Flooding Prediction Onboard a Damaged Ship

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ABSTRACT

Progressive flooding inside a damaged ship can seriously endanger the safety. Level sensors can be used to detect the flooding, and based on this data the breach can be estimated. For decision support the prediction of flooding extent and the intermediate phases is necessary. For this purpose a new simplified, but still reasonable accurate, flooding prediction method has been developed. Details of this algorithm and some test cases, including comparisons to experimental data and time-accurate flooding simulation results, are presented. The application of the developed prediction method as a decision support tool is also discussed.

Keywords: *Progressive flooding, damage stability, decision support, time-to-capsize*

1. INTRODUCTION

When the hull of a ship is breached due to collision or grounding, the floodwater enters the damaged compartments. Open doors and various pipes may result in progressive flooding to undamaged compartments, thus making the situation even more critical. Also before the final floating position the ship may pass through intermediate positions that are more dangerous than the final one. Thus for decision support it is necessary to check the whole process of progressive flooding.

Previously *Ölcer and Majunder (2006)* have presented a system that is based on a database of pre-calculated damage cases. Also *Nilsson and Rutgersson (2006)* have described decision support systems that are based on real-time monitoring and static stability calculations. More recently, *Jasionowski (2011)* has presented a system that estimates the survival probability, and especially, the effect of open watertight doors. However, the method is based on the final condition after flooding. Yet it demonstrates very efficiently the importance of keeping all watertight doors closed while at sea.

A new approach, using the online data from 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. 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 also provides a rough estimation on the time-to-flood. Leaking and collapsing of non-watertight structures (such as closed fire doors) are also taken into account.

The developed new flooding prediction method is tested against both full-scale measurement data and time-accurate simulations with a short time step. In the latter case also leaking and collapsing fire doors are included.

2. BREACH DETECTION

2.1 Use of Level Sensor Data

For reliable flooding prediction the breach size and location need to be known. This is possible only if the ship is equipped with level sensors. The flooding rates can be calculated based on the measurements, compartment geometry and floating position. And further the breach can be estimated based on the flow rates.

IMO has established some basic requirements for flooding detection systems on passenger ships, *IMO (2008)*. A more comprehensive and detailed recommendation has been developed within the FLOODSTAND project, *Penttilä (2012)*.

The idea of using inverse method for prediction of the breach size and location on the basis of level sensor data and short simulations was described in *Penttilä and Ruponen (2010)*. The results were promising but the method was a little too time-consuming, especially when considering that the available input data is rather rough. Therefore, a simplified but faster method was needed.

2.2 Simplified Method

In the simplified approach, flooding predictions are done by modelling each measured flooding as a separate breach to the sea. Thus it is assumed that all floodwater is detected and measured. Consequently, for each flooding detector (or for each compartment with measurement data), there is a corresponding breach definition.

Each individual breach is modelled to extend from deck to deck. This simplified modelling avoids the problems related to the vertical location of the breach. For rooms that are not connected to the hull surface, a simple point opening in the middle of the room (lowest point) is used. These are illustrated in Fig. 1. Thus the following assumptions are done:

- All floodwater is detected and measured
- The vertical location of the breach has no (significant) effect on progressive flooding
- a room, which is not connected to hull may still be flooding (through a breach)

The breach sizes are calculated separately, based on the measured flooding rate, by using Bernoulli's equation. This means that 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. However this method does not take into account the possibility of undetected flooding.

Separate analysis of breach penetration is not needed since breach detection is based on measured flooding rates.

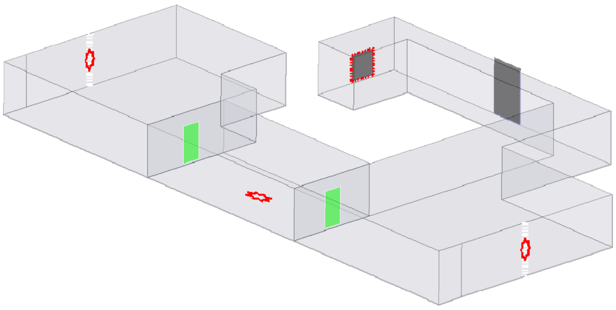

Figure 1: Modelling of small breaches.

