May 2019

On the Effect of Uncertainties on Onboard Progressive Flooding Simulation

Luca BRAIDOTTI [a,b,1], Alberto MARINÒ [a] and Vittorio BUCCI [a]
[a] *Department of Engineering and Architecture, University of Trieste*
[b] *Faculty of Engineering, University of Rijeka*

Abstract. Nowadays, the quasi-static techniques devoted to progressive flooding simulation are present in the literature. Most of them can be applied onboard to support crew decisions after a flooding casualty. However, in real scenarios, the input parameters, adopted to carry out time domain simulations, are often not accurately assessed or even unknown. The aim of this paper is to study the effect of these uncertainties affecting the damage geometry, the ship geometry and the loading condition at damage occurrence. A sensitivity study on the relevant input parameters has been carried out on a box-shape barge, showing that most of them have a strong influence on progressive flooding simulation. Regarding damage geometry which is directly connected to damage detection algorithms, the internal subdivision geometry has a stronger impact compared with damage location and area. Further study is required, especially when internal spaces are connected by small openings. Nevertheless, the paper highlights the importance of an accurate preparation of ship model and assessment of loading condition, providing some insights on these problems.

Keywords. Progressive flooding, sensitivity study, quasi-static approach, linearised technique

1. Introduction

In recent years, the time-domain simulation of progressive flooding has been an important topic discussed by the maritime community. In particular, their onboard application was studied within Decision Support Systems (DSS) devoted to aiding masters and officers immediately after a flooding casualty [1]. Nowadays, due to the high computational effort required by dynamic and computational fluid dynamics methods, the only viable solution for this issue is the adoption of quasi-static simulation techniques.

Many quasi-static procedures have been recently developed [2, 3, 4]. Some of them have been specifically designed for onboard application [5, 6]. Although several comparisons between different techniques have shown a quite good agreement [7], a systematic study on the uncertainties effect that may affect the accuracy of onboard progressive flooding simulations is not present in literature. Nevertheless, often several input parameters are only roughly estimated or even unknown in a real environment. In fact, the dam-

---

[1] Corresponding Author: Luca Braidotti; Department of Engineering and Architecture, University of Trieste, via A. Valerio, 10, 34127 Trieste, Italy; Faculty of Engineering, University of Rijeka, Vukovarska 58, 5100 Rijeka, Croatia; E-mail: lbraidotti@units.it.

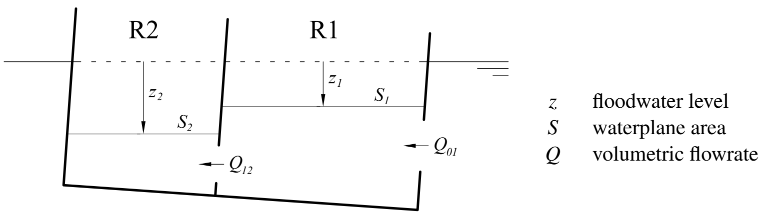

Figure 1. Sketch of a simple two rooms (R1, R2) geometry

age location and dimensions cannot be measured after a real casualty and they are estimated by means of a damage detection algorithm [8, 9]. Moreover, the assumptions on hydraulic coefficients, the ship model accuracy, as well as the tolerances on initial loading condition (i.e. the loading condition at damage occurrence) can have a heavy impact on the progressive flooding process, leading to erroneous assessment of the time-to-flood or even of the final outcome (new equilibrium, foundering or capsize).

The aim of the present work is to analyse the effect of input parameters' uncertainties on a progressive flooding simulation. To this end, a linearised approach has been adopted to carry out the progressive flooding simulations of an asymmetric damage scenario on model scale. After a brief presentation of the simulation technique, the effect of the input parameters variation is presented and discussed, highlighting which are the main problems to overcome, in order to assure the accuracy of progressive flooding simulations for onboard application.

2. Flooding Simulation Technique

The progressive flooding simulations are performed by means of a linearised quasi-static approach [6] based on a single loop over a constant time step Δt. The equilibrium floating position [10] of the ship is considered constant over the time step. The sea free surface and the flooded rooms waterplanes are considered flat and parallel. The level z_i inside the i-th flooded room is defined at each time step according to initial floodwater volume v_i as the distance between its waterplane and sea free surface (Fig. 1). After the assessment of the new levels by means of linearised technique, the volumes of floodwater are updated accordingly, being used to define the next step displacement and centre of mass. All dynamic phenomena and air-compression are neglected in order to reduce the computational effort.

