ON THE APPLICATION OF PRESSURE-CORRECTION METHOD FOR SIMULATION OF PROGRESSIVE FLOODING

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ABSTRACT

The application of the pressure-correction method for analysis of progressive flooding in a damaged large passenger ship is studied through a case study. The emphasis is on the efficient convergence of the pressure-correction iterations. In addition, a simple method for estimation of increased flooding due to waves and implementation of pumping and closing of open doors into the pressure-correction equation are presented.

Keywords: *progressive flooding, simulation, pressure-correction, damage stability*

1. INTRODUCTION

1.1 Background

Progressive flooding to undamaged compartments can result in the capsizing or sinking even if the ship would have survived the flooding of the damaged compartments. During the intermediate phases large heeling angle or waves can cause flooding on to the bulkhead deck and further down to the undamaged compartments through the trunks and staircases. Furthermore, progressive flooding typically includes also leaking and collapsing of non-watertight structures. Thus the chain of flooded compartments can be long. Time-domain flooding simulation provides a tool for analyzing such critical damage cases and allows better design of subdivision and counter-flooding devices.

Implicit method, based on the pressure-correction technique has proven to be an efficient approach for this problem. Its iterative nature ensures numerical stability and accuracy also in very complex flooding cases. The application of this technique is further tested on a large passenger ship design. The efficient use is studied and the implementation of new features for assessing the effects of the sea state on the flooding process and active counter actions are presented.

1.2 Case Study Ship

The application of the pressure-correction method for flooding simulation is presented with a case study. The principal dimensions of a large passenger ship design are given in Table 1 and the layout of the flooded compartments is shown in Fig. 1. The main interest is in the progressive flooding on the bulkhead deck. All A-class[1] bulkheads and cross-flooding arrangements have been modelled but the B-class subdivisions (e.g. in the cabin areas) are excluded. Therefore, the applied simplification is based on the detail level II, presented in the previous study, Ruponen et al. (2006). It is recognized that during the transient phase in the beginning of flooding, the internal layout of the compartments below the bulkhead deck might have a notable effect on the heeling. However, this study concentrates on the phase of

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[1] The terms A-class and B-class refer to fire protection

progressive flooding, and thus the modelling of compartments that are rapidly flooded is not very detailed.

The critical pressure heads for leaking and collapsing of closed A-class fire doors, presented in SLF47/INF.6, IMO (2004), are used. However, it should be noted that these values are only rough estimates, and dedicated research on this subject is needed in order to increase the reliability of the flooding simulations, Ruponen (2007a). The freeboard is unrealistically minimal (1.6 m) in order to ensure substantial progressive flooding even in calm water. Cross-flooding arrangements are modelled with single openings. A constant discharge coefficient $C_d = 0.65$ is used for all openings.

1.3 Damage Scenario

A two-compartment rectangular-shaped side damage that is located slightly forward of the midship, is studied. The damage length is 10.4 m. One watertight door is open (see Fig. 1), resulting in more extensive flooding and immersion of the bulkhead deck. Sea is considered to be calm and the dynamic roll motion is calculated by using simple model with only linear damping. Trim and heave motion are assumed to be quasi-stationary. The A-class fire doors to the staircases are closed. Other doors in the service corridor are assumed to be open.

Table 1. Case study ship data.

Length	285 m
Breadth	36 m
Draft	9.50 m
GM_0	2.50 m
Natural roll period	20 s

2. PRESSURE-CORRECTION METHOD

2.1 Principles

A detailed description of the application of pressure-correction technique for flooding simulation is given in Ruponen (2006), (2007a) and (2007b). Some validation results are presented also in Ruponen et al. (2006). The method can also be applied to the calculation of counter air pressures, but for simplicity, in this study a constant air pressure is assumed.

