ratio cannot decrease or a collapsed door cannot be closed anymore when the effective pressure head decreases.

Significant leaking and especially the collapsing of closed doors open new routes for progressive flooding and thus this needs to be accounted also in a simplified flooding progression analysis. In general, the same approach as in the time-domain simulation (*Ruponen, 2007*) is used. The values from the FLOODSTAND deliverable D2.2b (*Ruponen and Routi, 2011*) are used in the test cases.

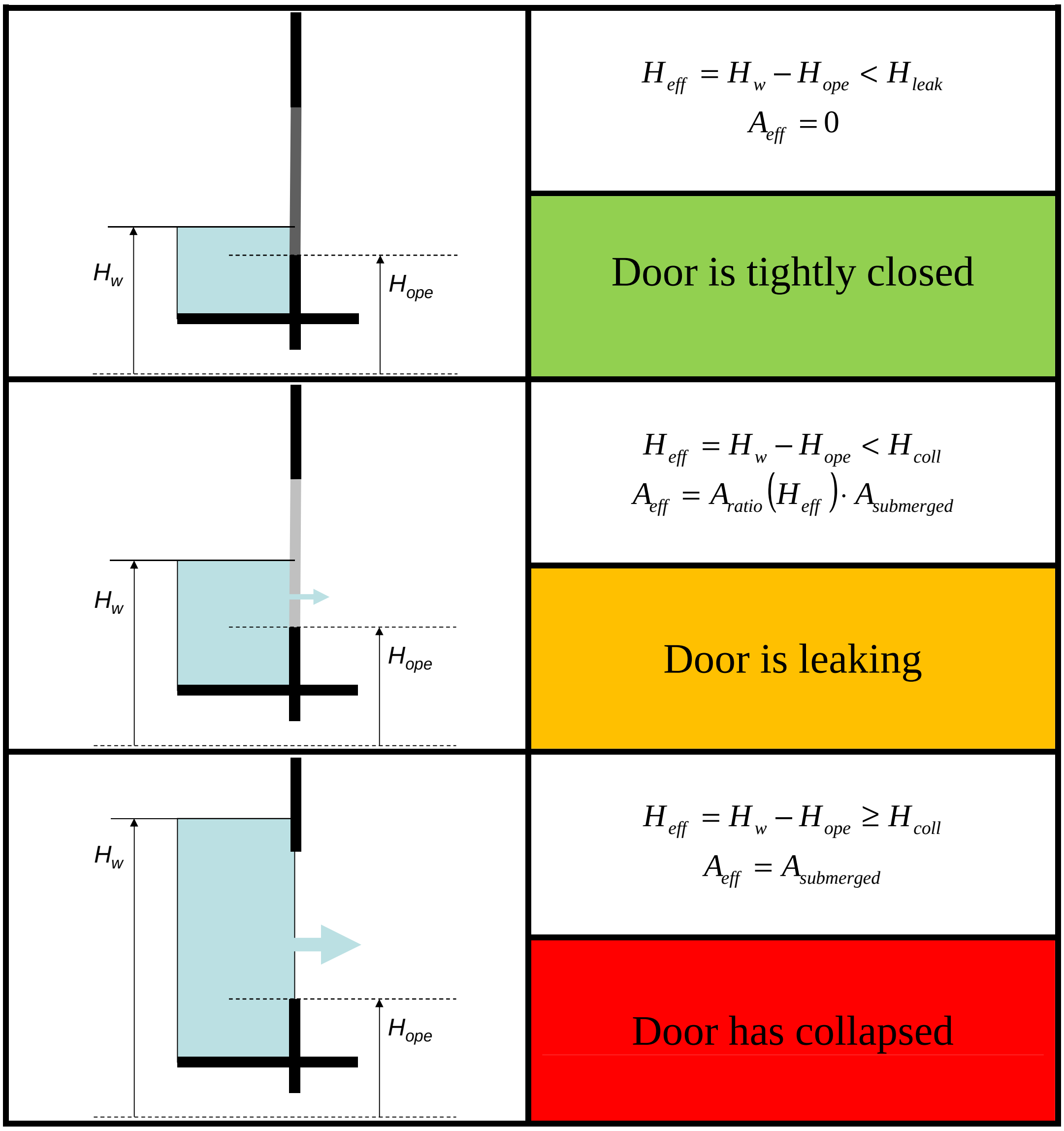

Figure 12: Modelling of leaking and collapsing of closed doors

Based on the full-scale experiments with doors in Task 2.1, *Jakubowski and Bieniek (2010)*, it was found out in the deliverable D2.2b, *Ruponen and Routi (2011)*, that for many door types the leakage area ratio increases practically linearly as a function of the effective pressure on the door. In addition, both the leakage area ratio and the critical pressure head for collapsing may depend on the direction of the pressure (especially for hinged doors). All these factors need to be accounted also in the prediction of progressive flooding.

In the presented method for flooding prediction, the leakage area ratio is taken into account in the dimensional coefficient, equation (13), so that:

$$C_F = C_d A_{ratio} A \sqrt{2g} \tag{20}$$

The calculation method also raises an event, when a closed door is collapsed. This can be passed to the user interface.

It is noteworthy that the opening parameters (C_d, H_{leak}, H_{coll} and A_{ratio}) are approximate and based on various simplifications. Within Task 2.6 of the FLOODSTAND project a dedicated sensitivity analysis was carried out, *Karlberg et al. (2011)*. The main conclusion in that study was that variation in the opening parameters does not have a significant effect on the flooding characteristics like the maximum transient heeling and the intermediate phases of flooding. On the other hand, especially the applied leaking area ratio can have a major effect on the time-to-flood.

5.2 Test Case 1: Comparison to Full-Scale Measurements

5.2.1 Damage Scenario

The recent full-scale flooding tests with the decommissioned Fast Attack Craft *TURKU* of the Finnish Navy provided a unique opportunity to compare the simple calculation of progressive flooding against measurements, not just detailed simulation results. A comprehensive description and analysis of the experiments along with comparative time-domain flooding simulations are presented by *Ruponen et al. (2010)*.

The studied flooding case is illustrated in Figure 13 and the principal dimensions of the ship are listed in Table 1. All flooded compartments were practically fully vented through large air pipes and openings to the tween deck. The flooded rooms include empty side tanks, a pump room and an equipment room.

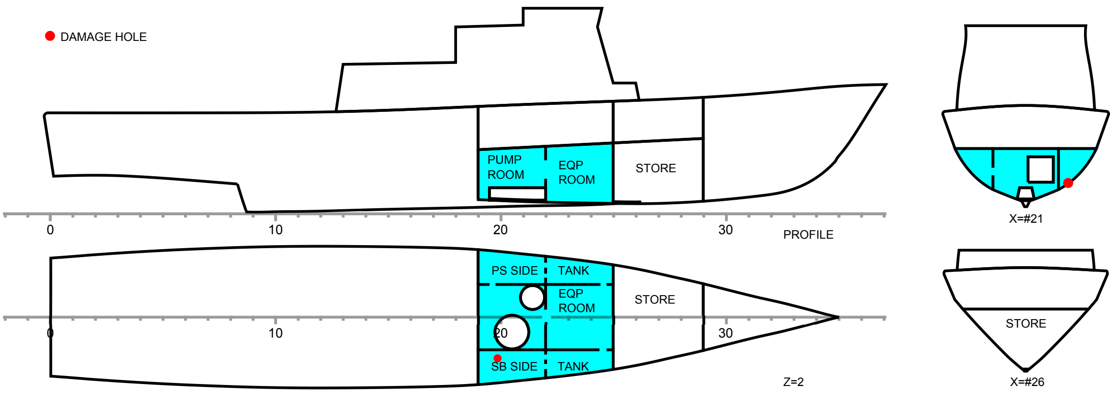

Figure 13: Studied damage scenario

Table 1: Principal dimensions of the test ship and damage extent

Parameter:	Value:	Unit:
Length over all:	45	m
Maximum breadth:	8.8	m
Displacement:	221	ton
Metacentric height (intact):	1.10	m
Damage size:	0.049	m^2

5.2.2 Results

The developed calculation method for progressive flooding is compared to both measurements and detailed time-domain flooding simulation with a time step of 0.2 s. The simulation with detailed input data has been found out to correspond very well with the measurements, *Ruponen et al. (2010)*.

In the original study with the full-scale flooding tests, simulations were performed with rough and detailed input data. In the present analysis the detailed input data (discharge coefficients and permeabilities) is used for both the time-domain simulation and the new prediction tool for progressive flooding.

Figure 14 shows the results for heeling angle. The simplified method for progressive flooding predicts well the maximum heeling angle and the qualitative development of the flooding process. Also the final equilibrium floating position is the same as with the detailed simulation and measurement.

The comparison of computation times is presented in Table 2. The simplified method for progressive flooding is over 20-times faster than the more accurate flooding simulation with a short time step. The computation time is about 200-times faster than the real measured time-to-flood.

It should be noted that for this test only the calculation was performed without any graphical user interface (GUI). For the actual decision support system the total time is expected to be slightly longer due to the interface.

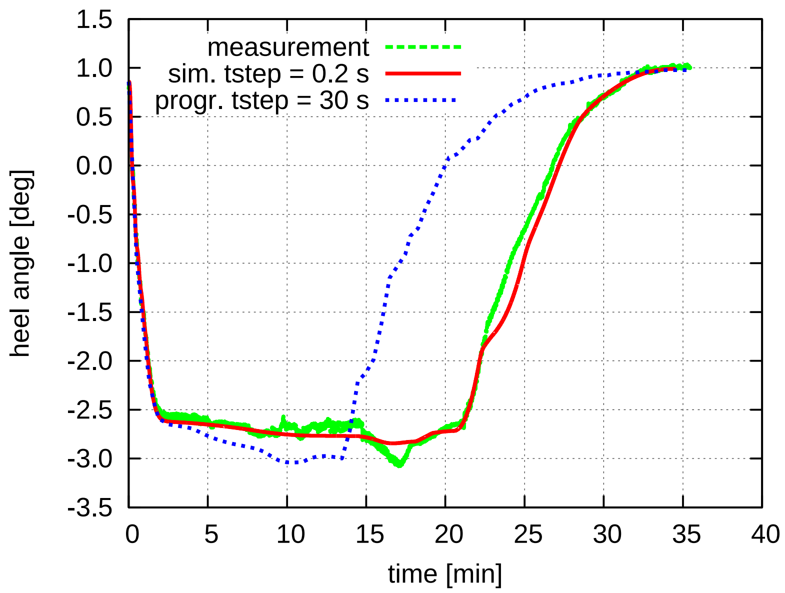

Figure 14: Test Case 1 – comparison of measured heel angle and calculation results with both detailed flooding simulation and the new method for progressive flooding prediction

Table 2: Comparison of computation times[5] for Test Case 1

Calculation method:	Time (s)	%
Experiment (real time)	2100	100.0
Flooding simulation (Δt = 0.2 s)	245	11.7
Progressive flooding (Δt = 30 s)	9	0.5

[5] Calculated with a laptop (Intel i7-820QM processor), without a graphical user interface (GUI)

5.3 Test Case 2: Progressive Flooding and Collapsing Doors

5.3.1 Damage Scenario

The FLOODSTAND Sample Ship Design A, *Kujanpää and Routi (2009)*, is used as a second test case with a much larger damage hole size. A damage scenario with up flooding through staircases and lift trunks in two watertight compartments is used. This damage scenario was originally created in the Task 2.6 for the sensitivity analysis. For details, see FLOODSTAND deliverable D2.6, *Karlberg et al. (2011)*.