2.1. Governing Equations

The governing equations of progressive flooding process are the mass and momentum conservation, which have to be simultaneously satisfied at each time step for all the flooded rooms and all the interconnections among them. Assuming a constant waterplane area inside i-th room, the mass conservation equation for a room i connected to other j rooms by N_i openings can be written as:

$$\dot{z}_i \mu_i S_i \approx \dot{V}_i = \sum_{j=1}^{N_i} Q_{ji} \tag{1}$$

where Q_{ji} is the volumetric flowrate through the opening connecting j-th to i-th rooms, V_i, S_i, μ_i and z_i are the volume inside the i-th room, its waterplane surface, its permeability and its level of floodwater measured orthogonally from the sea free surface (Fig.1) respectively. The conservation of momentum shall be applied to each opening and, assuming a quasi-stationary flow, can be described with Bernoulli equation. Neglecting flow velocity in the free surface centre the volumetric flowrate can be written as:

$$Q_{ji} = K_{ji} \operatorname{sgn}(z_j - z_i) \sqrt{|z_j - z_i|} \tag{2}$$

where $K_{ji} = C_{dji} A_{ji} \sqrt{2g}$ is a constant depending upon opening geometry: C_{dji} is a nondimensional discharge coefficient, A_{ij} is the opening area and g the gravity acceleration.

2.2. Floodwater Levels Assessment

At a generic time instant t^*, a number n of rooms are partially filled by floodwater according to a level vector $\mathbf{z}^* = (z_1(t^*), ..., z_n(t^*))$. Combining the equations (1) and (2), a system of non-linear ordinary differential equations is obtained in the form $\dot{\mathbf{z}} = f(\mathbf{z})$. Defining a level perturbation $\mathbf{z}^{'} = \mathbf{z} - \mathbf{z}^*$, the system can be linearised in $\mathbf{z}^*$:

$$\dot{\mathbf{z}}^{'} = \mathbf{J}(\mathbf{z}^*)\mathbf{z}^{'} + f(\mathbf{z}^*) \tag{3}$$

where $\mathbf{J}$ is the Jacobean matrix of $f(\mathbf{z})$ evaluated in $\mathbf{z}^*$, wich is diagonalisable [6]. Thus, applying the single value decomposition as $\mathbf{J}(\mathbf{z}^*) = \mathbf{V} \times \mathbf{D} \times \mathbf{V}^{-1}$ and defining $\mathbf{u} = \mathbf{V}^{-1}\mathbf{z}^{'}$, the Equation 3 can be rewritten as:

$$\dot{\mathbf{u}} = \mathbf{D}\mathbf{u} + \mathbf{V}^{-1} f(\mathbf{z}^*) \tag{4}$$

Being $\mathbf{D}$ a diagonal matrix, the differential equations of the system (4) are decoupled. Therefore, an algebraic solution can be easily obtained and used to estimate the floodwater levels at the next time step.

3. Sensitivity Analysis

In the present section, the effects of the uncertainties on progressive flooding simulations is studied by means of a sensitivity analysis. To this end, several simulations have been carried out with a systematic variation of a selected set of input parameters. The test case is represented by a box-shaped barge present in the literature [11]. The barge's main characteristics are given in Table 1, whereas internal subdivision layout is provided in Figure 2. The hull and the rooms are modelled by means of a non-structured mesh with panel area not exceeding 0.001 m^2. Unitary permeability has been adopted, being the boundaries thickness directly taken into account in the 3D model. The rooms are interconnected by a set of openings described in Table 2 and meshed by means of triangu-

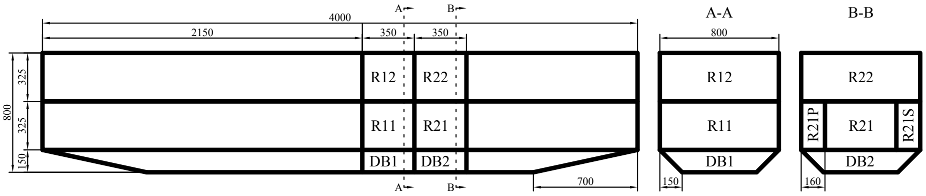

Figure 2. Internal Subdivision of the box-shaped barge (dimensions in mm)