3. PREDICTION OF PROGRESSIVE FLOODING

3.1 Governing Equations

During the past decades several calculation methods (see e.g. *ITTC, 2008*) have been developed for prediction of progressive flooding inside a damaged ship. Usually these are based on Bernoulli's equation. The background for the developed method is described in the following.

Conservation of Momentum

Similarly to time-accurate flooding simulation, e.g. *Ruponen (2007)*, the calculation of flow velocities in the openings 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:

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

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 inviscid and irrotational flow. For water flow the density is constant and thus equation (1) reduces to:

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

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, air pressure is assumed to be constant. Consequently, the volumetric flow rate through a small opening is:

$$Q = \mathrm{sign}\left(H_{eff}\right) \cdot C_d \cdot A_{eff} \sqrt{2g\left|H_{eff}\right|} \qquad (3)$$

where C_d is the discharge coefficient (usually assumed to be 0.6), A_{eff} is the effective area of the opening and H_{eff} is the effective pressure head ($h_B - h_A$).

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 approximate, also the integration can be simplified. In principle, this is done simply by calculating the submerged area of the opening. Consequently, the resulting water flows are somewhat too large but this is a conservative approach, and thus well justified.

Conservation of Mass

At each time step the conservation of mass must be satisfied in each flooded room. The equation of continuity is:

$$\int_\Omega \frac{\partial \rho}{\partial t} d\Omega + \int_S \rho \mathbf{v} \cdot d\mathbf{S} = 0 \qquad (4)$$

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

$$\rho \int_S \mathbf{v} \cdot d\mathbf{S} = 0 \qquad (5)$$

In practice this means that for each flooded room:

$$\frac{dV_w}{dt} = \sum_{i=1}^{n} Q_i \qquad (6)$$

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

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[1]. 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

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[1] E.g. for calculation of the s-factor

added weight and only the possible 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, based on the real flooding scenario. 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[2], the effect of waves on the flooding process can be considered as minimal.

3.2 Principles of the Method

Progressive flooding forms chain(s) of flooded compartments. The principle idea is to keep track on these chains or routes. These are illustrated in Fig. 2. The starting point for each chain is the sea or a damaged compartment that is considered to be open-to-sea (lost buoyancy).

The mass balance in the flooded compartments is solved compartment by compartment, but in a reverse order. Thus the calculation is started from the compartment that was flooded last in the chain. This procedure 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 reverse order has been found out to significantly stabilize the solution of the governing equations, thus allowing explicit time integration with a long time step.

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 due to changes in the floating position of the ship.

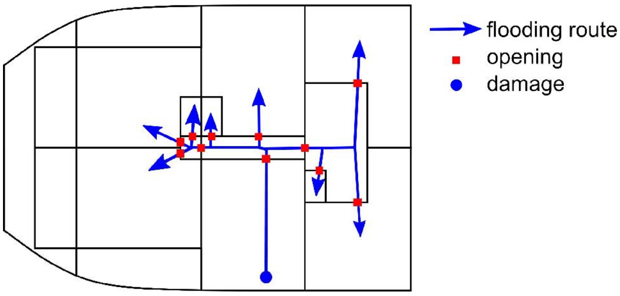

Figure 2: Chains of flooded compartments.

3.3 Calculation of Flooding Progression

Let us first consider the flow through a single opening between two flooded compartments. The situation is illustrated in Fig. 3. For simplicity, it is assumed that $h_1 > h_2$. Based on Bernoulli's equation (3), the volumetric flow rate through the opening is:

$$Q = C_d A \sqrt{2g(h_1 - h_2)} \tag{7}$$

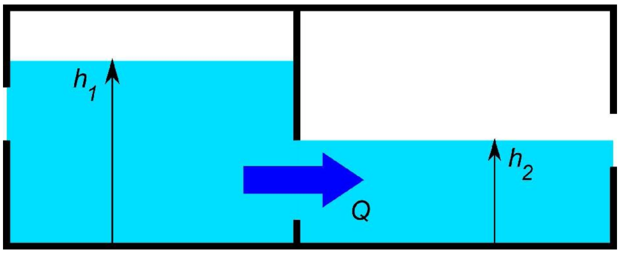

Figure 3: Water flow through an opening.

