Extensions to a Pressure-Correction Method for Simulation of Progressive Flooding

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ABSTRACT

The latest improvements and advances of the simulation method for progressive flooding of damaged passenger ships, developed at Helsinki University of Technology in close co-operation with Napa Ltd are presented. This includes the derivation of the pressure-correction equation for openings with high vertical extent and a simple sensitivity analysis of the developed method for the opening parameters, such as critical pressure heads.

KEYWORDS

Flooding simulation, progressive flooding, pressure-correction method, sensitivity analysis

INTRODUCTION

Napa Ltd and Helsinki University of Technology have in co-operation developed a novel time-domain simulation method for progressive flooding. The principle idea of applying pressure-correction technique for flooding simulation was presented in Ruponen (2006), based on the assumption that all openings are relatively small. Some examples of the validation of this method were presented in Ruponen et al. (2006). In this paper, an extension of this simulation method is presented, along with a brief revisit to the theoretical background. Furthermore, a preliminary study on the sensitivity of the simulation results on the applied parameters for the modelled openings is presented.

The pressure-correction technique is very suitable for the flooding cases, where also air compression and the resulting airflows are significant. However, for the cause of simplicity, in this paper it is assumed that the air pressure is constant throughout the flooding process.

PRESSURE-CORRECTION METHOD FOR FLOODING SIMULATION

Background

Usually flooding simulation methods are based on the volumes of floodwater that are integrated explicitly from the flow velocities that are calculated from Bernoulli’s equation. The water height differences are then calculated from the volumes of water with the heel and trim angles taken into account. However, the applied simulation method is based on a completely different approach, where the volumes are calculated on the basis of water heights and the heel and trim angles. This is reasonable as the water height is physically more meaningful than the volume of water since it represents the hydrostatic pressure. Consequently, the progress of the floodwater can be solved implicitly on the basis of the pressures in the rooms and the velocities in the openings.

The ship model for flooding simulation can be considered as an unstructured and staggered grid (Fig. 1). Each modelled room is used as a single computational cell. However, the flux through a cell face is possible only if there is an opening that connects the rooms (cells).

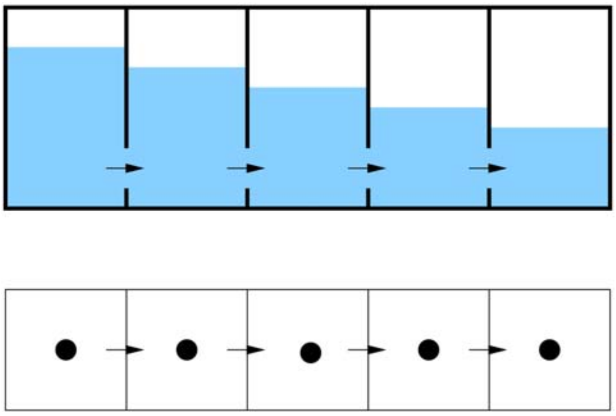

Fig. 1: Staggered grid in flooding simulation

Governing Equations

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

$$\int_{\Omega} \frac{\partial \rho}{\partial t} d\Omega = -\int_{S} \rho_w \mathbf{v} \cdot d\mathbf{S} \qquad (1)$$

where ρ_w is density, $\mathbf{v}$ is the velocity vector and $\mathbf{S}$ is the surface that bounds the control volume Ω. The normal vector of the surface points outwards from the control volume, hence the minus sign on the right hand side of the equation.

The mass balance for water, i.e. the residual of the equation of continuity, in the room i can be expressed as:

$$\Delta \dot{m}_{w,i} = \rho_w S_{fs,i} \frac{dH_{w,i}}{dt} + \rho_w \sum_k Q_{w,k} \qquad (2)$$

where S_{fs} is the area of free surface in the compartment (assumed to be constant during the time step), H_w is the water height and Q_w is the volumetric water flow through an opening in the compartment. The index k refers to an opening in the room i.

The velocities in the openings are calculated by applying Bernoulli's equation for a streamline from point A that is in the middle of a flooded room to point B in the opening:

$$\int_A^B \frac{dp}{\rho} + \frac{1}{2}\left(u_B^2 - u_A^2\right) + g\left(h_B - h_A\right) = 0 \qquad (3)$$

where p is air pressure, u is flow velocity and h is height from the reference level. It is assumed that the flow velocity is negligible in the center of the room ($u_A = 0$).