Table 1. Main characteristics of box-shaped barge

Description	Value		Description	Value	
Length overall	4.000	m	Draught	0.500	m
Breadth	0.800	m	Heel	0.0	deg
Height	0.800	m	Trim	0.0	deg
Volume (at draught 0.500 m)	1.450	m^3	Vertical centre of gravity	0.278	m
Block coefficient	0.906		Metacentric Height (GM)	0.110	m

Table 2. Openings main characteristics

Opening	Type	Size (m)	X_C (m)	Y_C (m)	Z_C (m)	C_d (-)
SEA-R21S	Rectangular	0.060×0.040	2.675	0.395	0.315	0.78
R21-R21S	Rectangular	0.020×0.200	2.675	0.240	0.260	0.75
R21-R21P	Rectangular	0.020×0.200	2.675	-0.240	0.260	0.75
R21-R11	Circular	$D = 0.020$	2.500	0.000	0.315	0.80
R21-R22	Rectangular	0.100×0.100	2.750	0.160	0.475	0.72
R11-R12	Rectangular	0.100×0.100	2.400	0.160	0.475	0.72

$C = (X_C, Y_C, Z_C)$: Centre of opening; C_d: Discharge coefficient.

lar elements with panel area not exceeding 0.0001 m^2. The opening SEA-R21S (Tab. 2) simulates a side damage in the starboard wing tank.

In the present study, the analysed parameters are related to three main categories: damage geometry, ship geometry and initial loading condition. Different damage geometries have been tested varying separately damage location and area. The ship geometry has been altered in terms of rooms' permeability and discharge coefficient of the openings. Moreover, different upright initial conditions have been tested changing the height of the centre of mass and the displacement. All simulations have been carried out applying the linearised technique with a constant time step of 0.25 s. For each simulation, the trends of heel ϕ, trim θ and sinkage s have been compared highlighting the effect of parameter alteration. In addition, the effect on several overall quantities, characterizing the progressive flooding process, has been also studied. In detail, these are:

- the time-to-flood t_f, which is of utmost importance for decision support purposes;
- the minimum value of metacentric height $\overline{GM}_{min}$ measured during the progressive flooding, considered representative of the ship stability;
- the maximum heeling angle ϕ_{max}, having a influence on people mobility and, thus, on evacuation time;
- the final floating position of the barge in terms of trim θ_e and sinkage s_e.

3.1. Damage geometry

The geometry of the damage has been studied in terms of the damage area A_d and its location. As mentioned, both parameters cannot be directly measured but only estimated in a real environment. The shape of the damage has not been considered since it is usually modelled by means of a proper discharge coefficient in onboard codes. Regarding A_d, it has been increased and reduced by a 5.0% and 10.0% assuming a constant position of the centre of the damage. On the contrary, the centre of damage $(X_{C_d}, Y_{C_d}, Z_{C_d})$ was moved longitudinally and vertically along the wing tank side assuming a constant damage area. The results of simulations as a function of damage area and damage location are provided in Table 4 and 3, respectively.

The geometry of damage does not affect the final floating position of the barge. Concerning the damage location, the only relevant parameter which drives to significant differences on outcomes is its vertical position, while longitudinal translations (and transversal ones too) do not result in notable differences (Fig. 3). The vertical position has a small impact on t_f which increases with Z_{C_d} and a greater effect on ϕ_{max} due to different heeling moments induced by the floodwater level inside the starboard wing tank.

Table 3. Overall effect of damage location

id	**0**	**1**	**2**	**3**	**4**
X_{C_d} (m)	2.675	2.375	2.975	2.375	2.975
Y_{C_d} (m)	0.395	0.395	0.395	0.395	0.395
Z_{C_d} (m)	0.315	0.455	0.455	0.175	0.175
t_f (s)	330.50	340.75	339.75	330.00	330.00
error	-	3.10%	2.80%	-0.15%	-0.15%
$\overline{GM}_{min}$ (m)	0.0956	0.0957	0.0957	0.0956	0.0956
error	-	0.07%	0.09%	-0.03%	-0.03%
ϕ_{max} (deg)	0.629	0.364	0.362	0.645	0.645
error	-	-42.05%	-42.37%	2.52%	2.52%
s_e (m)	-0.0639	-0.0639	-0.0639	-0.0639	-0.0639
error	-	0.00%	0.00%	0.00%	0.00%
θ_e (deg)	1.370	1.370	1.370	1.370	1.370
error	-	0.00%	0.00%	0.00%	0.00%