Similarly to sensitivity study in Task 2.6, an additional longitudinal A-class bulkhead has been added to the centreline on Deck 02 in order to increase the asymmetry of flooding and the transient heeling in intermediate phases. The flooded rooms are illustrated in Figure 15 and the detailed general arrangement of the flooded compartments is shown in Figure 16.

The store room and the laundry on the Deck 01 are damaged. The flooding progresses upwards through the staircases and the service lift trunks to the stores on the Deck 02, and further up to the cabin areas on the Deck 03.

The A-class doors to the staircases are hinged and the other doors are of sliding type. The watertight door between the flooded compartments is tightly closed. 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 closed watertight doors are considered to be fully watertight. In addition, the double bottom tanks are flooded separately and filled up during the first minutes of the flooding. Consequently, there are total of three separate chains of progressively flooded compartments. Two of these chains contain several closed fire doors that will leak. The doors on the lower deck will also eventually collapse.

The applied parameters for leakage and collapsing of closed non-watertight doors are based on the guideline values from the FLOODSTAND deliverable D2.2b, *Ruponen and Routi (2011)*. A constant discharge coefficient $C_d = 0.6$ was used for all openings.

The intact condition is the deepest subdivision draught and there are no liquid loads in the ship. 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.

The reference results are calculated with time-domain flooding simulation, *Ruponen (2007)*, with a constant time step of 0.2 s. These are the same results that were used also in the Deliverable D2.6, *Karlberg et al. (2011)*.

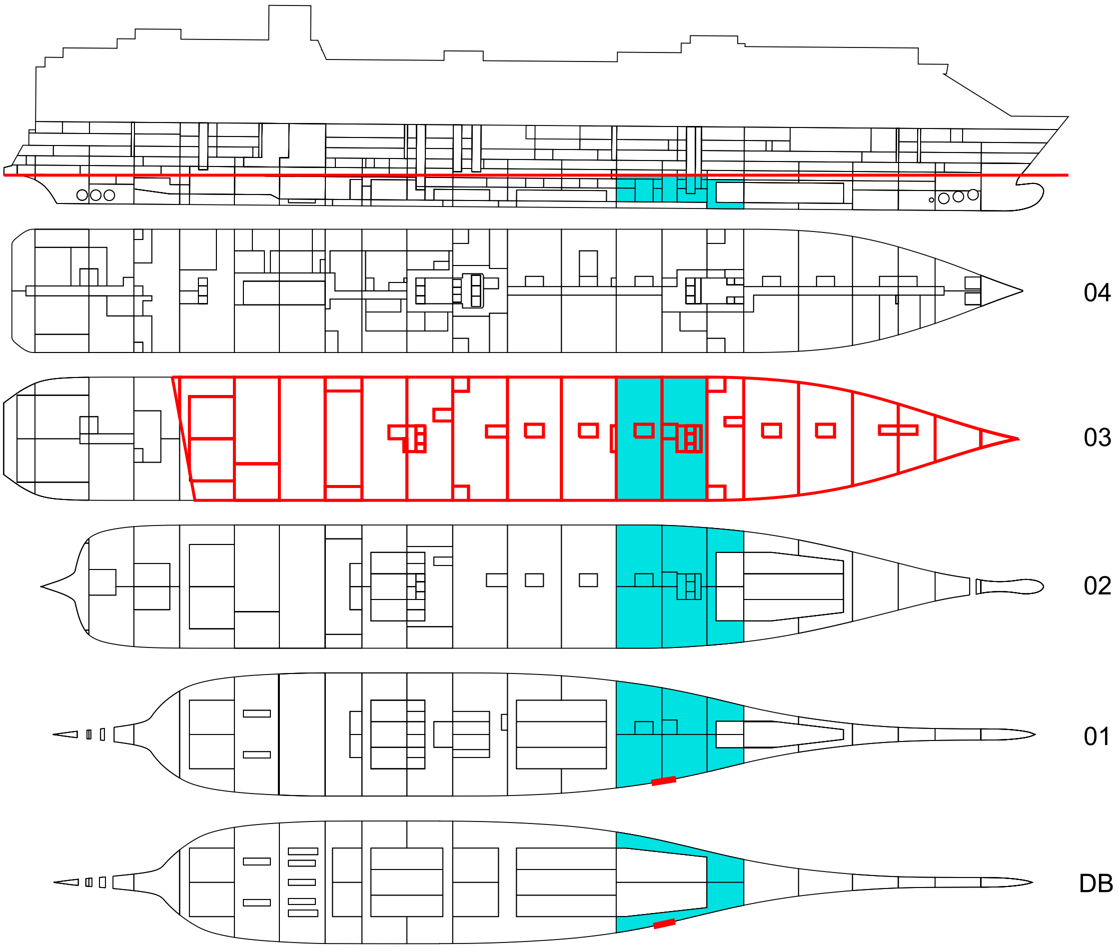

Figure 15: Studied damage scenario

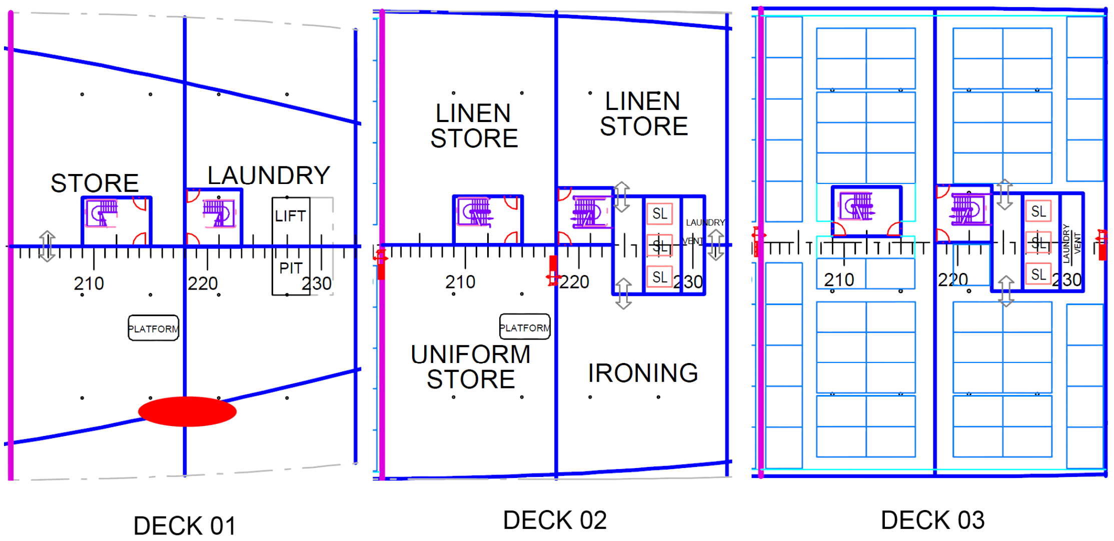

Figure 16: General arrangement of the three topmost flooded compartments. Damage area on Deck 01 marked as a red ellipse.

5.3.2 Results

Results with different calculation methods are presented in Figure 17 and Figure 18 for the heeling angle and total mass of the floodwater, respectively. The method for progressive flooding predicts the transient heeling very accurately, even though the floating position calculation is pure quasi-static and dynamic roll motion was calculated with the flooding simulation. On the other hand, the second peak of heeling is underestimated.

The progressive flooding calculation somewhat underestimates the amount of flooded water between 5 min and 10 min. This is caused by the much longer time step. Thus the collapsing of the closed A-class fire doors takes place later and the total flooding rate is underestimated. This is illustrated in Figure 19. The difference in the results is about the same as with the 25% increase in the applied critical pressure head for collapsing (Deliverable D2.6, *Karlberg et al, 2011*). Also, the total mass of floodwater in the final condition is just slightly smaller than with time-domain simulation. Some comparisons to simulation results with variation in the leaking and collapsing parameters is presented in Figure 20.

The computation times are compared in Table 3. The results are not fully comparable since with the progressive flooding prediction method the calculation continues until the defined maximum time of 3 hours, even though the changes are minimal. The flooding simulation stopped at a final equilibrium condition after 7280 s (about 2 h). The progressive flooding prediction method is roughly 500-times faster than real time. However, it should be noted that for this test only the calculation was performed without any graphical user interface (GUI). For the actual decision support system the total time is expected to be slightly longer due to the interface.

Increasing the time step from 30 s to 60 s does not have a major effect, neither on the results nor on the computation time. The reason for this is that the time step has to be temporarily shortened during the early flooding phases based on equation (19).