The equation (3) applies for inviscid and irrotational flow. The pressure losses in the openings and pipes are taken into account by applying semi-experimental discharge coefficients. Consequently, the mass flow through an opening k is:

$$\dot{m}_{w,k} = \rho_w Q_{w,k} = \rho_w C_{d,k} A_k u_k \qquad (4)$$

where $Q_{w,k}$ is the volumetric flow through the opening, $C_{d,k}$ is the discharge coefficient, A_k is the area of the opening and u_k is velocity. Basically equation (4) applies only to very small openings. In the next chapter, the handling of tall openings is considered in detail.

Bernoulli's equation for water flow through the opening k that connects the compartments i and j (positive flow from i to j) can be written in a form of a pressure loss:

$$\frac{1}{2} K'_k \dot{m}_{w,k} \left|\dot{m}_{w,k}\right| = \left(P_i - P_j\right)_k \qquad (5)$$

where the absolute value is used to define the direction of the flow. The dimensional pressure loss coefficient is defined as:

$$K'_k = \frac{1}{\rho_w C_{d,k}{}^2 A_k^2} \qquad (6)$$

The total pressure difference for an opening k that connects the compartments i and j is:

$$\left(P_i - P_j\right)_k = \rho_w g \cdot [f(i,k) - f(j,k)] \qquad (7)$$

where the following auxiliary function is used:

$$f(i,k) = \max\left(H_{w,i} - H_{o,k}, 0\right) \tag{8}$$

where H_w is the height of the water level and H_o is the height of the opening, measured from the same horizontal reference level. It is also possible to deal with openings that can be formed when structures (e.g. closed doors or down-flooding hatches) collapse under the pressure of the floodwater.

Pressure-Correction Equation

The linearization of equation (5) results in:

$$K'_{w,k}\left|\dot{m}^{*}_{w,k}\right|\dot{m}'_{w,k} = P'_i - P'_j \tag{9}$$

Consequently, by using equations (2) and (9), the following pressure-correction equation can be derived (see Ruponen, 2006):

$$\sum_k \frac{F(i,k)\cdot H'_{w,i} - F(j,k)\cdot H'_{w,j}}{K'_{w,k}\rho_w\left|Q^{*}_{w,k}\right|} + \frac{3}{2}\frac{\rho_w S_{fs,i}}{\Delta t}H'_{w,i} = -\Delta\dot{m}^{*}_{w,i} \tag{10}$$

where the following auxiliary function is used:

$$F(i,k) = \max\left[\operatorname{sign}\left(H_{w,i} - H_{o,k}\right), 0\right] \tag{11}$$

Equation of Motion

The previous study (Ruponen et al., 2006) was based on the assumption of quasi-stationary motions of the flooded ship. In order to get more realistic results, the roll motion $\phi(t)$ is solved from the following equation:

$$A_{xx,tot}\cdot\ddot{\phi} + B_{xx,tot}\cdot\dot{\phi} + M_{st}(\phi) = M_{ext}\left(V_{w,i}\right) \tag{12}$$

where $A_{xx,tot}$ is the sum of inertia and added mass and $B_{xx,tot}$ represents linear damping. M_{st} is the righting moment and M_{ext} is the heeling moment due to floodwater. The natural roll period and critical damping ratio for the intact ship can be obtained from the roll decaying test or seakeeping calculations. The trim and draft are still considered to be quasi-stationary.

EXTENDED HANDLING OF TALL OPENINGS

Calculation of Volumetric Flow

In the previous chapter, a pressure-correction equation was derived by assuming that the openings are so small that they can be considered as points. In practice, this simplification is not always valid. Therefore, it is essential that the simulation method is extended to deal with tall openings as well.

A more realistic, yet simple, representation for an opening with significant vertical height, such as an open door, is a straight line with a given area. A similar approach was used in Dillingham (1981) for calculation of two-dimensional flow over a bulwark and in Pawlowski (2003) for an opening with a constant width. However, in practice this method requires an additional assumption that the flow velocity is always perpendicular to the opening. The opening line can be considered as three separate openings since the sections $\overline{AB}$, $\overline{BC}$ and $\overline{CD}$ are treated individually, see Fig 2.