Table 4. Overall effect of damage area

$\boldsymbol{dA_d}$	**-10.00%**	**-5.00%**	**0.00%**	**5.00%**	**10.00%**
t_f (s)	332.50	332.25	330.50	329.25	327.75
error	0.61%	0.53%	-	-0.38%	-0.83%
$\overline{GM}_{min}$ (m)	0.0957	0.0957	0.0956	0.0956	0.0957
error	0.11%	0.10%	-	0.01%	0.02%
ϕ_{max} (deg)	0.583	0.611	0.629	0.649	0.706
error	-7.30%	-2.86%	-	3.18%	12.30%
s_e (m)	-0.0639	-0.0639	-0.0639	-0.0639	-0.0639
error	0.00%	0.00%	-	0.00%	0.00%
θ_e (deg)	1.370	1.370	1.370	1.370	1.370
error	0.00%	0.00%	-	0.00%	0.00%

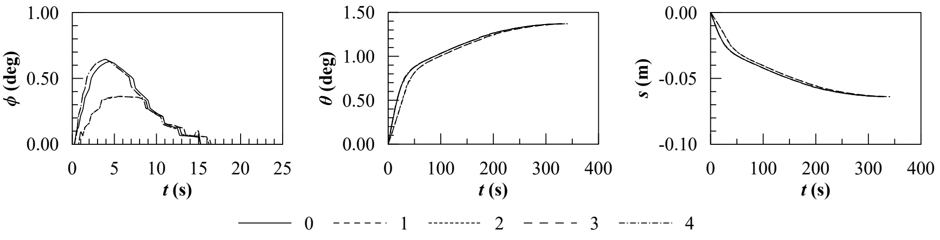

Figure 3. Effect of damage location on floating position

Regarding the effect of damage area, the t_f decreases with A_d. However, the increment is heavily dependent on the area of the other openings connecting the first flooded room to the other internal spaces. If such openings are small compared to damage size, the effect of A_d could become even negligible. Moreover, in this case study, the heeling moment during the transient phase increases with damage size, leading to greater ϕ_{max} value. It can be concluded that the effect of damage geometry heavily depends on the internal subdivision. In fact, if multiple rooms are involved in progressive flooding, the damage geometry has a strong influence only on the damaged rooms, thus, in case of large damages that cause an instantaneous filling of such rooms, it can be even negligible.

3.2. Ship geometry

The internal layout of bulkheads and decks was not modified, while different permeabilities and discharge coefficients have been applied to all the rooms and all the openings respectively. Simulations were carried out applying constant permeabilities to all rooms, ranging from 1.00 (default value) to 0.85. The results are provided in Table 5. The default discharge coefficients (Tab. 2) for barge internal openings were assessed experimentally. However, in real scenarios, the value of these coefficients is uncertain and usually ranges between 0.6 and 0.8 [12]. Nevertheless, it is common practice to assume a value equal to 0.6 in full-scale simulations [13]. In order to quantify the error associated with default values of discharge coefficients, their effect on progressive flooding process has been studied. To this end, all the experimental values of the openings discharge coefficients

Table 5. Overall effect of permeabilities

μ	**1.00**	**0.95**	**0.90**	**0.85**
$d\mu$	0.00%	-5.00%	-10.00%	-15.00%
t_f (s)	330.50	327.50	325.25	324.25
error	0.00%	-0.91%	-1.59%	-1.89%
$\overline{GM}_{min}$ (m)	0.0956	0.0954	0.0951	0.0947
error	0.00%	-0.21%	-0.53%	-0.92%
ϕ_{max} (deg)	0.629	0.611	0.579	0.547
error	0.00%	-2.85%	-7.94%	-13.08%
s_e (m)	-0.0639	-0.0610	-0.0571	-0.0533
error	0.00%	-4.45%	-10.56%	-16.53%
θ_e (deg)	1.370	1.310	1.226	1.145
error	0.00%	-4.43%	-10.51%	-16.45%