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):

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[2] No large open spaces like a vehicle deck

$$Q = -\frac{\partial V_1}{\partial t} = -\frac{\partial V_1}{\partial h_1}\frac{\partial h_1}{\partial t} = -S_1 \dot{h}_1 \qquad (8)$$

or:

$$Q = \frac{\partial V_2}{\partial t} = \frac{\partial V_2}{\partial h_2}\frac{\partial h_2}{\partial t} = S_2 \dot{h}_2 \qquad (9)$$

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

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

$$C_F = C_d A \sqrt{2g} \qquad (10)$$

Also the effects of leakage and partially submerged opening can be taken into account by modifying this (dimensional) coefficient.

By combining the equations (8) and (9) and taking into account Bernoulli's equation (7), the time derivative of the pressure head $(h_1 - h_2)$ is:

$$\begin{aligned}\dot{h}_1 - \dot{h}_2 &= -Q\left(\frac{1}{S_1} - \frac{1}{S_2}\right)\\ &= -C_F\sqrt{h_1(t) - h_2(t)}\left(\frac{1}{S_1} - \frac{1}{S_2}\right)\end{aligned} \qquad (11)$$

Thus the following differential equation is obtained:

$$\frac{\dot{h}_1 - \dot{h}_2}{\sqrt{h_1(t) - h_2(t)}} = -C_F\left(\frac{1}{S_1} - \frac{1}{S_2}\right) \qquad (12)$$

Integration of this results in:

$$\begin{aligned}&\sqrt{h_1(t) - h_2(t)} =\\ &-\frac{1}{2}C_F\left(\frac{1}{S_1} - \frac{1}{S_2}\right)t + \sqrt{h_1(0) - h_2(0)}\end{aligned} \qquad (13)$$

It should be noted that based on the notation (10), the equation (7) for the volumetric flow through the opening is:

$$Q = C_F\sqrt{h_1(t) - h_2(t)} \qquad (14)$$

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

$$\begin{aligned}\Delta V &= \int_0^{\Delta t} C_F\sqrt{h_1(t) - h_2(t)}\,dt\\ &= C_F\left[\sqrt{h_1 - h_2}\,\Delta t - \frac{1}{4}C_F\left(\frac{1}{S_1} - \frac{1}{S_2}\right)\Delta t^2\right]\end{aligned} \qquad (15)$$

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:

$$\Delta t = \min\left[\Delta t_0, \frac{2\sqrt{h_1 - h_2}}{C_F\left(\frac{1}{S_1} - \frac{1}{S_2}\right)}\right] \qquad (16)$$

where Δt_0 is the initial time step. This situation is illustrated in Fig. 4.

The limitation is necessary for numerical stability but usually it is needed mainly in the beginning of the flooding process, or sometimes when a closed door collapses, since in these cases the flow rates can be large.

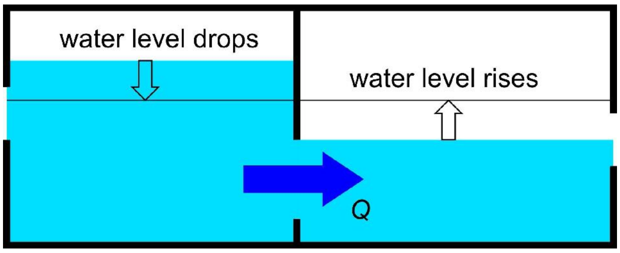


Figure 4: Limitation of time step due to fast flooding.

4. TEST CASES

4.1 Full-Scale Measurements

The first test case is slow progressive flooding through a small opening. The measurement data from the full-scale test with a decommissioned fast attack craft of the Finnish Navy was used. Details of the test case and corresponding time-domain simulations are described in *Ruponen et al. (2010)*.

The damage case is illustrated in Fig. 5. The damage hole is located in an empty side tank and the diameter of the hole is 0.25 m. Water progresses to equipment room and pump room, and finally the heeling is equalized when the side tank on the intact side is also flooded.

The comparison of measured and calculated heel angle is presented in Fig. 6. 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 measured and obtained with the detailed simulation, whereas the time-to-flood is slightly shorter.

The computation times are listed in Table 1. The calculations were done on a typical laptop and without a user interface for decision support. Thus the presented times do not include the update of the result tables and graphical representation of the situation.