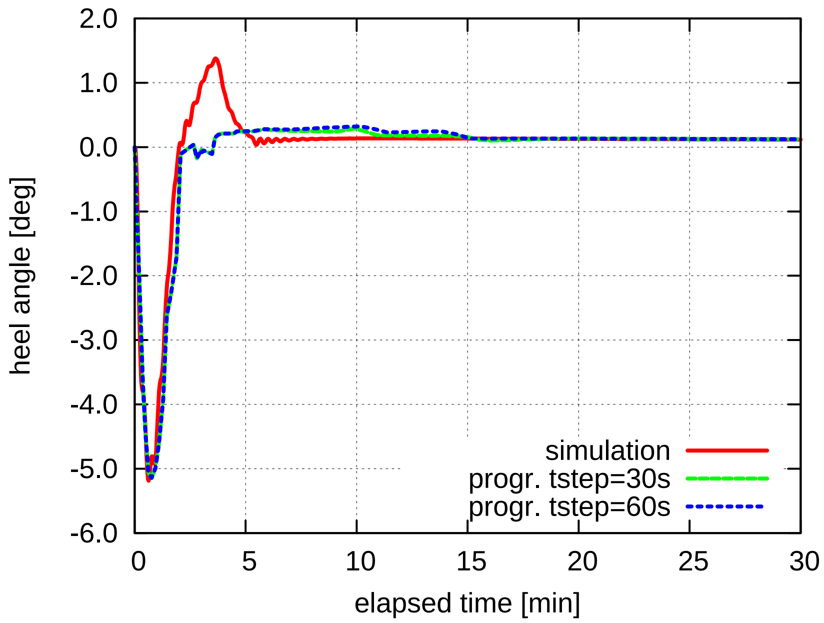

Figure 17: Test Case 2 – comparison heeling angle with detailed flooding simulation and calculation of progressive flooding (range is limited to the early phases since there is no change in heel angle after 30 min)

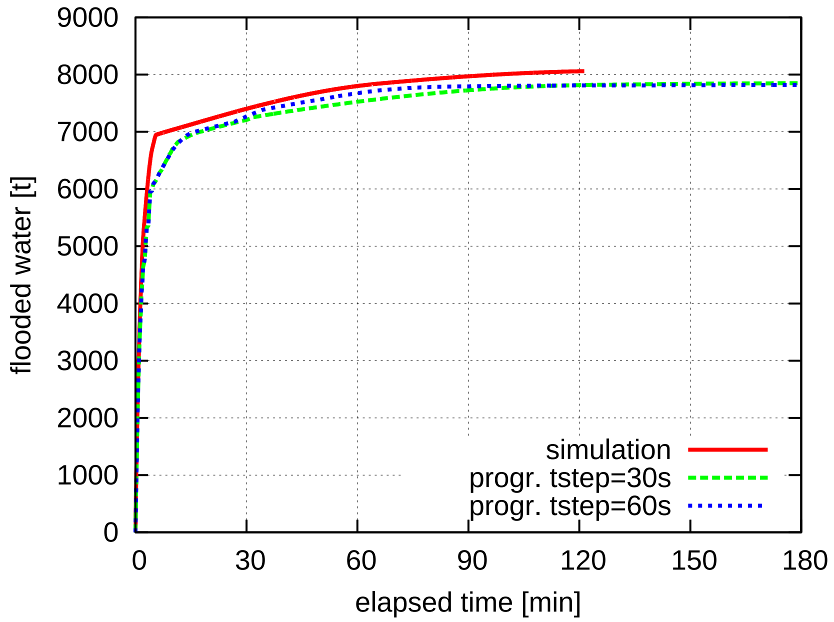

Figure 18: Test Case 2 – comparison total volume of floodwater with detailed flooding simulation and calculation of progressive flooding

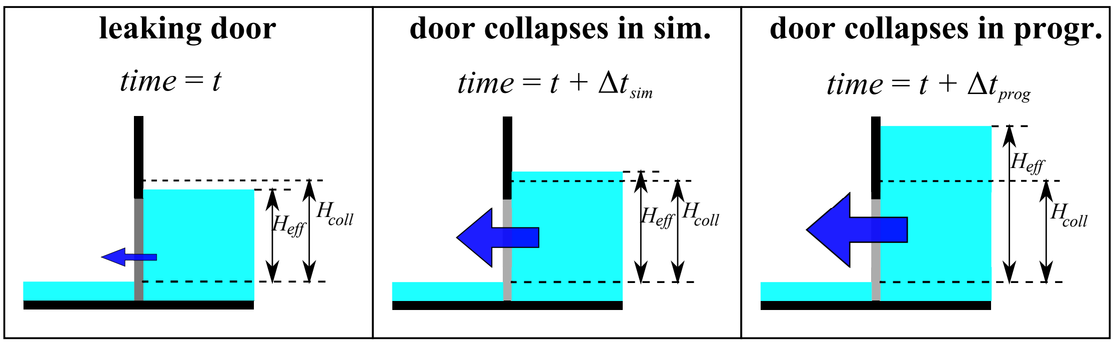

Figure 19: Effect of time step in the collapsing of a closed door

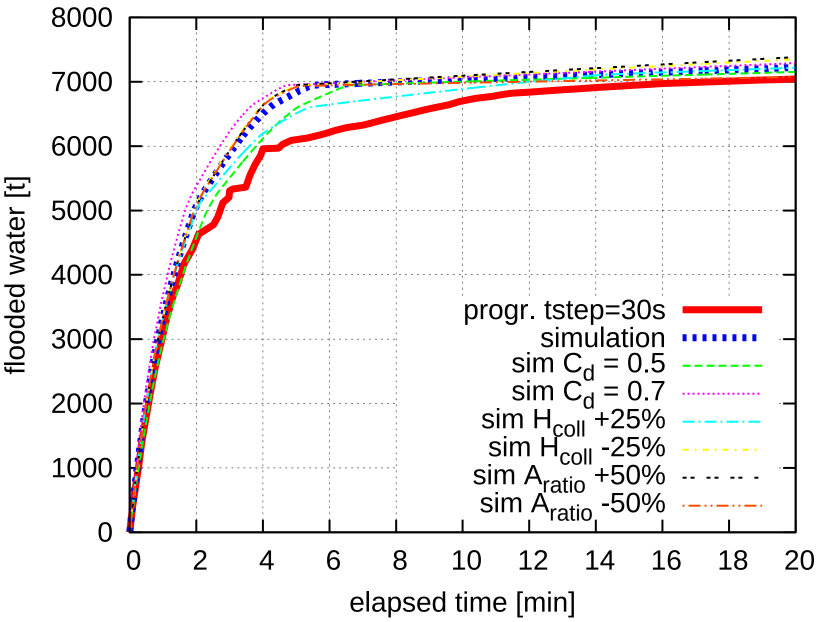

Figure 20: Test Case 2 – comparison of floodwater mass with the progressive flooding calculation against simulations with variation of parameters for the openings; time range is limited to 20 min in order to emphasize the differences

Table 3: Comparison of computation times for Case 2

Calculation method:	Time (s)	%
Time-to-flood (simulated time)	7 280	100.00
Flooding simulation (Δt = 0.2 s)	2 915	40.04
Flooding simulation (Δt = 1.0 s)	728	10.00
Progressive flooding (Δt = 10 s)	52	0.71
Progressive flooding (Δt = 30 s)	16	0.22
Progressive flooding (Δt = 60 s)	14	0.19

5.4 Test Case 3: Progressive Flooding Near Waterline

5.4.1 Damage Scenario

The same FLOODSTAND Sample Ship Design A is used. The damage case is the same as Case B in Deliverable D2.6, *Karlberg et al. (2011)*. The aim is to investigate the suitability of the developed method for assessing progressive flooding near the waterline, where the pressure heads on the openings are small. In the Test Case 2 the flooding progressed mainly vertically through the staircases and lift trunks, but in this case the water flows mainly laterally along the decks.

The damage case and the final floating position are shown in Figure 21. 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

Note that in this study the watertight doors at frames #21 and #36 (see Figure 22) had to be kept open, against the regulations and good seamanship, in order to achieve more extensive progressive flooding in this damage case.