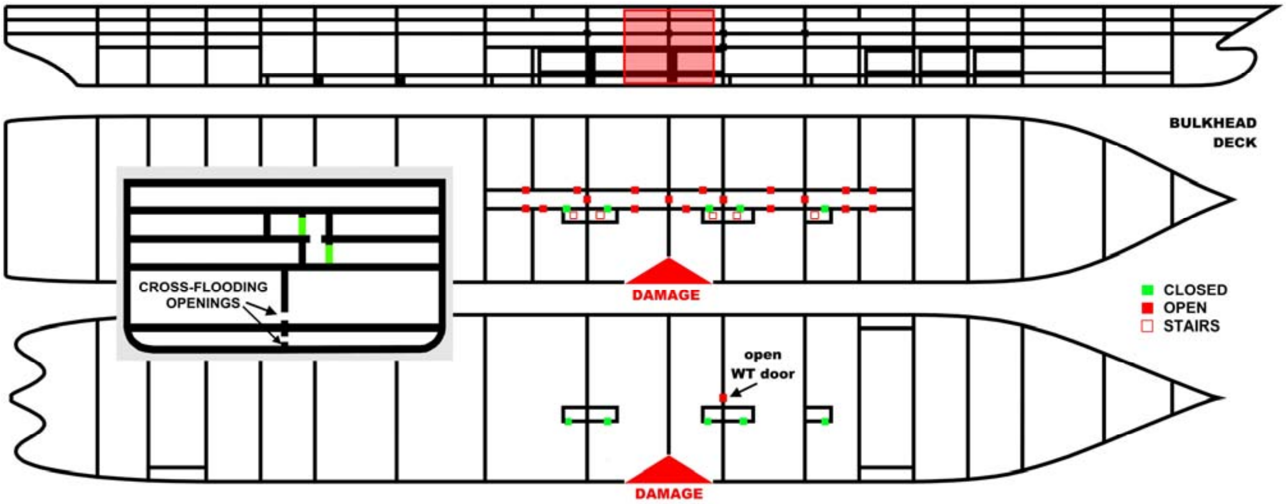

Figure 1. General arrangement, studied damage case and modelled openings.

The ship model is considered as an unstructured and staggered grid. Each modelled room is used as a single computational cell. However, the flux (water flow) through a cell face is possible only if there is an opening that connects the rooms (cells). The method is based on pressures, and thus the volume of water is presented as a water height from a common reference level. The workflow for one time step is presented in Fig. 2. The volumes of water are calculated after each time step from the converged water heights by taking into account the heel and trim angles. The initial values for each iteration round are marked with an asterisk (*) and corrections with an apostrophe (′).

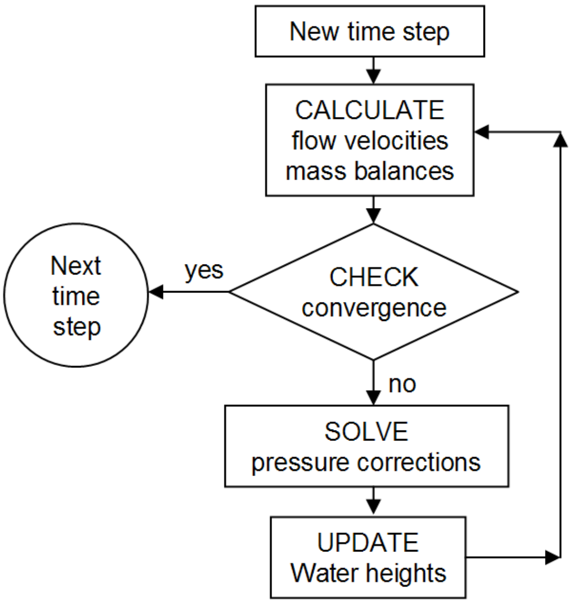

Figure 2. Flow chart for one iteration round.

2.2 Governing Equations

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

$$\int_{\Omega} \frac{\partial \rho}{\partial t} d\Omega = -\int_{S} \rho \mathbf{v} \cdot d\mathbf{S} \tag{1}$$

where ρ 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:

$$\Delta \dot{m}_{w,i} = \rho S_{fs,i} \frac{dH_{w,i}}{dt} + \rho \sum_{k} Q_{w,k} \tag{2}$$

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:

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

where p is air pressure, u is flow velocity, g is acceleration due to gravity 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 applies for inviscid and irrotational flow. The pressure losses in the openings are taken into account by applying semi-empirical discharge coefficients (C_d). Consequently, the mass flow through an opening k is:

$$\dot{m}_{w,k} = \rho Q_{w,k} \approx \rho C_{d,k} A_k u_k \tag{4}$$

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. The implementations of tall openings and subsequent modifications to the pressure-correction equation have been presented in Ruponen (2007a) and (2007b).

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:

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

where the absolute value is used to define the direction of the flow.