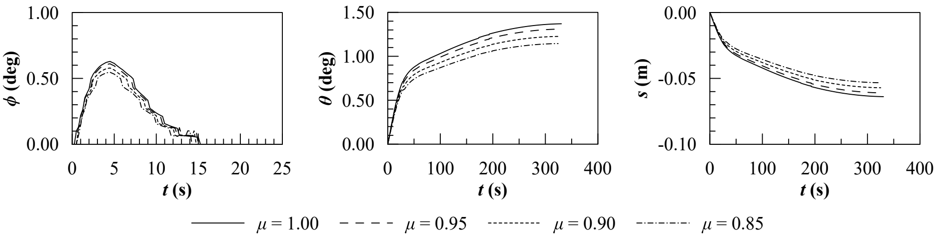

Figure 4. Effect of permeability on floating position

Table 6. Overall effect of discharge coefficients

dC_d	**-7.50%**	**-5.00%**	**-2.50%**	**0.00%**	**2.50%**	**5.00%**	**7.50%**
t_f (s)	357.25	348.75	339.25	330.50	317.25	312.75	306.75
error	8.09%	5.52%	2.65%	-	-4.01%	-5.37%	-7.19%
$\overline{GM}_{min}$ (m)	0.0956	0.0957	0.0957	0.0956	0.0960	0.0957	0.0957
error	-0.02%	0.03%	0.08%	-	0.42%	0.10%	0.11%
ϕ_{max} (deg)	0.623	0.617	0.624	0.629	0.631	0.629	0.632
error	-0.90%	-1.89%	-0.75%	-	0.39%	0.03%	0.44%
s_e (m)	-0.0639	-0.0639	-0.0639	-0.0639	-0.0639	-0.0639	-0.0639
error	0.00%	0.00%	0.00%	-	0.00%	0.00%	0.00%
θ_e (deg)	1.370	1.370	1.370	1.370	1.370	1.370	1.370
error	0.00%	0.00%	0.00%	-	0.00%	0.00%	0.00%

(including damage) have been reduced and increased by 2.5%, 5.0% and 7.5% (representative of a realistic uncertainty on these coefficients' values). The results are provided in Table 6.

The permeability has a heavy impact on the ship floating position during the whole progressive flooding process (Fig. 4), since it acts on the volume of floodwater loaded onboard. For the simple geometry of the test barge, the reduction of trim, heel and sinkage is proportional to the difference on permeabilities. It is worth to notice that the effect on $\overline{GM}_{min}$ and on t_f is not very strong. In fact, although a lower volume is loaded onboard, the resulting lower draught at openings drives to lower velocities, which nearly compensates the time-to-flood reduction.

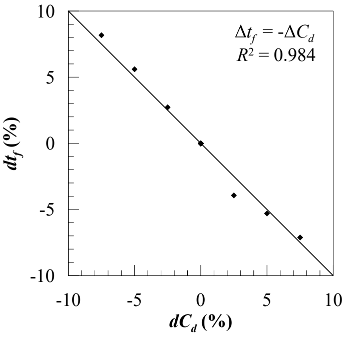

Figure 5. Effect of uncertanties on discharge coefficients on time to flood

As expected, the discharge coefficient has no effects on progressive flooding except for the time evolution. In fact, the floating position, the stability and the levels of floodwater assume the same values being shifted in time proportionally to the difference between actual and original discharge coefficient. Therefore, the percentage error on time-to-flood dt_f can be considered equal and opposite to the percentage difference in discharge coefficients dC_d applied to all the openings (Fig 5).

3.3. Initial Loading Condition

In an operative condition, often the actual displacement, the position of mass centre and the water density are not accurately defined. An uncertainty within 5% on ship weight assessed via loading instrument compared with the displacement corresponding to the measured draughts is considered acceptable. This is why the impact of the initial condition on the progressive flooding process has been herein studied.

To this end, different values of displacement Δ and hight of the centre of mass $\overline{KG}$ have been tested. The water density ρ was not analysed, since it has no influence on the progressive flooding, provided that the same initial draught is applied. Regarding the displacement, it has been increased and reduced by 2.5% and 5.0% and the results are provided in Table 7. The $\overline{KG}$ has been instead increased and reduced by a 5.0% and 10.0% and the overall results are provided in Table 8.