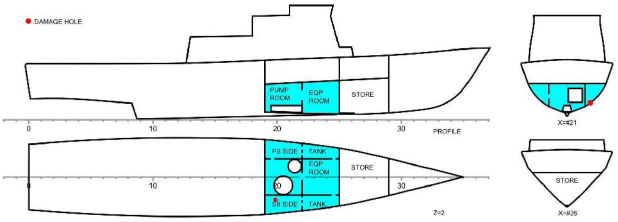


Figure 5: Damage scenario for the full-scale flooding case.

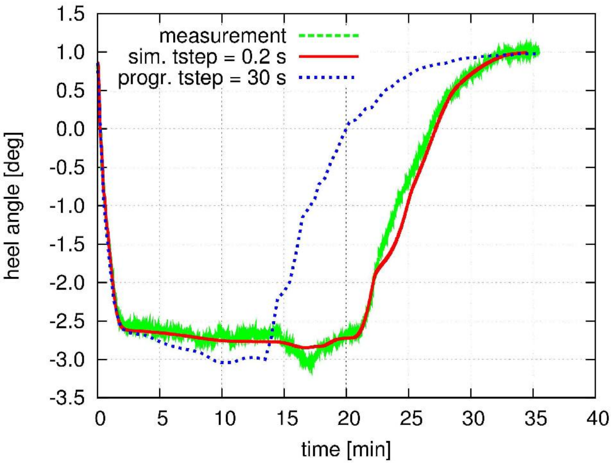


Figure 6: Comparison of heel angle for the full-scale damage case.

Table 1: Comparison of computation times.

Calculation method	Time (s)	%
Experiment (real time)	2100	100.0
Flooding simulation ($\Delta t = 0.2$ s)	245	11.7
Progressive flooding ($\Delta t = 30$ s)	9	0.5

4.2 Extensive Progressive Flooding

The second case study is two-compartment damage in a large passenger ship. The breach is in the lower decks and flooding progresses through staircases and lift trunks to the upper decks. The fire doors are closed and they start to leak, and some of them eventually collapse, under the pressure of the floodwater. The guideline values from the FLOODSTAND project are used for modelling the leaking and collapsing, *SLF 54/INF.8/Rev.1 (2011)*. The flooding scenario is illustrated in Fig. 7.

Results for heel angle and total mass of floodwater with different calculation methods are shown in Fig. 8 and Fig. 9, respectively. The computation times are listed in Table 2. The peak of the heeling angle is predicted rather well, even through the method is fully quasi-stationary. The time-to-flood is a little longer than in time-accurate simulation. However, this mainly concerns the phase of very slow flooding of the cabin areas on the deck 04 through the leaking closed fire doors.

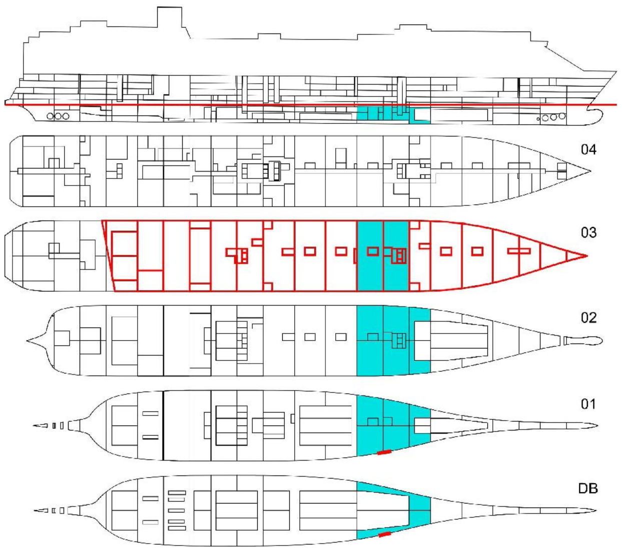


Figure 7: Damage scenario for progressive flooding through leaking and collapsing doors.