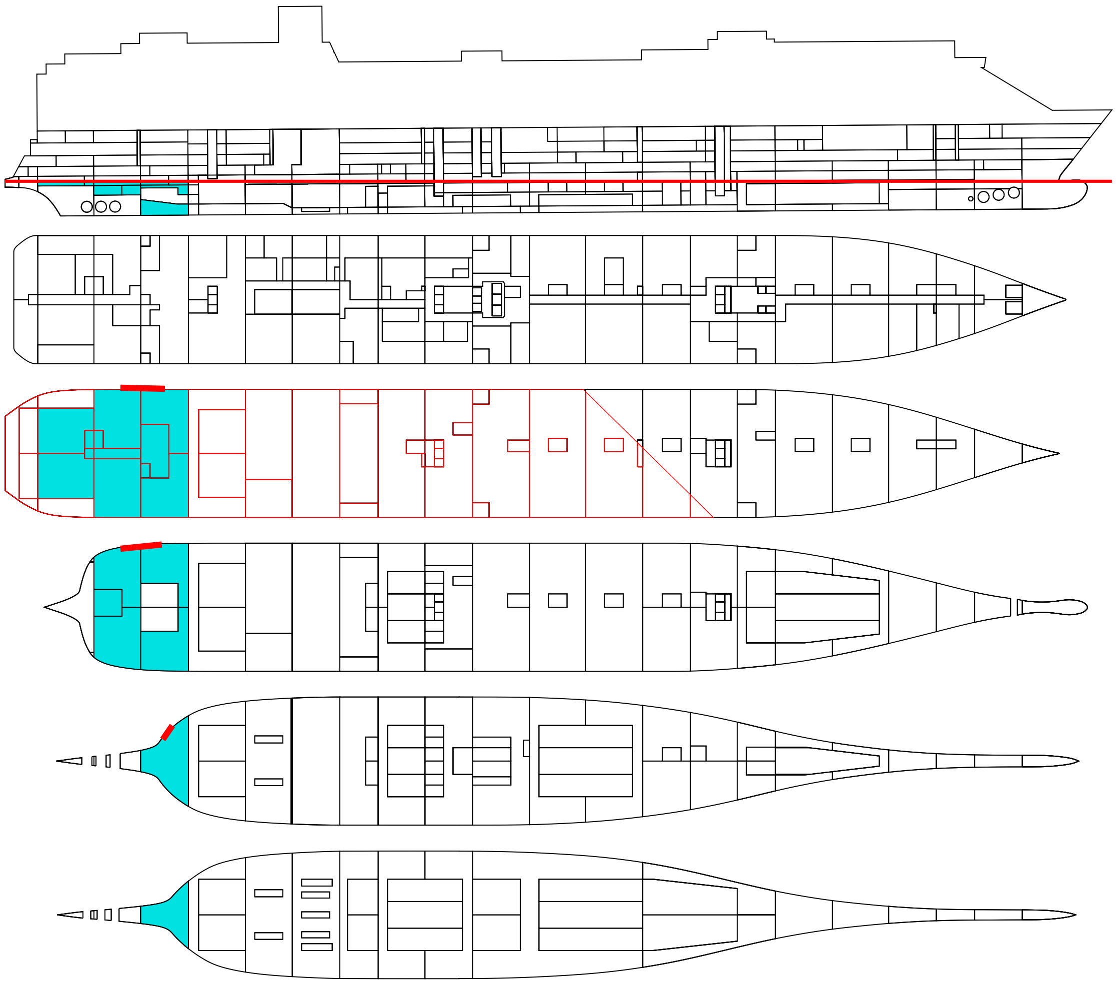

Figure 21: Damage scenario for Test Case 3

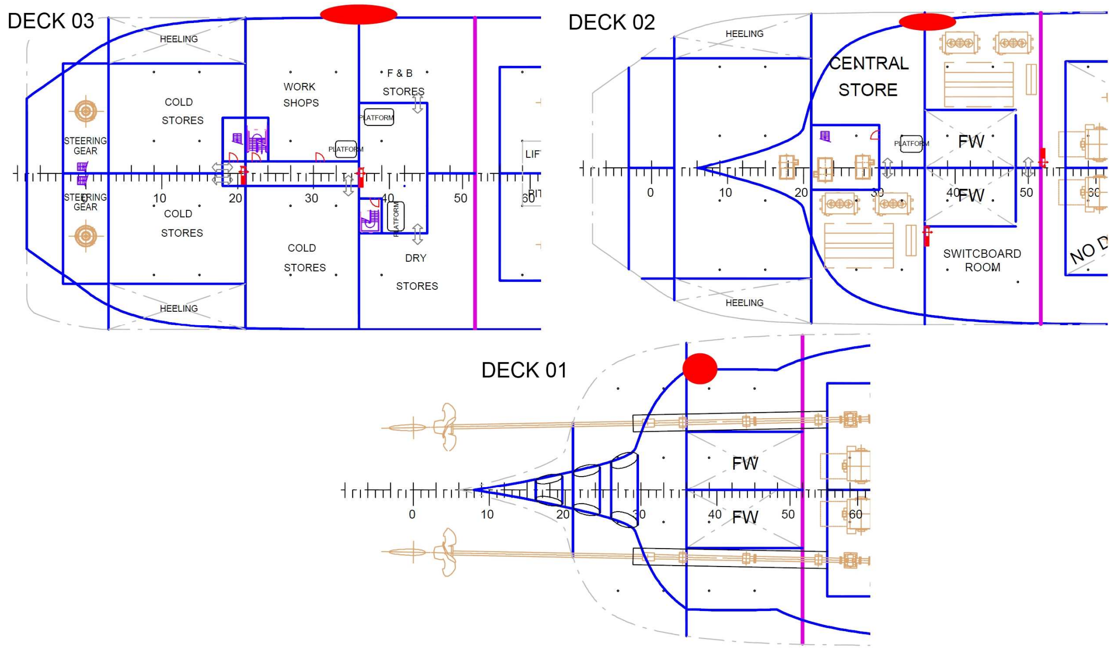

Figure 22: General arrangement of the flooded compartments in Test Case 3, damage holes are marked with red ellipses

5.4.2 Results

Similarly to the previous damage case, the method for progressive flooding prediction captures the transient heeling very accurately. The results are presented in Figure 23 for the whole time-to-flood and in Figure 24 for the transient phase.

In time-accurate simulation the heeling angle decreases somewhat faster. In addition the progressive flooding method results in some small steps in the curve that are not obtained with the simulation. Yet, the global behaviour of the heeling is predicted very accurately.

Results for the total mass of floodwater are shown in Figure 25. The simulation results in slightly faster flooding rate during the early phases. This is due to the critical pressure head for collapsing of closed doors is reached earlier with a much shorter time step (as illustrated in Figure 19).

The final flooding condition and the time-to-flood are well predicted by the progressive flooding method. However, the static equilibrium is not found and the calculation continues until the given maximum time of 4 hours.

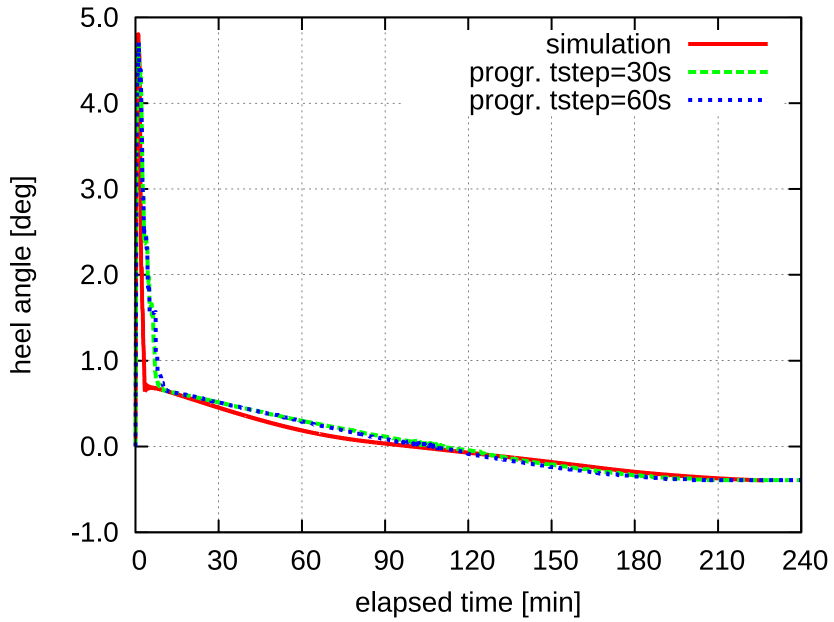

Figure 23: Test Case 3 – comparison heeling angle with detailed flooding simulation and calculation of progressive flooding

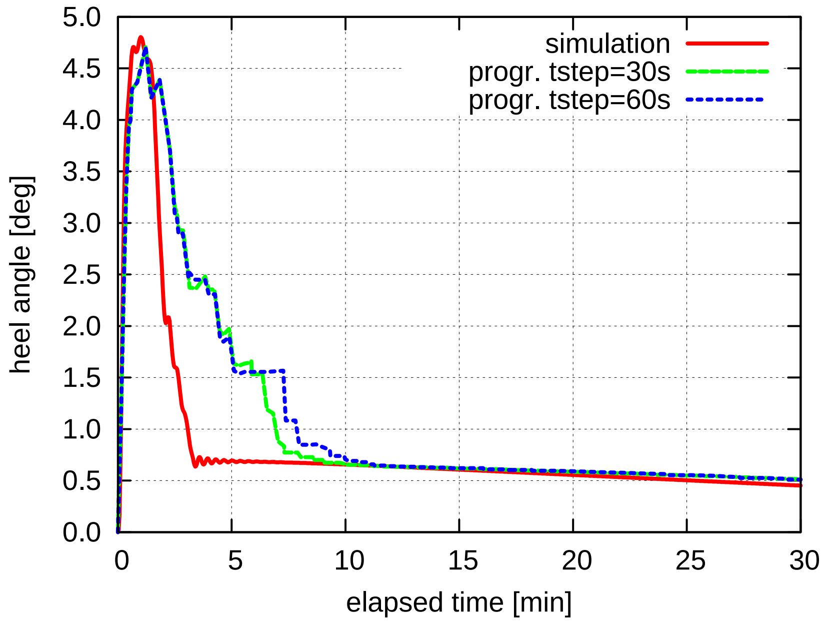

Figure 24: Test Case 3 – comparison of transient heeling with different methods

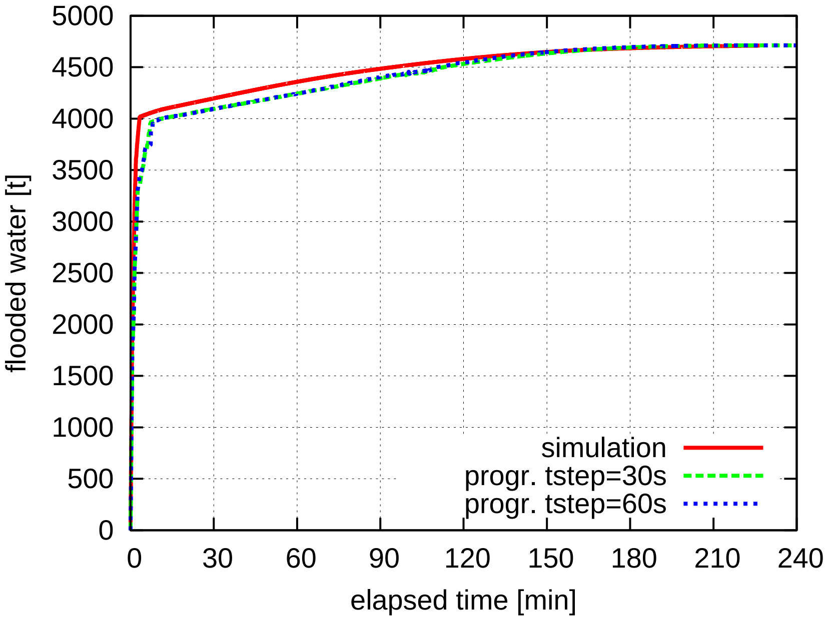

Figure 25: Test Case 3 – comparison total volume of floodwater with detailed flooding simulation and calculation of progressive flooding

Table 4: Comparison of computation times for Case 3

Calculation method:	**Time (s)**	**%**
Time-to-flood (simulated time)	13 600	100.00
Flooding simulation (Δt = 0.2 s)	5 725	42.00
Progressive flooding (Δt = 30 s)	34	0.25
Progressive flooding (Δt = 60 s)	26	0.19

6 UNCERTAINTIES AND CONFLICTING RESULTS

The uncertainties in the flooding prediction analysis onboard a damage ship result mainly from the following:

- Accuracy of the sensors
  - flood water levels
  - floating position
- Accuracy of the room modelling
  - Permeability
  - calculation of flow rates from measurements
- Accuracy of openings
  - Opening location and geometry
  - Opening parameters
    - Discharge coefficients
    - Leaking (A_{ratio} and H_{leak})
    - Collapsing (H_{coll})
- Estimation of breach size and location
- Modelling of environmental conditions
  - Waves
    - Effect on ship motions
    - Effect on flooding through the breach
  - Wind
- Calculation of flooding progression
  - Numerical error

The list is long and it is easy to understand that any flooding prediction method for a real damage case cannot be treated as “accurate”, especially when time is considered.