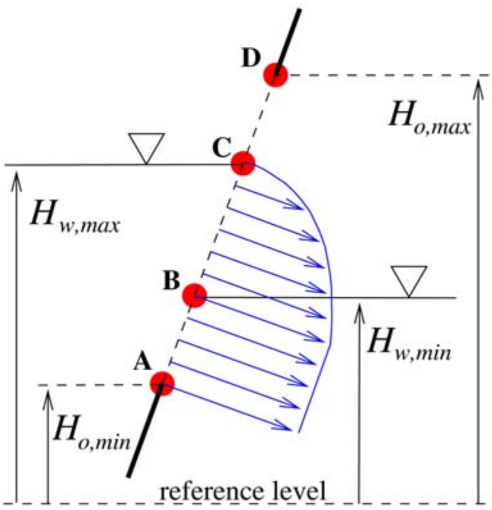

Fig. 2: Opening line

The section $\overline{AB}$ corresponds to an opening point with the same area since the flow through this section depends on both water heights but not on the vertical location of the opening. Consequently, no separate handling is needed.

The section $\overline{CD}$ corresponds to an opening point for airflow. Consequently, the shape of the opening has no effect on the computation of airflow. In this paper, it is assumed that all rooms are fully vented, and consequently air pressure is constant.

The section $\overline{BC}$ needs to be treated with a different way since the volumetric flow through this section must be integrated. This affects also the pressure-correction equation for water heights. A detailed description of the applied methods is given in the following.

The volumetric water flow through the section $\overline{BC}$ is obtained by integration of the flow velocity u over the corresponding part of the opening line (see Fig. 3):

$$Q_{w.BC} = b \cdot \int_0^{\overline{BC}} u \cdot dl \tag{13}$$

where b is the width of the opening.

Similarly to the case of a one-dimensional opening point, let us consider a streamline from point E that is in the middle of the flooded room, to point F that is in the opening between the points B and C. The following heights for the points along the streamline are used:

$$\begin{aligned} h_E &= H_C \\ h_F &= H_B + l \cdot \sin\beta \end{aligned} \tag{14}$$

where l is the distance from the point B along the opening line and β is the angle between the reference level and the opening line, see Fig. 3.

The flow velocity is obtained from equation (3) and the pressure losses are taken into account in the form of a discharge coefficient. Consequently, the following equation for the volumetric water flow through the section $\overline{BC}$ can be obtained:

$$Q_{w.BC} = C_d b \int_0^{\overline{BC}} \sqrt{2g\left[H_{w,max} - \left(H_B + l \cdot \sin\beta\right)\right]}dl \tag{15}$$

where C_d is the discharge coefficient for the opening when the jet discharges into air.

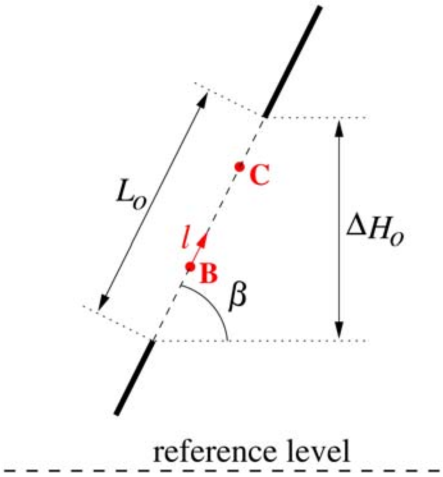

Fig. 3: The angle between the opening line and the horizontal reference level

It is practical to assume that the changes of the water height are rather small, so that $H_{w,max} \approx H_C$ and $H_{w,min} \approx H_B$. Consequently, equation (15) can be written as:

$$Q_{w.BC} = C_d b \cdot \int_0^{\overline{BC}} \sqrt{2g\left[H_C - \left(H_B + l \cdot \sin\beta\right)\right]}dl \tag{16}$$

This can be evaluated analytically:

$$Q_{w.BC} = C_d \cdot b \cdot \frac{2 \cdot \sqrt{2g}}{3 \cdot \sin\beta} \cdot \left[\left(H_C - H_B\right)^{\frac{3}{2}} - \left(H_C - H_B - \overline{BC}\sin\beta\right)^{\frac{3}{2}}\right] \tag{17}$$

The inclination angle of the opening line, i.e. the angle between the water levels and the opening (Fig. 3), can be evaluated on the basis of the vertical distance between the end points of the opening line (ΔH_o). Consequently:

$$\sin\beta = \Delta H_o / L_o \tag{18}$$

Equation (17) can be presented in a simpler form since the vertical distance between the points B and C is:

$$H_C - H_B = \overline{\mathrm{BC}} \cdot \sin\beta \qquad (19)$$

Hence, the volumetric flow, equation (17), can be approximated with the following equation:

$$Q_{w.BC} = C_d \cdot b \cdot \frac{2\cdot\sqrt{2g}}{3\cdot\sin\beta}\left(H_C - H_B\right)^{\frac{3}{2}} \qquad (20)$$