Table 7. Overall effect of displacement

$d\Delta$	**-5.00%**	**-2.50%**	**0.00%**	**2.50%**	**5.00%**
t_f (s)	321.25	325.25	330.50	334.25	340.75
error	-2.80%	-1.59%	-	1.13%	3.10%
$\overline{GM}_{min}$ (m)	0.0894	0.0924	0.0956	0.0990	0.1025
error	-6.54%	-3.35%	-	3.56%	7.15%
ϕ_{max} (deg)	0.727	0.655	0.629	0.609	0.572
error	15.55%	4.16%	-	-3.09%	-9.04%
s_e (m)	-0.0594	-0.0616	-0.0639	-0.0661	-0.0683
error	-6.98%	-3.49%	-	3.49%	6.99%
θ_e (deg)	1.280	1.325	1.370	1.415	1.459
error	-6.60%	-3.29%	-	3.25%	6.47%

Table 8. Overall effect of mass centre height

$d\overline{KG}$	**-10.00%**	**-5.00%**	**0.00%**	**5.00%**	**10.00%**
t_f (s)	330.75	330.50	330.50	330.50	328.50
error	0.08%	0.00%	-	0.00%	-0.61%
$\overline{GM}_{min}$ (m)	0.1219	0.1088	0.0956	0.0826	0.0696
error	27.49%	13.78%	-	-13.66%	-27.20%
ϕ_{max} (deg)	0.500	0.558	0.629	0.779	0.919
error	-20.46%	-11.27%	-	23.87%	46.07%
s_e (m)	-0.0638	-0.0638	-0.0639	-0.0639	-0.0639
error	-0.03%	-0.01%	-	0.02%	0.04%
θ_e (deg)	1.357	1.364	1.370	1.377	1.384
error	-0.94%	-0.47%	-	0.48%	0.97%

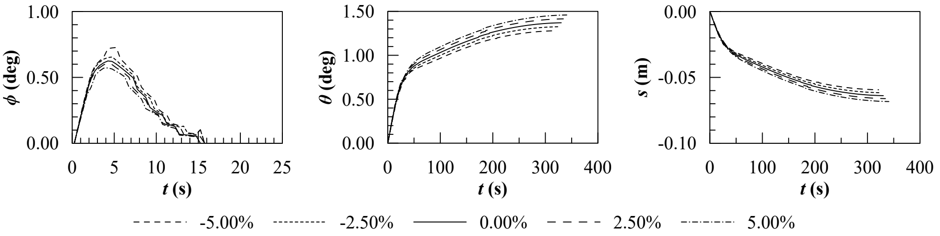

Figure 6. Effect of initial displacement on floating position

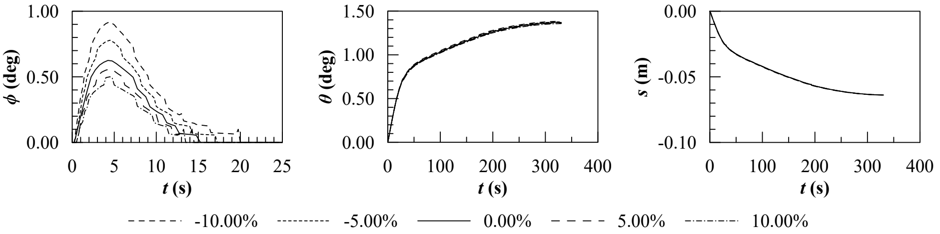

Figure 7. Effect of initial mass centre height on floating position

It can be noticed that the initial condition has a heavy impact on progressive flooding. In particular, an increased displacement causes an increment of time-to-flood, metacentric height, final draught and trim, whereas a reduction of healing angle during the transient phase is experienced. The vertical position of the mass centre has a relevant effect only on ship stability and thus also on heeling angle during the transient phase. A modest effect on trim was also observed, but it was not sufficient to cause relevant alterations on the water level inside compartments. However, it should be noted that the barge has a large value of initial $\overline{GM}$; or for less stable ships (e.g. large passenger ships) or in case of more extended asymmetric flooding scenario, $\overline{KG}$ is likely to have even a greater impact. Moreover, a low value of $\overline{KG}$ could lead to a rapid capsize, reducing drastically the time-to-flood.