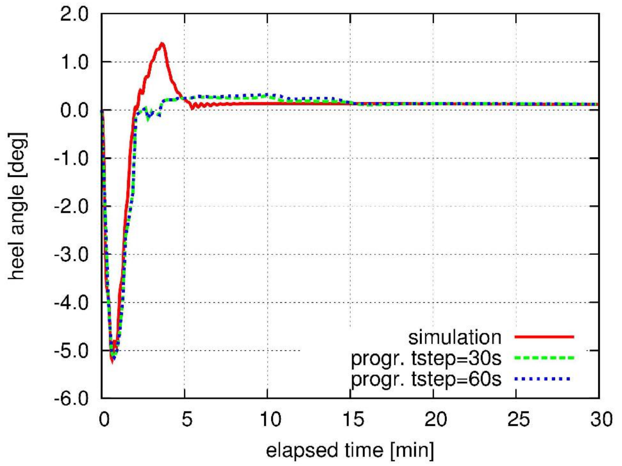


Figure 8: Comparisons of heel angle with different calculation methods.

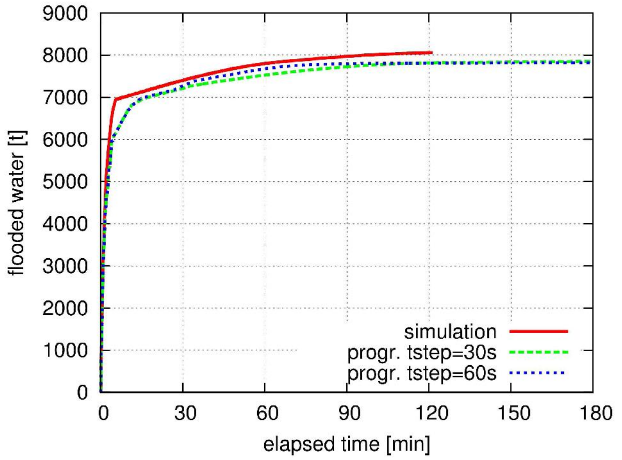


Figure 9: Comparisons of total floodwater mass with different calculation methods.

Table 2: Comparison of computation times.

Calculation method	Time (s)	%
Time-to-flood (from simulation)	7280	100.00
Flooding simulation ($\Delta t = 0.2$ s)	2915	40.04
Progressive flooding ($\Delta t = 30$ s)	16	0.22
Progressive flooding ($\Delta t = 60$ s)	14	0.19

The applied time step in the prediction method has only a small effect on the results, and moreover, the computation times are almost identical. This results from the fact that the longer time step of 60 s is more frequently automatically shortened, as defined in equation (16).

The prediction method does not find the equilibrium condition. The likely reason for this is circulating or oscillating flow between the flooded compartments.

4.3 Effect of Collapsing Doors

The flooding prediction method is intended to be used with a rather long time step in order to get the results as fast as possible. The down turn of this is the notable error in the time when the critical pressure head for the collapsing of a closed door is reached. The situation is illustrated in Fig. 10. This can also be clearly seen as a lower flooding rate during the early phases of the presented test case, Fig. 9.

On the other hand, the delayed collapsing of closed doors often results in larger heeling due to the increased asymmetry of the flooding, especially if there are longitudinal A-class bulkheads in the flooded compartments.

In the presented case study this effect seems to correspond very well with the transient dynamic heeling.