The area of the opening between the points B and C is:

$$A_{BC} = b \cdot \overline{\mathrm{BC}} = b \cdot \frac{(H_C - H_B)}{\sin\beta} \qquad (21)$$

Therefore, equation (20) can be simplified to:

$$\begin{aligned} Q_{w.BC} &= C_d b \frac{2\sqrt{2g}}{3\sin\beta}(H_C - H_B)\sqrt{H_C - H_B} \\ &= C_d A_{BC}\,\frac{2}{3}\sqrt{2g(H_C - H_B)} \end{aligned} \qquad (22)$$

The basic form of the rearranged equation for the volumetric flow (22) is the same as in the equation for the flow through a one-dimensional opening, multiplied by the coefficient 2/3. This relation is used in the following when the pressure-correction equation is derived.

Pressure-Correction Equation

The equation (22) can be presented in the form of a pressure loss, similarly to equation (5). The mass flow of water through the section $\overline{\mathrm{BC}}$ is:

$$\dot{m}_{w,BC} = \rho_w \cdot C_d \cdot A_{BC} \cdot \frac{2}{3}\sqrt{2g\left(H_C - H_B\right)} \qquad (23)$$

and the square of the mass flow, divided by two is:

$$\begin{aligned} &\frac{1}{2}\dot{m}_{w,BC}\left|\dot{m}_{w,BC}\right| \\ &= \rho_w^2 \cdot C_d^2 \cdot A_{BC}^2 \cdot \frac{4}{9}\cdot g\left(H_C - H_B\right) \end{aligned} \qquad (24)$$

This can be rearranged to:

$$\begin{aligned} &\frac{1}{2}\cdot\left(\frac{1}{\frac{4}{9}\cdot\rho_w\cdot C_d^2\cdot A_{BC}^2}\right)\cdot\dot{m}_{w,BC}\left|\dot{m}_{w,BC}\right| \\ &= \rho_w g\left(H_C - H_B\right) \end{aligned} \qquad (25)$$

Moreover, this can be simplified by applying the dimensional pressure loss coefficient, defined in (6). Therefore, equation (25) can be written as:

$$\frac{1}{2}\cdot\frac{9}{4}\cdot K'_w \dot{m}_{w,BC}\left|\dot{m}_{w,BC}\right| = \rho_w g\left(H_C - H_B\right) \qquad (26)$$

The basic form of this equation is similar to the pressure loss equation for one-dimensional opening (5), but the dimensional pressure loss coefficient is multiplied by a constant factor of 9/4. Therefore, the same form of the pressure-correction equation can be used when this additional coefficient is taken into account.

The total volumetric water flow through the opening k consists of two parts:

$$Q^*_{w,k} = Q^*_{w,AB,k} + Q^*_{w,BC,k} \qquad (27)$$

Consequently, the pressure-correction equation (10) for water heights in the case of two-dimensional openings can be rewritten as:

$$\begin{aligned} &\sum_k \left[\begin{aligned} &\frac{H'_{w,i} - H'_{w,j}}{K'_{w,AB,k}\rho_w\left|Q^*_{w,AB,k}\right|} \\ &+\frac{4}{9}\cdot\frac{G(i,,j)\cdot H'_{w,i} - G(j,i)\cdot H'_{w,j}}{K'_{w,BC,k}\rho_w\left|Q^*_{w,BC,k}\right|} \end{aligned}\right] \\ &+\underline{\frac{3}{2}\frac{\rho_w S_{fs,i}}{\Delta t}H'_{w,i}} = -\Delta\dot{m}^*_{w,i} \end{aligned} \qquad (28)$$

where the following auxiliary function is used:

$$G(i,j) = \max\left[\mathrm{sign}\left(H_{w,i} - H_{w,j}\right),0\right] \qquad (29)$$

The first term on the left hand applies for the water flow discharging into water since the mass flow depends on both water heights. The second term on the left hand side is for the water flow discharging into air since this part of the mass flow only depends on the water height on the maximum pressure side. The underlined term is taken into account only if the room is not filled with water. In principle, the basic form of the pressure-correction equation is exactly the same as in the case of one-dimensional opening points, equation (10).

Discontinuities should be avoided during the iteration process in order to ensure convergence,. Therefore, the points B and C are kept constant during the time step. This simplification should not cause significant error if the applied time step is sufficiently short.