The opening parameters have been studied extensively in WP2 of the FLOODSTAND project. The guideline values for modelling leaking and collapsing non-watertight structures, *Ruponen and Routi (2011)* are directly applicable also to flooding prediction onboard.

The sensitivity analysis in Task 2.6, *Karlberg et al. (2011)*, showed that the leakage area ratio can have a significant effect on the time-to-flood. On the other hand even large changes in the opening parameters had no significant effect on the flooding progression and the intermediate phases. Naturally, only a few flooding scenarios were investigated. However, it could be concluded that if the heeling of the ship uprights during the flooding process the subsequent heeling direction after this phase often depends on the small details such as the opening parameters.

The size and location of the breach are significant in the beginning of the flooding. In progressive flooding stage some other openings are usually the “bottle necks” that limit the flooding rate from the sea. Consequently, the estimated breach size may have only a small effect on the time-to-flood. Naturally, the breach size has a larger effect on the transient motions, immediately after the damage creation. However, these initial transient phases are not so significant for prediction of progressive flooding onboard the ship, as it becomes meaningless if the ship capsizes already during the transient heeling.

The effect of the sea state is illustrated in Figure 26 for moderate (H_s = 2.5 m) and heavy sea state (H_s = 6.5 m). In the simulations by *Manderbacka (2011)*, the coupling between the flooding progression and dynamic ship motions was only partial but some conclusions can still be drawn. The dynamic roll motion is fluctuations around the quasi-static heel angle. Higher waves simply result in larger fluctuation. This should be taken into account when evaluating the reliability and accuracy of the flooding prediction results. In practice this could simply be a reduced value for the criterion of critical heeling angle in higher waves.

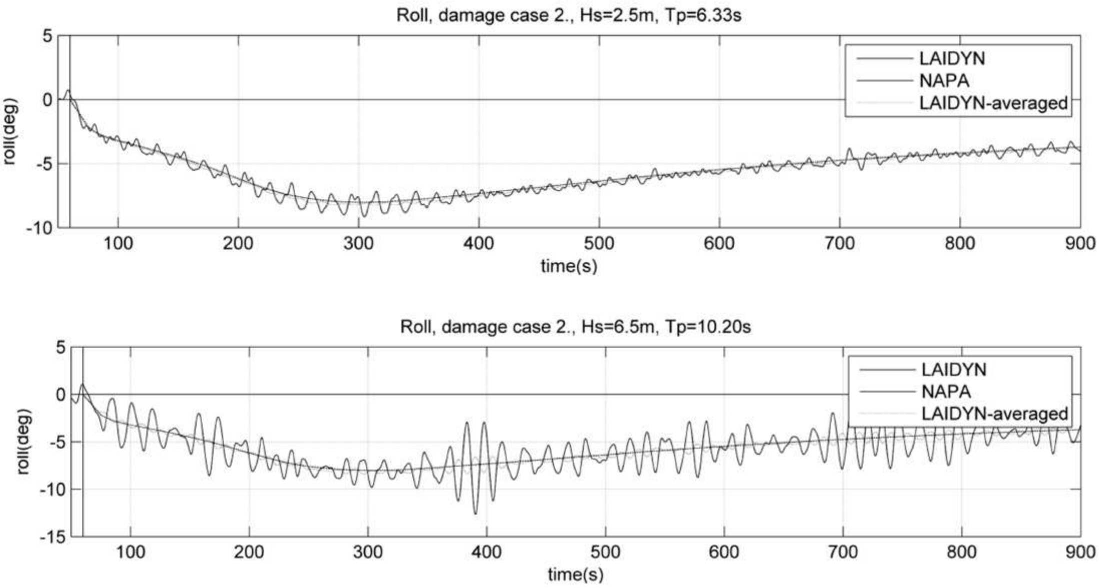

Figure 26: Effects of moderate and heavy sea state, *Manderbacka (2011)*

7 CONCLUSIONS

Progressive flooding inside a damaged passenger ship is an extremely complex process and thus reliable flooding prediction onboard the damaged ship is a very challenging task. In principle this can be divided into two separate problems:

- estimation of the damage extent (size and location)
- prediction of the progressive flooding in time-domain (i.e. the flooding extent)

Simplified and fast methods for both problems have been developed in Task 3.1. The main emphasis was on the development and testing of a fast but still reasonably accurate tool for prediction of progressive flooding in time-domain.

Flooding detection with level sensors can be used to calculate the flooding rates to the flooded compartments. Based on this measurement data the breach size and location can be estimated. This can be done with an inverse method that finds the breach that results in progressive flooding that has the best match with the measurements for a short period. This is a rather laborious task, and thus a more simplified, and also more approximate, approach has been adopted. It is also noteworthy that for large damages the exact breach size and location is not so significant since the damaged rooms are flooded so rapidly. In this case the damaged rooms can be considered as “open to sea” and treated with the lost buoyancy method in the calculations.

The developed method for prediction of progressive flooding has been tested against both measurements from full-scale flooding tests and detailed simulation results for more extensive progressive flooding cases in a large passenger ship. In all three presented test cases the progressive flooding prediction provided very good results, when compared to detailed flooding simulation[6] with a short time step. The main characteristics of the flooding process, such as the maximum heeling angle and the phases of flooding progression were predicted accurately. The time-to-flood was not estimated as accurately, but in general the results were slightly conservative.

In the prediction of progressive flooding, the application of rather long time steps (e.g. 30 s) results in small local error for prediction of the collapsing moment for closed doors. Consequently, the flooding rate is underestimated for a short period. However, the effects are small and local. In general the magnitude of the error in the total mass of floodwater is about the same as with 25% error in the applied critical pressure head for the collapsing of the A-class fire doors, *Karlberg et al. (2011)*. Since it is practically impossible to model the leaking and collapsing of closed non-watertight doors very accurately, it can be concluded that the application of the developed method for progressive flooding prediction does not significantly increase the uncertainty of results.

It is also noted that the progressive flooding prediction may not always find static equilibrium for the final flooding condition[7] since with a long time step there can be oscillating flows between the compartments. In theory, this situation could be tracked by averaging over a short period. However, in practice this is not needed since the calculation is so fast. And on the other hand the tracking would often be unnecessary and might also end up in a premature equilibrium condition.

Based on the presented test cases, it can be concluded that the developed flooding prediction method is able to capture all relevant phases of the flooding process and to give a reasonable estimation on the time-to-flood.

In this report, the new prediction method has been compared to a detailed flooding simulation with a short time step. In these first tests no graphical user interface (GUI) has been used. Thus the calculation times are directly comparable. The demonstration platform for the developed tools will be reported separately in Task 7.2 of the FLOODSTAND project. In general the GUI and preparation of calculation results for visualization will naturally take some time. These issues are discussed in detail in the Deliverable D7.2b.

[6] The applied simulation tool has been successfully validated against the full-scale experimental data
[7] Even when such a static equilibrium flooded condition exists

It is recognized that flooding prediction onboard the damaged ship contains several uncertainties, related to the available flood level sensor data, applied opening parameters and simplifications, as well as to the assumptions in the actual prediction method. These factors should be taken into account when the prediction results are reviewed and used to support the decisions onboard. In any case, the flooding prediction that is based on the actual measurement of floodwater levels and door statuses in the damaged ship is considered to be more useful and reliable than any pre-calculated results. The prediction can always be improved by defining more information on the actual damage case. This could include for example details of the damage opening above the sea level since it may become submerged at later stage and increase the flooding extent. However, it is noteworthy that this would make the user interface more complex.

In principle the numerical error due to the simplified calculation of progressive flooding is considered to be much smaller than the uncertainties that are related to the accuracy of modeling the ship and the environmental conditions. Thus the developed calculation method is believed to be an efficient and practical tool for assessing progressive flooding to provide information for decision support.

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APPENDIX A: ICCGS 2010 Paper

Penttilä, P., Ruponen, P. (2010) Use of Level Sensors in Breach Estimation for a Damaged Ship, Proceedings of the 5th International Conference on Collision and Grounding of Ships, ICCGS, June 14th - 16th 2010, Espoo, Finland, pp. 80-87.

Use of Level Sensors in Breach Estimation for a Damaged Ship

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Abstract:
The flow of flood water from a breach in the hull into a ship is studied. The problem of estimating the size and location of the breach is discussed from the point of view of reliable flooding simulations and predictions in a real situation onboard a damaged ship. An inverse method is introduced for detecting a breach. The method is tested with a large passenger ship design by calculating a large set of randomly generated single breach damages with various combinations of sensor density, noise and filter length. The results and applicability of breach detection and flooding simulation as a part of decision support system are discussed.

Introduction

The concern for ship safety has risen as the number of passengers has increased onboard commercial vessels. The safety of passengers on a large cruise ship is a top priority. Ships have therefore become widely populated with various safety systems, namely for fire, stability, evacuation and of course flooding control. This study will focus on flooding and more specifically on breach detection. Progressive flooding in passenger vessels has been studied for several years and some very good methods have been developed during that time. However, these tools are yet to be fully utilized, especially in decision support on commercial vessels. So far *Ölcer and Majuner (2006)* have presented a method that is based on pre-calculated simulations and recently another flooding simulation tool, based on the actual initial conditions has been implemented in the Onboard-NAPA software (*The Naval Architect, 2008*).

The IMO regulations, *IMO MSC 77/4/1 (2003)*, require that all watertight spaces below the bulkhead deck should have a system to evaluate and/or quantify water ingress. Nowadays most new large passenger ships have been equipped with flooding sensors in cabin areas, machinery spaces and void spaces. A recent IMO report of a correspondence group, *IMO SLF-51/11 (2008)*, recognizes that all information used in the operational decisions should be as accurate as possible and be based upon the actual damage, flooding extent and the rate of flooding. Regarding day to day operation and decisionmaking in actual conditions, this means calculating the expected or simulated results of the flooding. In order to calculate a prediction, the initial condition, namely the location and size or area of the breach, has to be determined.

In this study the word “breach” is used to describe an opening that connects a damaged room to sea. There may be several breaches with several damaged rooms in different compartments forming one large breach but in this text the word breach is used only to mean a single opening involving one damaged room. It is assumed that if the area and location of all breaches can be calculated automatically (without human intervention) from flooding sensor output, it is then possible to calculate how the flood water will progress, thus enabling a powerful decision support system that is able to produce accurate predictions. The target of this study is to find out whether a breach can be calculated purely from the flooding sensor measurements.