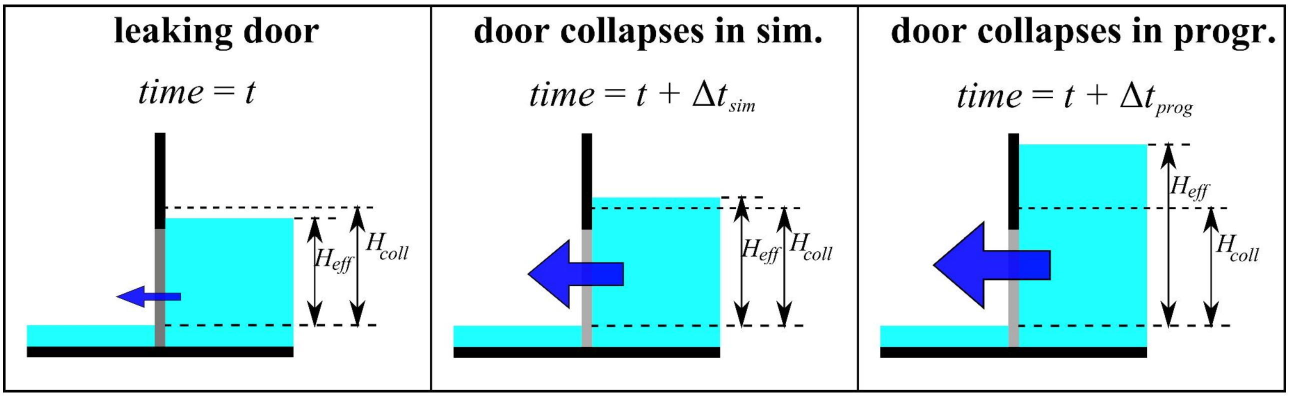
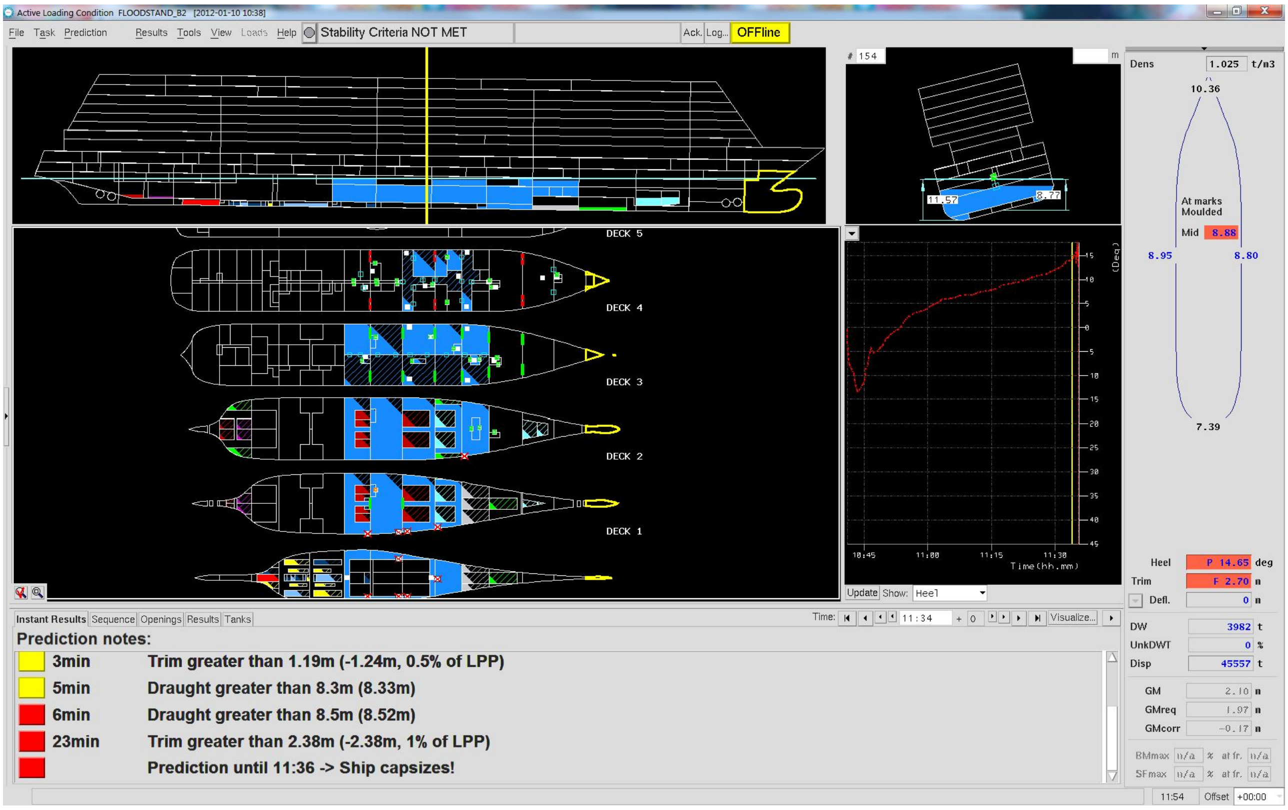


Figure 10: Applied time step Δt affects the time when a closed door collapses, i.e. when the effective pressure head H_{eff} exceeds the collapsing pressure head H_{coll}.