The applicability of this implementation has been tested by performing comparative simulations, where the tall openings were modelled with several individual points. An example of the comparisons is presented in Fig. 4.

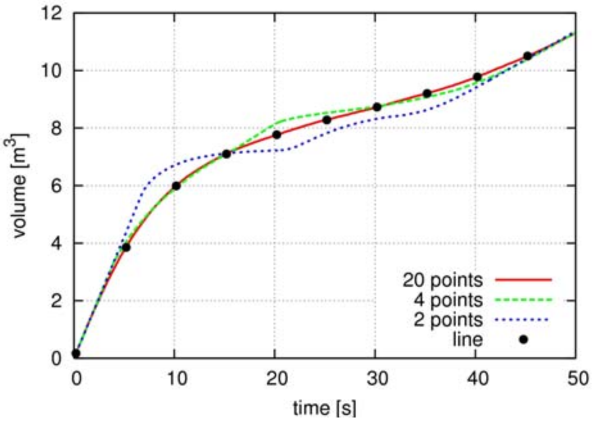

Fig. 4: Comparison of different modelling techniques for a tall opening

In this case, 20 evenly distributed opening points give practically the same result as one vertical opening line. The difference is increased as the number of opening points is decreased. When the whole opening is submerged (volume of floodwater is larger than 10 m^3) the modelling of the opening does not affect anymore.

SENSITIVITY ANALYSIS

Background

The current knowledge on leaking and collapsing of non-watertight structures is rather limited. The presented case study provides some initial framework for the future experimental studies with various structures.

Damage Case

The studied case is a two-compartment damage in a medium sized passenger ship of 40 000 GT. The flooded compartments contain crew cabins and store areas. All doors are considered to be initially closed. The modelled rooms and openings (i.e. the computational grid) are shown in Fig. 5.

Simulations were performed with a constant time step of 1.0 s. The applied convergence criterion corresponds to a water height difference of 0.05 mm. It was checked that a shorter time step or a stricter criterion did not affect the results.

The values for leaking and collapsing pressure heads and leaking ratios, presented in IMO SLF47/INF.6 (2004) were used as a basic case. However, the presented A_{ratio} values, are quite high. Vartiainen (2006) has concluded that much smaller values might be more realistic. Therefore, these values were reduced by 50 % for the other simulations. The applied values are listed in Table 1. In all cases, H_{leak} = 0.0 m and C_d = 0.6 were used for all openings.

The equilibrium floating position is shown in Fig. 6 and the calculated time histories for heeling and total volume of floodwater are presented in Fig. 7 and Fig. 8, respectively. In the studied case the heeling is very minimal due to the large initial stability and symmetry in the flooding process. The applied A_{ratio} values seem to have a remarkable effect on the time-to-flood. On the other hand, a 20 % increase in the critical pressure head for collapsing has much smaller effects on the flooding process.