The required sensor accuracy for measuring a breach was discussed in *Penttilä (2008)* and the accuracy of typical sensors was considered to be sufficient for the purpose of breach estimation. A general approach for solving the breach properties from level sensor signals was also introduced in *Penttilä (2008)*. The approach involves an inverse method for breach calculation, which is an attempt to determine the breach by matching progressive flooding simulation parameters to the measured results. The principles of this method are presented briefly. This study continues to examine the applicability of the inverse method in breach detection using a statistical set of different damages. A typical flood sensor arrangement on a large passenger ship is used and a case study of 433 random damages is used to get an approximation of the applicability of the inverse method.

Flooding Prediction Method

This study uses a time-domain flooding simulation method, described in *Ruponen (2007),* which is based on the conservation of mass and Bernoulli’s equation with semi-empirical discharge coefficients for each opening. The implicit scheme ensures numerical stability even with long time steps. The simulation method has been extensively validated against experimental results. A principal assumption is that the water levels inside the vessel are flat and horizontal. This is considered to be very reasonable for passenger ships with dense non-watertight subdivision. The simulation method can also deal with air compression, but in this study it is assumed that all flooded rooms are fully ventilated.

Based on Bernoulli’s theorem for an incompressible flow, the rate of flooding through an opening with an area A and discharge coefficient C_d is:

$$\frac{dV}{dt} = A \cdot C_d \cdot \operatorname{sign}\left(H_{w,out} - H_{w,in}\right) \cdot \sqrt{2g\left|H_{w,out} - H_{w,in}\right|} \qquad (1)$$

where g is the acceleration due to gravity and H_w is the water level height. This equation forms the basis for both flooding simulation and breach detection.

Due to the inviscid nature of equation (1), Ruponen’s applied method of solving progressive flooding is relatively fast and enables calculation of multiple simulations within a reasonable time with current computing power. Another advantage of this simulation method is that when the real *measured* breach is used, the results are then based on the real initial condition. This effectively eliminates the interpolation problems related to applications based on pre-calculated cases, such as *Ölcer and Majunder (2006)*. When calculation is directly based on the actual initial condition, it is not necessary to make additional assumptions regarding the routes for floodwater progression, which are required when results are interpolated within a limited set of pre-calculated results.

In Ruponen's applied method, also the leaking and collapsing of non-watertight structures, such as closed fireproof doors, are taken into account. But at the time of writing, the critical pressure heads are still based on rough estimations, presented in *IMO SLF47.INF6 (2004)*. In addition a constant discharge coefficient 0.6 is used for all openings. Within the ongoing project FLOODSTAND (see acknowledgements), comprehensive experimental and numerical studies will be carried out in order to increase the reliability of the applied parameters in the flooding simulation method. This is important also for the inverse method, because when the reliability of the simulation method is increased, consequentially as a side effect, the reliability of the inverse method is also increased.

Inverse Method for Breach Analysis

Principles

Determining the source of the flooding constitutes as an inversion problem and in this section the inverse method for breach analysis is briefly introduced. A more comprehensive description on the principles of the method is given in Penttilä (2008).The method is based on the assumption that if the hull of a ship is breached below the waterline, water starts to flood in and the flood water flows in a deterministic and usually non-reversible way. Therefore all measurable water levels inside the ship have an explicit dependency on time. The ship's floating position is also a function of time. Whatever happens is assumed to be the consequence of the breach and the breach only. This means that each breach or a set of breaches forms a unique and recognizable pattern. However the pattern is unique only in respect to the measurement accuracy. The problem is to find the right set of breaches that result in matching flooding simulation results with the observations within the measurement accuracy. In general an inverse problem is to determine the parameters that produce the known outcome. In this case the outcome is the group of measured flood water levels and the parameters are the breach set properties, like the number of damaged rooms (or the number of flood water sources), the corresponding areas of all flood water entry points and also the ship's initial loading condition. The initial loading condition is usually known due to regulations and onboard loading computers. However because of the complexity of the inverse problem, the number of flood water sources is limited in this study to a single breach.Inversion problems typically have more than one solution. The number of solutions can be reduced, by limiting the degrees-of-freedom for the breach location and changing the level of abstraction in the ship model (less detailed). The X-coordinate is ignored in this study and the Y- and Z-coordinates can be connected with the valid assumption that the breach is always located at the hull surface (Figure 1). According to *Penttilä (2008)* the Z-coordinate has the greatest significance, but only near the waterline. In this study the approximation described in *Penttilä (2008)* is used in both direct and inverse calculations and the exact location of the breach in the joint hull area (JHA) of a damaged room is not studied. At the level of abstraction of this study, the most critical task is to determine from flooding sensors which rooms are damaged. The exact location and area are secondary. The success of determining the correct damaged room depends highly on the sensor arrangement; how many, and where, the flood water sensors are installed inside the vessel. The degrees-of-freedom can be great if there is no possibility to measure the flood water in the rooms, which are primarily flooded. Such cases are more likely to fail.

If the number of different possibilities for flood water entry points can be limited, so that each combination can be calculated within a reasonable time, the breach can be solved literately by comparing the results of each possible breach to the actual measurement so that the "best-fit" results determine the breach.

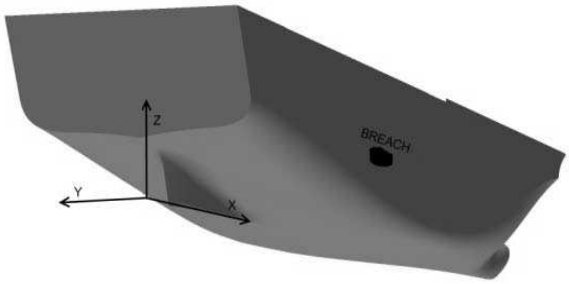


Fig. 1 Applied co-ordinate system and location of the breach

Description of the Method

In this study a number of different cases are calculated. Each case is calculated with various amounts of added random noise. The amount of noise is considered to be known. It is expected that in further studies this can be derived from the applied sensor type. In order to calculate the breach origin from level measurement a specific algorithm has been developed. This is illustrated in Figure 2. Each case contains a specific known amount of added noise and the expected correlation can be calculated from this. From the detected water levels in rooms and the known connections between watertight structures, all possible entry points for flood water are derived.

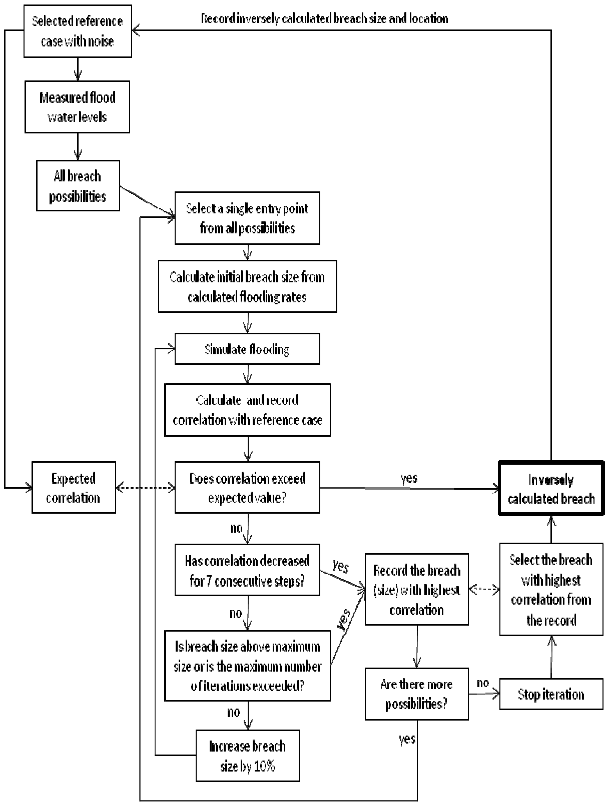


Fig. 2 Process description of the inverse iteration algorithm

The flood water can penetrate through non watertight structures and the number of different entry points can be very great. Each entry point is calculated with different breach areas from the initial area upwards in 10% increments until maximum size 2 m^2 is reached. The initial area was estimated from the flooding rates calculated from the reference data. Because the iteration works upwards from a small breach towards a larger breach size, the calculated initial size was divided by 3, to make sure the initial guess is smaller the actual size.

The iteration proceeds until the calculated correlation exceeds the expected value or until maximum number of iterations is exceeded. The expected correlation is estimated from the amount of added noise by:

$$c_{expected} = \frac{1}{\left(1 + \dfrac{noise}{2.5}\right)} - 0.01 \qquad (2)$$

The purpose of the expected correlation is simply to reduce the required calculation time in the iteration. The constants in equation (2) are empirical coefficients and further research is still needed.

The iteration also stops if the calculated correlation decreases for 7 consecutive steps. The correlation is calculated by comparing the relative mean difference in water levels in compartments and the relative mean differences in trim and list between the simulated results and the reference case.

After iteration of a specific breach has stopped, the next possible case is selected and the process continues until all possibilities have been calculated or until the expected correlation value is exceeded. The size and location of the breach with the highest correlation is recorded for further analysis.

Case Study

Large Passenger Ship Design

A modern Panamax size cruise ship design of 90 000 GT was used as a test case. The main dimensions of the ship are listed in Table 1.

Table 1. Case study ship data

Gross tonnage	90 000
Length over all	290 m
Breadth	32 m
Draft	7.7 m
Initial GM	2.0 m

The ship is divided into 19 watertight compartments extending to the bulkhead deck. The NAPA-model has a total of 312 openings, which connect 170 rooms. A room is always by definition watertight and water can only spread to other rooms through openings. An example of the 3D model rooms and openings is presented in Figure 3.

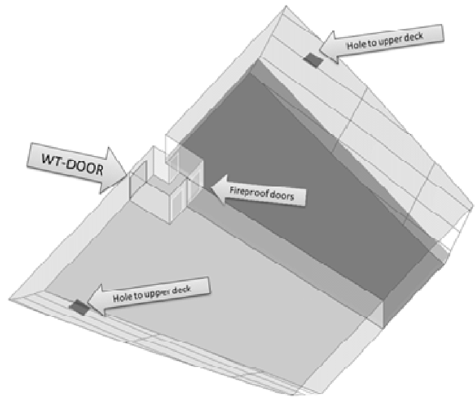


Fig. 3 Example of the 3D model and level of detail during flooding

Damage Cases

A set of 433 damage cases were generated by Monte Carlo simulation on the basis of damage statistics for collisions. However, cases with high penetration/length ratio were ignored since in those damage cases the colliding ship is likely to have a notable effect on the flooding through the breach. Each damage case was limited to a single breached room and the area of the breach was limited between 0.01 – 2.0 m^2. The limitation is necessary due to current measurement capabilities. If the breach was very large, the damaged compartments would fill with such speed that neither the selected time step for simulation nor a real flooding sensor would be able to measure the flooding rate. The applicability of the inverse method for very large breaches is not included in this study. However, in general it is considered that the damage location is easier to detect if the damage extent is large.