Dens 1.025 t/m3
Mid 8.88
Heel P 14.65 deg
Trim F 2.70 m
Defl. 0 m
DW 3982 t
UnkDWT 0 %
Disp 45557 t
GM 2.10 m
GMreq 1.97 m
GMcorr -0.17 m
BMmax n/a % at fr. n/a
SFmax n/a % at fr. n/a
11:54 Offset +00:00

Prediction notes:

🟨	3min	Trim greater than 1.19m (-1.24m, 0.5% of LPP)
🟨	5min	Draught greater than 8.3m (8.33m)
🟥	6min	Draught greater than 8.5m (8.52m)
🟥	23min	Trim greater than 2.38m (-2.38m, 1% of LPP)
🟥		Prediction until 11:36 -> Ship capsizes!

Figure 11: Graphical user interface for the flooding prediction tool, showing results of a damage scenario that ends in rapid capsize.

5. FLOODING PREDICTION IN DECISION SUPPORT

The developed calculation method for fast prediction of progressive flooding has been implemented into a loading computer for demonstration of the use as a decision support tool. The user interface is shown in Fig. 11.

Onboard a damaged ship, the breach size and location are automatically estimated on the basis of the online level sensor measurement data when flooding is detected. However, the tool can also be used for training purposes, and thus the breach can also be defined manually.

During the computation process some relevant information, such as large heel angle, is displayed immediately, Fig. 11. After the prediction, the results can be visualized either as an animation or for any time step. This kind of detailed analysis is considered to be very useful when the flooding prediction is used for training purposes.

6. CONCLUSIONS

A completely new approach for prediction of progressive flooding has been developed. It has been tested with two case studies. Firstly for flooding of a small fast attack craft, where full-scale measurement data is available, and then for two-compartment flooding case with a modern large passenger ship design. In both 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 seems to be somewhat conservative (faster than reality).

The developed method is relatively fast. With the current graphical user interface a one hour prediction is typically completed in less than a minute. Moreover, this may still be improved as the actual computation time for calculation of progressive flooding is much shorter.

The obtained prediction for progressive flooding and the intermediate phases are considered to be very valuable information for decision support in a crisis situation onboard a flooded ship.

7. ACKNOWLEDMENTS

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8. REFERENCES

IMO 2008, Guidelines for Flooding Detection Systems on Passenger Ships, MSC.1/Circ.1291, 8 December 2008.

ITTC 2008, The Specialist Committee on Stability in Waves, Final Report and Recommendations, Proceedings of the 25th ITTC, Vol. II, pp. 605-639.

Jasionowski, A. 2011, Decision support for ship flooding crisis management, Ocean Engineering, Vol. 38, pp. 1568-1581.

Nilsson, R., Rutgersson, O., 2006, Damage Stability and Decision Support – How can we be better prepared and what questions do the teaching face?, Proceedings of the 9th International Conference on Stability of Ships and Ocean Vehicles STAB2006, Rio de Janeiro, Brazil.

Ölcer, A. I., Majunder, J., 2006, A Case-based Decision Support System for Flooding Crises Onboard Ships, Quality and Reliability Engineering International; 22:59-78.

Penttilä, P., Ruponen, P., 2010, Use of Level Sensors in Breach Estimation for Damaged Ship, Proceedings of the 5th International Conference on Collision and Grounding of Ships ICCGS 2010, Espoo, Finland 14-16.6.2010, pp. 80-87.

Penttilä, P., 2012, Design Guidelines for Placement and Technical Requirements of Flooding Sensors in Passenger Ships, FLOODSTAND Deliverable D3.3, http://floodstand.aalto.fi/Info/public_download.html

Ruponen, P., 2007, Progressive Flooding of a Damaged Passenger Ship, TKK Dissertations 94.

Ruponen, P., Kurvinen, P., Saisto, I., Harras, J., 2010, Experimental and Numerical Study on Progressive Flooding in Full-Scale, Transactions of Royal Institute of Naval Architects, Vol. 152, Part A4, International Journal of Maritime Engineering, pp. A-197-207.

SLF 54/INF.8/Rev.1, 2011, Modelling of Leaking and Collapsing of Closed Non-Watertight Doors, submitted by Finland, 28 October 2011.

Spanos, D., Papanikolaou, A., 2011, Considerations on the Survivability Assessment of Damaged Ships, Proceedings of the 12th International Ship Stability Workshop, Washington D.C., U.S.A., pp. 45-52.

Tagg, R., Tuzcu, C., 2003, A Performance-Based Assessment of the Survival of Damaged Ships: Final Outcome of the EU Research Project HARDER, Marine Technology, Vol. 40, No. 4, pp.288-295.