The dimensional pressure loss coefficient is defined as:

$$K'_k = \frac{1}{\rho C_{d,k}^2 A_k^2} \tag{6}$$

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

$$\left(P_i - P_j\right)_k = \rho g \cdot \left[f(i,k) - f(j,k)\right] \tag{7}$$

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.

2.3 Pressure-Correction Equation

The linearization of Bernoulli’s 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) and the following notation:

$$F(i,k) = \max\left[\operatorname{sign}\left(H_{w,i} - H_{o,k}\right), 0\right] \tag{10}$$

the pressure-correction equation can be derived, Ruponen (2006) and (2007b):

$$\sum_k \frac{F(i,k)\cdot H'_{w,i} - F(j,k)\cdot H'_{w,j}}{K'_{w,k}\rho\left|Q^*_{w,k}\right|} \underline{\underline{+ C_{\Delta t}\frac{\rho S_{fs,i}}{\Delta t}}} H'_{w,i} = -\Delta\dot{m}^*_{w,i} \tag{11}$$

where Δt is time step (constant) and the mass balance is:

$$\Delta\dot{m}^*_{w,i} = \rho\sum_k Q^*_{w,k} + \underline{\underline{\rho S_{fs,i}\dot{H}^*_{w,i}}} \tag{12}$$

The coefficient $C_{\Delta t}$ depends on the applied differential for the time derivative *dH/dt*.

The underlined terms in equations (11) and (12) are zero for a room that is filled up with water. The water heights are updated by adding the solved corrections and the results are used as initial values for the next iteration round. This is continued until all mass balances are small enough.

In a matrix form the equation (11) is:

$$\mathbf{A} \bullet \mathbf{H}'_{\mathrm{w}} = -\text{Д}\dot{\mathbf{m}}_{\mathrm{w}} \tag{13}$$

Obviously, the coefficient matrix **A** is often very large and sparse, especially if the number of flooded rooms is large. Thus, application of a proper sparse matrix storage system will ensure the best possible performance. Also, it should be noted that since the method is iterative, it is not necessary to solve the pressure-corrections with high accuracy. Indeed, iterative methods for solution of a system of liner equations have proven to be superior. The conjugate gradient stabilized method (CGSTAB) was successfully used in this study.

3. CONVERGENCE ANALYSIS

3.1 Background

The convergence performance depends greatly on the applied time step and under-relaxation factor, Ferziger and Peric (2002). The optimum values depend on the problem. This study tries to outline the effects of these parameters and to present ideas for improving the performance. A case study with typical phenomena in progressive flooding is used as an example.

3.2 Under-Relaxation

In order to ensure convergence, the water height corrections are limited with an under-relaxation factor α:

$$H_{w,i} = H^{*}_{w,i} + \alpha \cdot H'_{w,i} \tag{14}$$

It is obvious that excessive under-relaxation (very small values of α) should be avoided since it slows down the convergence. However, sufficient under-relaxation is often necessary in order to achieve the convergence.

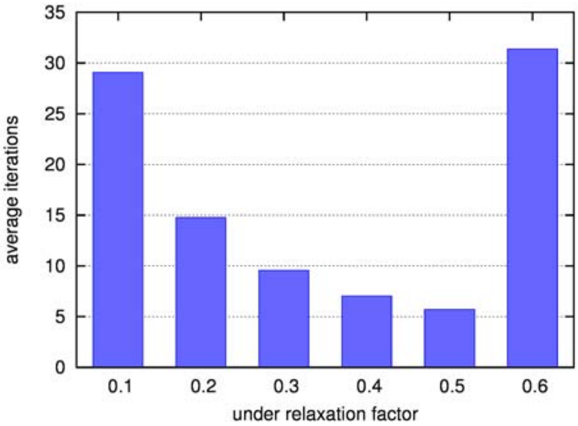

Figure 3. Average number of iterations with different under-relaxation factors.