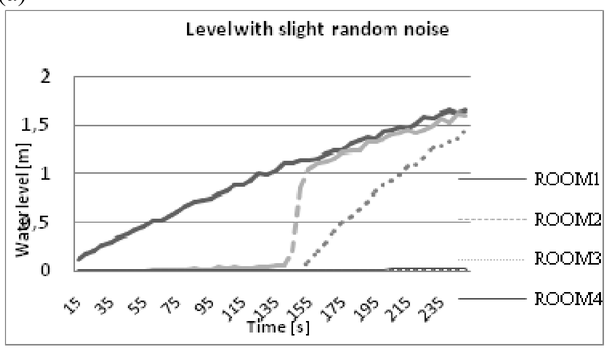
Each damage case was calculated using the NAPA software, which implements Ruponen's method (see Ruponen, 2007 and The Naval Architect, 2008), assuming a calm sea state. Total of 225 cases were calculated with all doors closed and 208 cases were calculated with all fireproof doors (total of 167) open. Most cases resulted in progressive flooding through various openings in the ship. On average 2.3 rooms were flooded during the simulation time (120 s) when all fireproof doors were closed and an average 2.7 rooms were flooded when the fireproof doors were open. All watertight openings were always defined as closed.

After each case was simulated the results were stripped in order to make the comparison for an authentic case. All data which would not be available in a real situation was removed. The available data after the stripping consists of the floating position and flood water levels in the rooms with sensors as functions of time. The entire process of testing the inverse method is illustrated in Figure 5.

Added noise in reference results

A true measurement always contains some measurement errors or noise. Possible sources for error in level measurement are discussed in *Penttilä* (*2008*). In this study two different amounts of random noise were added to the reference data. The Figures 4a and 4b illustrate the added noise to the measurement of 4 flooded rooms.

(a)



(b)

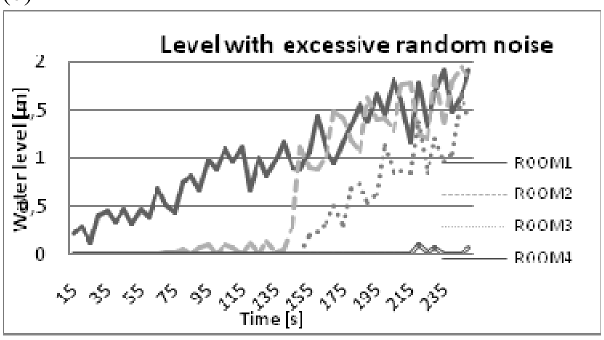


Fig. 4 (a) Level with slight added noise

The purpose of the generated random noise was to simulate disturbances in the flood water level measurements. The added noise makes it more difficult to calculate the initial flooding rate and the origin of the breach and makes the case more realistic. However, It should be noted that the added noise does not correspond to disturbances due to sloshing and is only an approximation of random measurement distubances. Typical flooding sensors described in *Penttilä* (*2008*) may also react to changes in air pressure due to flooding, but this effect is not studied in this text. All flooded spaces are assumed to be freely ventilated. The added noise is expected to decrease the likehood of determining the correct breach succesfully.

Inverse calculation

In this study the generated damage cases with various combinations of noise and time spans were fed in to an algorithm applying the inverse method to determine the location and area of the breach. The algorithm tries to determine the correct breach by iterating through different simulations and comparing the results to the available data. The available simulation data was limited to selected time spans. These time spans are referred to as "filter lengths" from the measurement analogy. The breach is being filtered from the level data. The purpose of adding noise and changing the time span of the available data was to study the effect of noise and filter length on the inverse method (discussed in *Penttilä 2008*). Same opening statuses were used in both direct and inverse calculation. The process of applying the inverse method to generated reference results is illustrated in Figure 5.

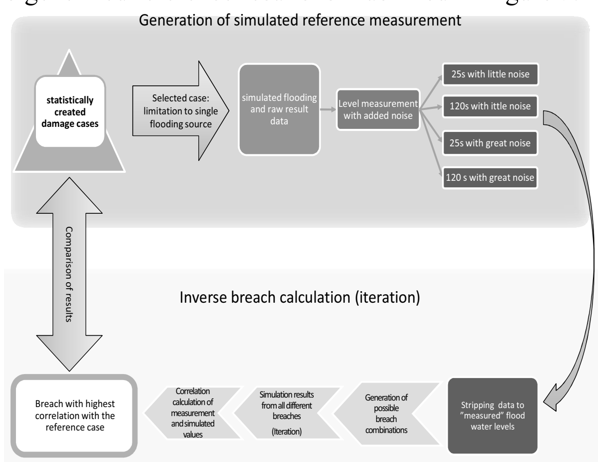


Fig. 5 Process diagram illustrating the method of testing the inverse method

The specific algorithm used in this study is optimized for a wide range of solutions and is expected to solve most cases which have a single breach solution. If the algorithm fails to produce the correct answer the reason may either be in the algorithm design or in the theoretical limitations of the method. These cases are not distinguished in this study. Research for improving the efficiency of the algorithm continues.

Inverse breach calculation is always done for a selected time span or filter length. In this study we assume that in a real damage scenario, the breach should be calculated as early as possible within the first minutes (if possible). Theoretically the inverse method is expected to determine the correct breach always if the available data is infinitely long and noiseless. However in real cases there is always some noise and the time available for measurement and calculation is limited.

The problem is similar to signal processing where a long filter is slow less susceptible to noise, whereas a short filter is fast but more sensitive to noise. The problem of breach measurement is similar to filtering also in the sense that the time span of the reference data has to be selected prior to the inverse calculation. Therefore the selected period is called in this text the *filter length*. In this study filter lengths of 25 s and 120 s are studied. These lengths fit the expected breach area (between 0.01 – 2.0 m^2). A more detailed description of the filter length selection criteria is described in *Penttilä* (*2008*). Time step used in the simulations and inverse calculation was 5 s.

Table 2. Summary of generated damage cases

	All doors closed	*Fireproof doors open*
Total number of generated damage cases	235	228
Flooding not detected by flooding sensors	11	22
Breach too small (no noticeable flooding)	70	61
Total number of remaining suitable damage cases	154	145
Average breach size	0.21 m^2	0.21 m^2
Average distance from waterline	0.98 m	1.17 m
Average number of flooded rooms (within 120 s)	2.29	2.66

Sensor arrangement

The ship is equipped with 57 flooding sensors in total of 245 rooms/tanks. 170 rooms are subject to progressive flooding and remaining 75 are closed and not connected to any other rooms by openings. There are 45 flooding sensors in the 170 rooms, of which 33 are located in rooms that are larger than 300 m^3. The "density" of the sensor arrangement in potential areas of progressive flooding is calculated by

$$\rho_{sensors} = \frac{n_{sensors}}{n_{connected\_rooms}} \quad (3)$$

In this case the density of the sensor arrangement is approximately 0.26.

The calculations were performed for two sensor arrangements. All cases were calculated first with the assumption that all rooms are equipped with a sensor (sensor density 1.0) and then with the sensor density 0.26. When each room is equipped with a sensor the success rate of calculating the correct breach is expected to be 100% and less for the case where only selected rooms are equipped with a flooding sensor.

In the case of a sparse sensor density (0.26), noise levels of 2% and 10% were considered realistic and were used in the calculation. But in the case of the high sensor density (1.0) noise levels were 5% and 35%. The higher noise levels were used because solving a breach with a very tight sensor arrangement is considered to be almost a trivial task. Therefore excessive noise was added in order to really test the method.

Results

A summary of the damage cases is presented in Table 2. Some of the generated damages resulted in too small a breach compared to the distance from the waterline. These damages did not result in noticeable flood water amounts and a total of 131 cases were left out from the inverse calculations because of this. It should be noted that with longer filter lengths also these damages could have been included. Also some damages did not result into flooding which could be detected by the flooding sensors. There were a total of 33 of these cases. It is not known whether flood water would have spread to rooms with flooding sensors if the time span had been longer. The final number of suitable cases for the inverse calculation was 299. Table 2 lists the cases in more detail.

The success rate of the inverse method was measured by checking whether the method was able to determine the correct damaged room (breach location) from detected flood water and whether the calculated breach area corresponds to the reference case within a ±30% margin. The general arrangement and the sensor arrangement of the ship model were such that in 64.6% of the cases the flood water was detected by a flooding sensor in the primarily flooded room.

Table 3 shows the results of the study for all 299 inversely calculated cases with the assumption that all rooms are equipped with a flooding sensor and Table 4 shows the results with a typical sensor arrangement of sensor density 0.26.

Table 3 Success rate of calculating the correct breach with sensor density 1

	All doors closed		*Fireproof doors open*	
	Location	Area	Location	Area
Filter 120s				
Noise 5%	99.6 %	60.7%	99.0 %	61.1%
Noise 35%	97.3 %	21.9%	98.1 %	25.0%
Filter 25s				
Noise 5%	100.0 %	68.0%	98.6 %	64.4%
Noise 35%	97.8 %	37.7%	98.1 %	41.1%

Table 4 Success rate of calculating the correct breach with a sensor density 0.26

	All doors closed		*Fireproof doors open*	
	Location	Area	Location	Area
Filter 120s				
Noise 2%	69.5%	64.5%	76.6%	65.8%
Noise 10%	67.5%	56.7%	74.5%	41.7%
Filter 25s				
Noise 2%	67.5%	31.7%	74.5%	41.7%
Noise 10%	68.2%	20.1%	70.3%	28.4%

Table 3 shows that the method used in this study is very likely to find the correct location for the breach even with high amounts of noise in the measurement data as long as each room is equipped with a sensor. The average success rate in finding the primarily flooded room was 98.6%. This is slightly less than the expected success rate of 100%. The success rate of calculating the correct breach area within the margin was more dependent on the filter length and noise than the success rate on locating the breach correctly.