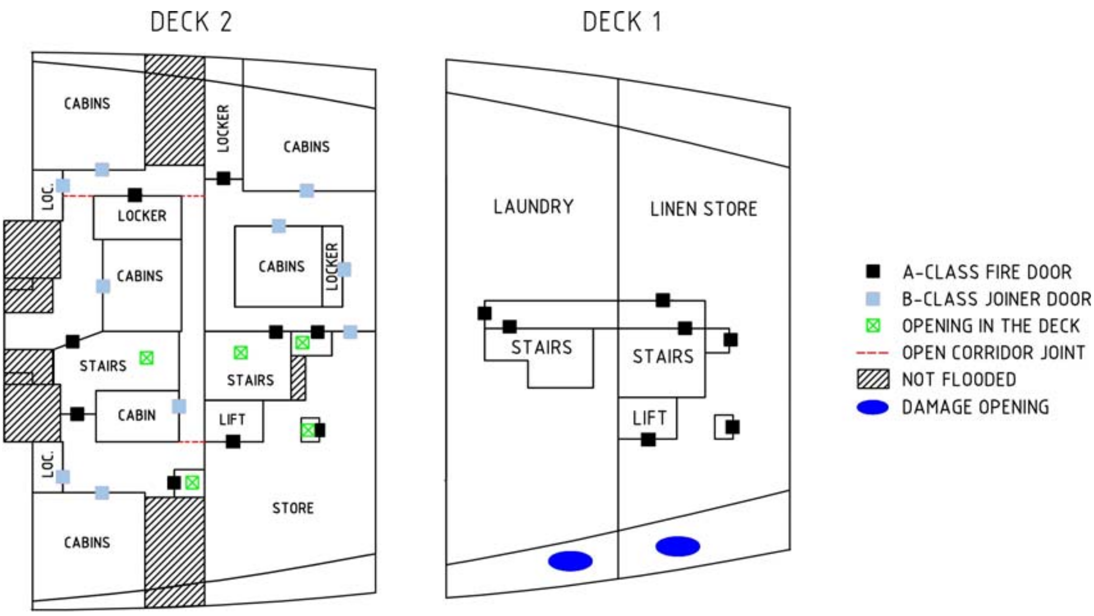

Fig. 5: Modelled rooms and openings, deck 2 (left) and deck 1 (right)

Table 1: Applied parameters for leaking and collapsing of non-watertight doors

Case	*A-class*		*B-class*	
	H_{coll}	A_{ratio}	H_{coll}	A_{ratio}
SLF47/INF.6	2.0 m	0.10	1.5 m	0.20
A_{ratio} –50%	2.0 m	0.05	1.5 m	0.10
A_{ratio} –50% H_{coll} +20%	2.4 m	0.05	1.8 m	0.10

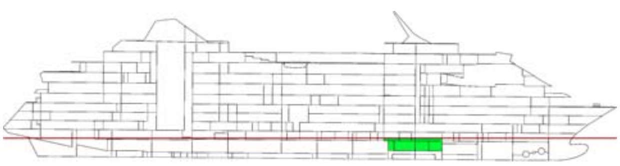

Fig. 6: Studied damage case, final equilibrium floating position

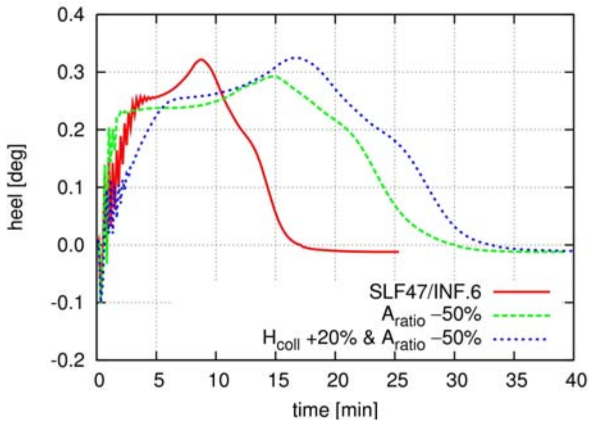

Fig. 7: Calculated heeling angle with various parameters for closed doors

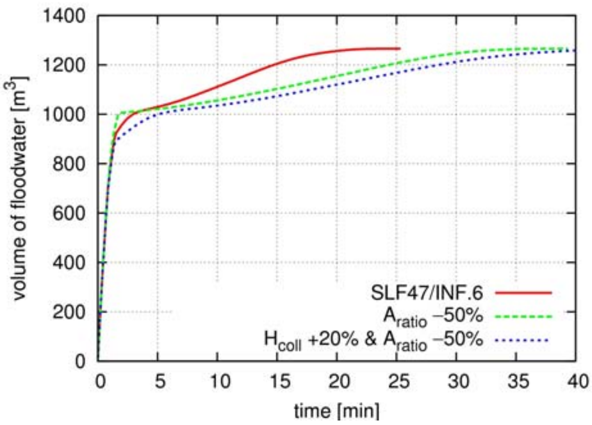

Fig. 8: Calculated total volume of floodwater with various parameters for closed doors

CONCLUSIONS

An enhanced version of the simulation method for progressive flooding with the use of pressure-correction technique has been presented. The calculated case study could be solved easily and the iterations converged properly.

Some notable conclusions can be drawn from the results of the sensitivity analysis. In particular, high A_{ratio} values can lead to a situation, where the door will not collapse at all, since the leaking through the door is so significant that the pressure difference remains small. In the studied case, collapsing of doors took place only on deck 1, during the first two minutes of the flooding. Consequently, it is of uttermost importance that the failure process of different door types is systematically studied with full scale experiments. On the other hand, the results are also promising since a small difference in the critical pressure head for collapsing does not cause significant changes in the time-to-flood and the overall flooding process.

Even the best simulation methods cannot provide realistic results if the input parameters for potential openings, such as closed doors, are not known, accurately enough. Therefore, systematic studies are necessary in order to increase the reliability of flooding simulations.

ACKNOWLEDMENTS

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