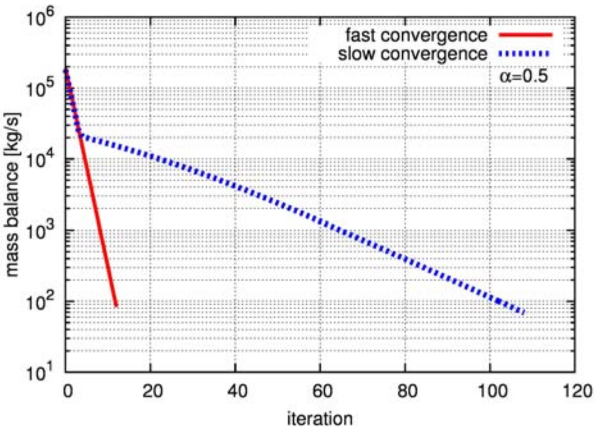

Figure 4. Examples of convergence.

3.3 Time Step

The applied time step has a significant effect on the computation time. In principle, when the time step is doubled the computation time is decreased by 30 .. 50 %. Examples from the case study with $\alpha = 0.5$ are shown in Fig 4. However, longer time step has also negative effects. The most notable one is that the numerical error is increased. In addition, a longer time step will also slow down the convergence. The reason for this is that the initial guess (result of previous step) is farther away from the solution and thus more iteration rounds are required. In fact, too long time step can easily lead to divergence of the pressure-correction iteration.

The optimal time step that provides sufficient accuracy and efficient computations may vary during the simulation. In the beginning of flooding, a relatively short step is usually needed in order to capture the fast flooding of the damaged compartments. Later, during the phase of progressive flooding, a longer step can be applied. However, if a long time step is used, it is also necessary to check that the effective pressure heads on closed doors are not resulting in collapsing since this may cause a short phase of fast flooding, at least locally. The maximum allowed value of the time step depends also on the motions of the ship. However, usually also heeling changes rather slowly during progressive flooding.

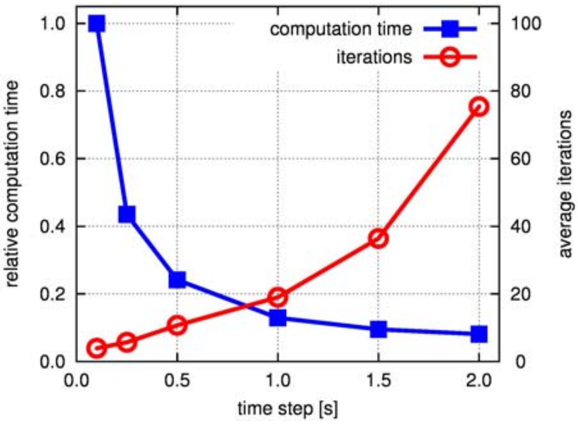

Figure 5. Computation time and average number of iterations with different time steps.

3.4 Adjustments during Simulation

Automatic adjustment of the applied under-relaxation factor during the simulation, and even during the iteration within one time step, can be used to improve the performance of the flooding simulation. In practice, this means that if the iteration seems to be diverging and the mass balances start to fluctuate, then the iteration is restarted and more under-relaxation is used. If iterations converge fast, less under-relaxation can usually be used for the next time step.

In some cases, it is also efficient to adjust the time step. This can be done with two different approaches: either gradually increasing or by sudden changes. The latter approach is used in this study. The applied time step was increased from 0.25 s to 0.625 s when the roll velocity had decreased to less than 0.1 °/s and the net flow rate was less than 10 m^3/s. These values were selected on the basis of simulation with short time step (0.25 s). It is recognized that the size of the ship and the details of the openings and flooded compartments may have a notable effect on the criteria for increasing the time step. In this case, the simulation results were practically identical and the adjustment of the parameters reduced the computation time by almost 50 %.

4. PRESSURE FLUCTUATION DUE TO WAVES

4.1 Background

For a damaged ship, the sea state has two different kinds of effects on the stability: wave induced ship motions and the pumping effect on the water flow through the damage hole. In the case of a large passenger ship, the pumping effect on the water inflow can be even more significant than the wave induced ship motions, especially in a moderate sea state.

Due to the waves, the effective height of the sea level can momentarily be much higher than the static sea level. As a result, the water inflow through the damage hole will be faster and also the rooms that are above the static sea level (e.g. on the bulkhead deck) can be flooded.

Further progressive flooding through, for example, service corridors, staircases and lift trunks can result in the flooding of undamaged compartments. Thus the flooding can be much more extensive than predicted by normal damage stability calculations in calm sea.

This phenomenon can be taken into account as a pressure fluctuation in the ghost cell (sea) that is used to set the boundary condition for the pressure-correction method. However, the applied time step must be much shorter than the wave period in order to capture the humps and hollows in the wave profile.