Table 4 shows that the same method, when used for a sparse sensor arrangement, is less likely to find the correct breach. The average success rate in determining the primarily damaged room was 71.1%. Again the effect of noise and filter length is more noticeable for the calculation of the breach area than the location. It should be noted that the two result sets were calculated with different amounts of noise and are not directly comparable. Naturally the opening status of the fireproof doors has a greater impact on the results when the sensor arrangement is sparse. When all fireproof doors are open, the method was 8.5% more likely to determine the breach correctly.

The inverse method is based on comparing correlations of the results of different breaches to the reference results. The correlation r between the simulated and the measured levels was calculated by:

$$r = 1 - \sigma_{rel} \tag{4}$$

where σ_{rel} is mean relative deviation between measured and simulated level. Also trim and list were included in the correlation calculation.

An example of a successful case is presented in Figure 6, showing a good correlation between the results with the predicted damage size and location and the generated measurement data with very significant amount of noise.

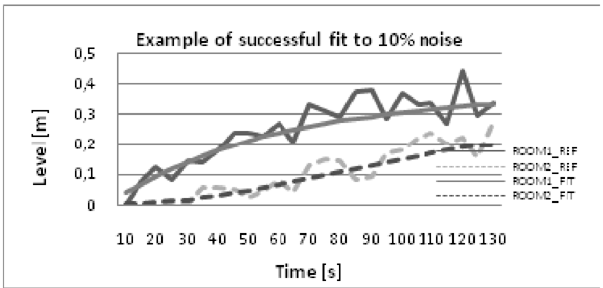


Fig. 6 Example of successful fitting of breach to level data

Also one failed case was analyzed in detail. In this case there was a breach in ROOM1 but there was an open pathway for the flood water to progress directly onto the lower deck. This case failed because there is no way to distinguish a breach in ROOM1 from a breach in ROOM2. The situation is illustrated in Figure 7.

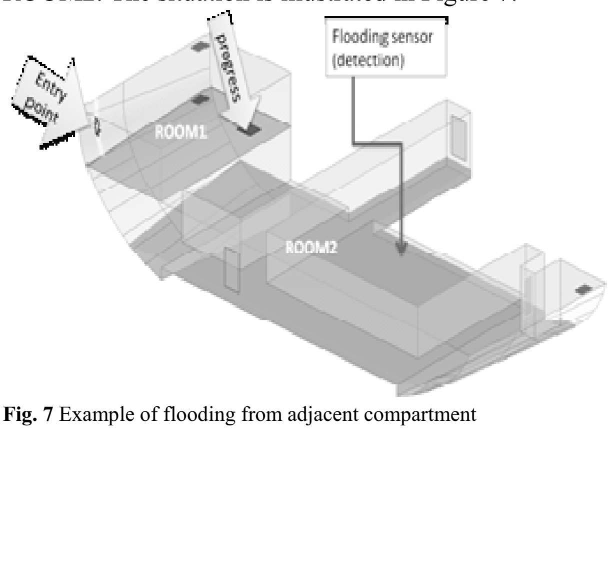


Fig. 7 Example of flooding from adjacent compartment

Flood water flows almost instantaneously through the open staircase to the lower deck and flooding remains symmetrical. There is no listing and the difference between the results of a breach in ROOM1 and ROOM2 is negligible as long as the flooding rates match. It should be noted however, that in this case, the errors in predictions due to a wrong breach location are minimal because the wrong breach produces very similar results to the correct breach. This is referred to as the "problem of similarities". Figure 8 illustrates how the fit seems to imply that the breach is correct.

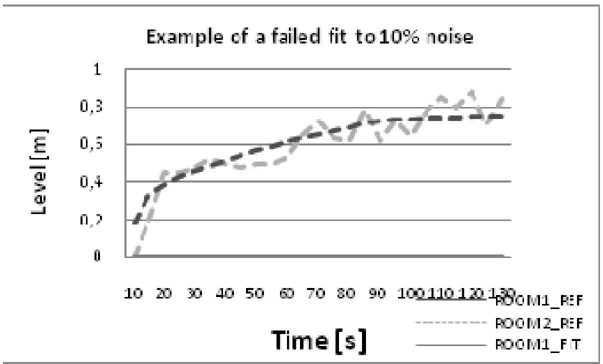


Fig. 8 Example of failed fitting of breach to level data (note the zero-level in ROOM1 in both the reference and fitted case)

Discussion

The results of the 299 inversely calculated damage cases with two different sensor arrangements strongly suggest that the inverse approach is applicable in breach detection but that the reliability of the method depends greatly on the sensor arrangement. The average likelihood of determining the breach correctly by using the inverse method was 71.1%. This is a good result compared to the sensor density of the vessel (0.26). But on the other hand the results in this study can be slightly too optimistic as such, because the number of breaches was limited to a single breach. The sensor arrangement of the vessel was considered typical.

The flooding sensor density of the ship was 0.26, which might suggest that flood water would be undetected in approx. 74% of the cases. However due to the progressive nature of flooding the flood water in most cases progressed to rooms which were equipped with flooding sensors. In 71.1% of these cases the flooding resulted in sufficiently recognizable patterns for the inverse method to work. The method resulted in almost 100% success rate when all rooms were simulated to have a flooding sensor. This does not necessarily mean that all rooms need to be equipped with flooding sensors for the inverse method to work, but it is unclear which sensors are critical. Another result is that when all fireproof doors were set open, the method more likely to find the correct breach. Fireproof doors are generally advised to be kept open during flooding in order to minimize asymmetrical flooding, but when the sensor arrangement is sparse this has also a positive effect on breach detection.

The effect of noise and filter length to the success rate is as expected. The method is more likely to find a correct solution if there is very little noise or the filter length is long. The change from little noise to excessive noise seems to decrease the success rate of finding the correct location on average by 2 percentage units. The effect of the filter length is less clear. The results would seem to indicate that 25 s filter length is in some cases not enough, but that 120 s filter length does not significantly increase the likelihood of finding the correct breach. Optimal filter length depends on the flooding rate and measurement accuracy.

The average success rate of determining the area of the breach within a reasonable margin was fairly low. On average the calculated breach size was within ±30% margin in 47% of the cases with sensor density of 1.0, and within margin in 44% of the cases with the sensor density of 0.26. Such low success rate on calculating the correct breach area indicates that the algorithm used in this study could be further developed.

Even though a more advanced algorithm is expected to increase the success rate of the inverse method, the maximum theoretical success rate is not known. It is believed by the authors that with 10% noise and 120 s filter length the theoretical maximum might be as high as 90% even with such a sparse sensor density. The example of the failed case shows that not all cases can be solved correctly even with a very dense sensor arrangement. This is because all sensors always have a specific zero-limit, which has to be exceeded before flood water is detected. If flood water does not rise up to the sensor and flows directly to another room, any method will surely fail. However if the difference in vertical location is not very great compared to the breach immersion, the actual location of a breach is not a real problem. This is because the prediction results would still remain the same. From this point of view, the results could be analyzed from the point of view of similar results and not by correct breach. The problem of similarities is however not studied in this text but it should be noted that this subject should be included in the study of optimal sensor arrangements.

The case of multiple breaches was not included in this study. Real damage situations are likely to involve multiple breaches flooding at the same time or at different times. Therefore the limitation to a single breach is a rough approximation. The problem of multiple breaches was excluded from this initial study due to the complexity. When a more advanced algorithm, able to solve multiple breaches, is developed, the same study can be repeated without the single breach limitation. It is believed by the authors that the resulting success rates would be similar or slightly less.

In this study the sensor accuracy was simulated by adding random noise to the measurement. However, real flood water sensor have another limitation, which is the minimum liquid level, that can be measured. Typical level sensors measure air pressure at 3 cm from the floor and because the air pressure in the room may change slightly there must be some zero-limit for the sensor to avoid false flooding detection. In this study the zero-limit for the sensors was 0 cm, which means that it is assumed that the sensors can measure flood water level with infinite accuracy down to 0 m. In real case the zero-limit is of order 10 cm and raising the zero-limit from 0 to 10 cm may have a decreasing effect on the success rates. However this effect was not studied in this text.

In addition to designing a suitable algorithm to solve cases with multiple breaches, another difficulty is trying to calculate the breach properties from flooding sensor output when all breaches are not yet immersed. Flooding sensors can never detect a breach, which has not yet started flooding and if there are multiple breaches, some may start to flood later on after sufficient changes in floating position. No method based on flooding sensors can solve such cases successfully with a short filter length.

Conclusions

The target of this study was to find out whether it is possible to determine the location and size of a breach purely from flooding sensor output without human intervention. A total number of 2392 cases (299 cases with two different sensor arrangements and combinations of 2 different filter lengths and 2 different amounts of random noise) were calculated inversely and the results strongly indicate that the inverse method is applicable in determining the breach from the water level data only if the sensor arrangement is dense enough. When calculated with a typical sensor arrangement, the method was able to successfully determine the correct floodwater origin in 71.1% of the cases. However the method was only able to derive the correct breach size within a reasonable margin in 44% of the cases.

It is believed by the authors that the inverse method can be developed further so that it can (if the sensor arrangement is dense enough) successfully solve a very high percentage of damage cases inversely and determine the breach size more accurately. However any method with sufficient noise will fail if the sensor arrangement is too sparse, therefore it should be noted that if a valid method can be produced, it has a theoretical maximum depending on how the flooding sensors are placed. A good method could therefore be used to study the optimal sensor placement. Well-placed sensors in a ship enable much higher precision decision support systems than what is possible today with current sensor arrangements.

An inverse method for determining the breach location and size from flooding sensor output was extensively tested. Unfortunately the results of this study are still somewhat inconclusive due to the limitation of a single flood water origin (single breach). However, so far the inverse approach in breach detection has proven to have great potential and it is believed that the general case would have similar results. Further development and testing of the presented method for the breach detection will be carried out within the FP7 Research Project FLOODSTAND.

Finally, it should be noted that even with a sophisticated breach detection analysis and carefully validated flooding simulation tools, the final outcome of any real flooding may always be different from the prediction. This is mainly because currently, the various applied parameters for openings, like collapsing pressure of a fireproof door, are not known very accurately. Furthermore, it is possible that the water will find unpredicted progression routes, such as pipes and ducts that may not be included in the simulation model. The result of any computer based decision support tool is always a prediction based on best approximations, intended to help in the decision making. The actual decision (e.g. to evacuate or to proceed to the nearest port) should always be made based on the real situation, including available support tools, visual observations and expertise of the crew and emergency response service.

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