4. Conclusions

The present work adopts a novel technique specifically developed for onboard simulation of progressive flooding. A sensitivity study has been carried out studying the effect of several parameters connected to damage geometry, ship geometry and loading condition at damage occurrence. The damage location appears to be relevant only in terms of the vertical position of damage centre. However, the damage geometry requires special attention, since its effect on progressive flooding process depends upon the internal geometry subdivision. In particular, as the damage size increases or a higher waterhead is applied, the effect of internal openings, connecting the damaged room to other spaces, becomes even more relevant. Further studies are advisable devoted to assessing the maximum damage size having some effect on the process as a function of room/openings geometry.

Concerning ship geometry, the permeability has not a significant effect on ship initial stability and neither on time-to-flood, which are the most important characteristics of progressive flooding process required to support decision after damage. Therefore, the application of standard values provided by regulatory bodies should not lead to critical errors on the estimation of damage scenario's final outcome. However, the permeability has an impact on the evolution of the floating position and thus, for more complex hull geometries, could reduce the ship stability too. This is why, whenever it is possible, a detailed analysis of internal volumes is recommended. Regarding discharge coefficients, they only have an influence on the time-to-flood applying a delay/advance proportional to their uncertainty.

The displacement and the height of the centre of mass have a strong influence on the progressive flooding process, leading to relevant differences on the considered overall quantities. Thus, the application of standard loading conditions (e.g. the ones included in the stability booklet) could lead to relevant errors. Finally, the sea water density has no effect on progressive flooding simulations provided that constant draughts (and the related different displacement) are applied in the initial condition. Therefore, to assure the accuracy of onboard simulations, it is always advisable to use the displacement assessed from measured draught, assuming a standard water density value.

References

[1] L. Braidotti, J. Prpić-Oršić, M. Valčić, G. Trincas, and V. Bucci. Fuzzy analytical hierarchical process to assess weights of importance in ship operation risk assessment. In *Proceedings of The 19th International Conference on Ships and Maritime Research - NAV 2018*, Trieste, Italy, 2018.

[2] P. Ruponen. Pressure-correction method for simulation of progressive flooding and internal air flows. *Ship Technology Research*, 53(2):63–73, 2006.

[3] H. Dankowski. *A Fast and Explicit Method for Simulating Flooding and Sinkage Scenarios of Ships*. PhD thesis, Technischen Universität Hamburg, Hamburg, Germany, 2013.

[4] J.M. Rodrigues and C. Guedes Soares. A generalized adaptive mesh pressure integration technique applied to progressive flooding of floating bodies in still water. *Ocean Engineering*, 110:140 – 151, 2015.

[5] P. Ruponen, M. Larmela, and P. Pennanen. Flooding prediction onboard a damage ship. In *Proceedings of the 11th International Conference on the Stability of Ships and Ocean Vehicles*, Athens, Grece, 2012.

[6] L. Braidotti and F. Mauro. A new calculation technique for onboard progressive flooding simulation. *Ship Technology Research*, (in press), 2018.

[7] F. van Walree and A. Papanikolaou. Benchmark study of numerical codes for the prediction of time to flood of ships: phase i. In *Proceedings of the 9th International workshop on Ship Stability*, Hamburg, 2007.

[8] P. Ruponen, A. Pulkkinen, and J. Laaksonen. A method for breach assessment onboard a damaged passenger ship. *Applied Ocean Research*, 64:236 – 248, 2017.

[9] G. Trincas, L. Braidotti, and L. De Francesco. Risk-based system to control safety level of flooded passenger ship. *Brodogradnja*, 68(1):31 – 60, 2017.

[10] L. Braidotti, G. Trincas, and V. Bucci. Analysis of the influence of pressure field on accuracy for onboard stability codes. In A. Marinò and V. Bucci, editors, *Proceedings of The 19th International Conference on Ships and Maritime Research - NAV 2018*, Trieste, 2018.

[11] P. Ruponen. *Progressive flooding of a damaged passenger ship*. PhD thesis, Helsinki University of Technology, Helsinki, 2007.

[12] C.D. Wood, D.A. Hudson, M. Tan, A.J. Sobey, and Y. Wang. Experimental investigation into factors affecting the transient flow of fluid through an orifice in realistic conditions. *Transactions of the Royal Institution of Naval Architects. Part A: International Journal of Maritime Engineering*, 158(3):1–12, 2016.

[13] P. Ruponen, P. Kurvinen, I. Saisto, and J. Harras. Experimental and numerical study on progressive flooding in full-scale. *International Journal of Maritime Engineering*, 152(A4):197–208, 2010. VK: T20404.