4.2 Wave Realization

The wave elevation as a function of time can be presented by a sum of the wave components, e.g. Ochi (2005):

$$\zeta(t) = \sum_{j=1}^{N} a_j \cos\left(-\omega_j t + \varepsilon_j\right) \tag{15}$$

In order to ensure that the generated time-series do not comprise repeating sequences, a random number generator is used to distribute discrete frequencies (ω_j) and to generate random phase angles (ε_j) of the wave components, e.g. Matusiak (2000).

The amplitude components a_j are calculated from the wave spectrum $S_\omega(\omega)$:

$$a_j = \sqrt{2 \cdot S_\omega(\omega_j) \cdot \Delta\omega_j} \tag{16}$$

The pressure head for the damage opening depends on the relative distance between the wave profile and the free surface at the location of the opening, Pawlowski (2003). Thus the effective pressure height of the sea that is used as the boundary condition for the progressive flooding calculation is:

$$H_{sea,eff}(t) = H_{sea} + \zeta(t) \tag{17}$$

where H_{sea} is the height of the static sea level. This is illustrated in Fig. 6.

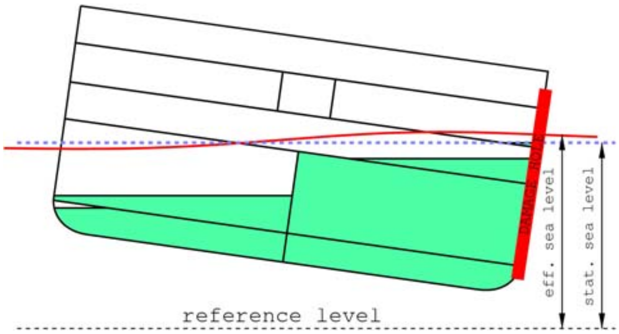

Figure 6. Momentary sea level as a boundary condition; dotted line is the static sea level.

4.3 Example

The damage scenario, described in Fig. 1 was calculated in calm water and in various sea states. The two-component ITTC wave spectrum was used. The ship is at beam seas with the damage facing the waves. The results are compared in Fig. 7 and Fig. 8, showing increased flooding in higher waves. With a significant wave height of 2.0 m, the waves are high enough to cause pumping of floodwater to the service corridor and further down to other compartments through the staircases. In reality, escape and lift trunks would provide even more routes for progressive flooding.

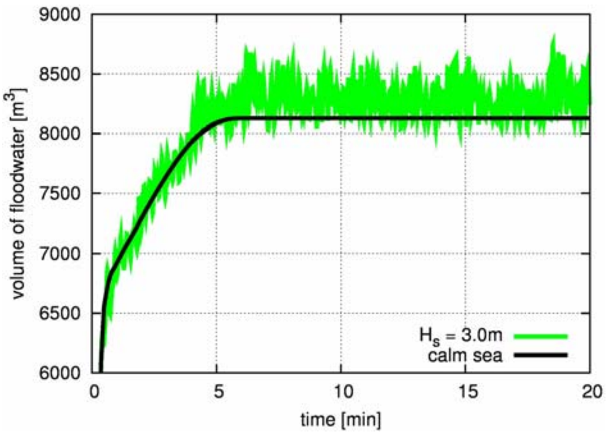

Figure 7. Volume of floodwater in waves and in calm sea.

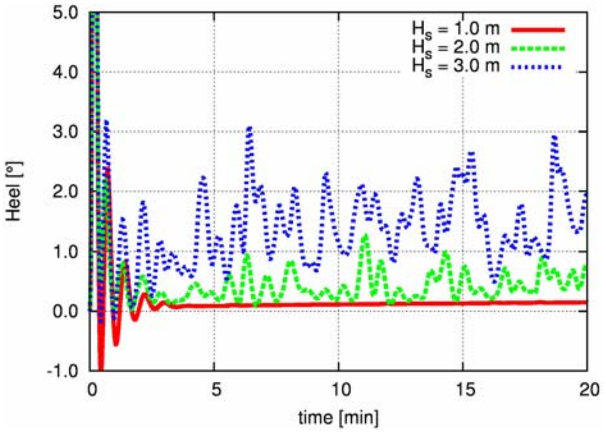

Figure 8. Heeling in different sea states.

When compared to the simulation in calm sea, the convergence is slowed down during the later phases of flooding. Most likely this is mainly caused by the slow and discontinuous flooding on the bulkhead deck and the down-flooding in the staircases.

In high waves the ship motions, especially heaving, may have a notable effect on the flooding.

5. ACTIVE COUNTER ACTIONS

5.1 Closing of Doors

Naturally, all watertight doors should be closed while at sea[2]. However, this is not always the real situation. Thus a flooding simulation tool must be capable to deal also with such counter actions.

Closing of open doors at the given time after the start of flooding is fairly simple. The effective area of the door is linearly decreased from the geometrical value to zero during the time span that it takes to close the door. Thereafter, the opening status is set to ”closed”. Naturally, the closed doors may then start to leak or even collapse under the pressure of the floodwater. The closing of a door does not affect the iteration within the time step.

5.2 Pumping

Another widely used counter action is pumping. The bilge pumps can be considered as openings with a constant flooding rate. Each pump connects two rooms (one can be sea). If the inlet is above the water level the flow is zero. Despite of the similarity to the ”normal” openings, pumps need to be treated separately in the pressure-correction equation.

For a pump, the flow direction and flow rate are constant and independent on the water heights, at least in theory. Therefore, the pumps do not affect the pressure-correction equation directly; but through the mass balance. Thus the equation (12) becomes:

$$\Delta m_{w,i} = \rho S_{fs} \frac{dH_{w,i}}{dt} + \rho \sum_{k=1}^{n_{o,i}} Q_{w,k} + \rho \sum_{k=1}^{n_{p,i}} Q_{p,k} \qquad (18)$$

where Q_p is the pumping rate. Outflow from the room i is defined to be positive.

5.3 Example

The open watertight door (see Fig. 1) is closed 60 s after the damage and the closing will take another 60 s. In addition a pump with constant rate is started 2.5 minutes after the damage. Volume of water in the room behind the WT-door is shown in Fig. 9. The addition of pumping and closing of a door did not have a notable effect on the convergence.

It should be noted, that in a real situation, it might be impossible to close the door since the frame may be distorted by the impact of the collision or the closing mechanism is not working properly e.g. due to short-circuits, caused by the floodwater, Swedish Accident Investigation Board (2005).

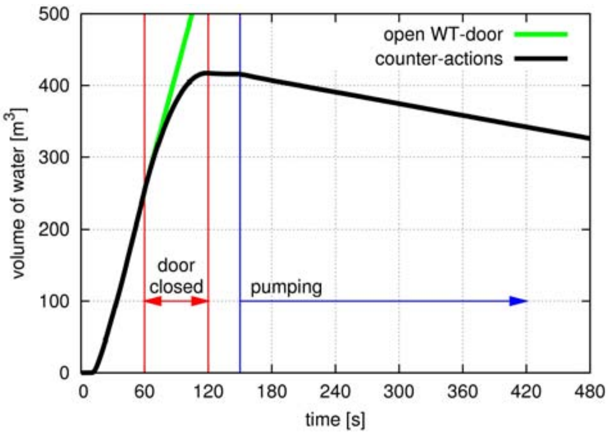

Figure 9. Effect of closing an open WT-door and pumping.

6. CONCLUSIONS

In general, the pressure-correction iterations converge rapidly. However, this is significantly affected by the applied time step and under-relaxation factor.

The automatic increase of time step during the simulation is a very effective way to decrease the computation time. However, the setting of proper criteria for this can sometimes be rather difficult and further studies on this subject are needed. The adjustment of under-relaxation is a more robust procedure that often

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[2] Exceptions have been allowed, especially for passenger areas

significantly improves the performance of the simulation tool since much under-relaxation is usually needed only on few time steps.

The application of momentary sea level as a boundary condition for progressive flooding was found out to model the flooding of the bulkhead deck rather realistically. However, the applied time step has to be short enough in order to properly capture the wave profile. In order to simulate different wave directions, a more detailed model of the boundary condition with separate ghost cells for each opening to sea may be required. However, more studies are still needed for assessing the effects of ship motions, especially heaving. Also experimental study would provide the necessary data for validation of this kind of simplified approaches.

Active counter-actions, such as closing of open doors and pumping can be easily implemented into the pressure-correction method for flooding simulation.

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