Fast Estimation of the Time-to-Flood on Simple Geometries

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Abstract. I corrected the abstract and conclusion a bit: Time-to-flood is a key parameter during a flooding emergency. Especially in complex geometries, it is important to know the time needed to fill the first flooded room, i.e., the damaged one. Here, a fast solution for the assessment of the time-to-flood of one or two parallelepiped rooms is proposed. The progressive flooding of the rooms is first simulated employing a linearised simulation technique that defines a database of damage cases covering a wide range of geometries. Explicit equations are then defined based on the main non-dimensional parameters governing the phenomenon. The work highlights the relationship between the geometry of a room, the damage opening, the connection opening, and the time to fill the first damaged room. The application of the equations is very fast and provides an instantaneous estimation of the time-to-flood. This makes them particularly suitable for direct application on board or when creating large datasets of flooding simulations.

Keywords. progressive flooding, time-to-flood, linearised simulation, explicit equations

1. Introduction

As a consequence of a collision or grounding, the ship's integrity might be compromised leading to progressive flooding. Due to the dimension and location of the damage and the complexity of the internal subdivision, the progressive flooding might last from a few seconds up to several hours. During a flooding emergency, the knowledge of the time-to-flood, i.e. the duration of the progressive flooding is widely recognised as key information for the crew [1]. In the recent past, several studies addressed the fast progressive flooding simulation in the time domain, e.g. [2,3,4,5], with the purpose to provide decision support on a damaged ship [6,7,8,9,10].

Besides the duration of the whole progressive flooding of a damaged ship, which is essential for emergency decision support purposes [11], it might be very useful to predict the time required to fill the damaged rooms that constitute the first item of the flooding chain. For instance, such a kind of information might be used to detect the damage dimension onboard [12] or to allow the definition of boundaries in the databases generation of progressive flooding simulations [13].

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To address these problems, in the present paper, the time frame is studied considering the progressive flooding of simple geometries. In detail, explicit equations are derived to predict the filling time of a parallelepiped room based on a large number of progressive flooding simulations. Then, a correction factor is defied to consider the effect of a second room connected to the first one. This approach might be easily applicable to modern ships such as cruise vessels, bulk carriers or tankers, where most of the internal rooms are shaped as parallelepipeds except for aft and fore slender bodies.

2. Material and Methods

In the present section, the mathematical formulation of the studied problems is defined distinguishing the one-room case and the two-rooms case. Both the problems are treated in a non-dimensional form to make the results independent from the scale of the considered geometries and enable a wider application of the results. Then, the adopted progressive flooding simulation technique is briefly outlined, along with the adopted optimisation method used to assess the coefficients of the explicit equations that best fits the results of the progressive flooding simulations.

2.1. Problem Definition

Considering a parallelepiped room in upright position (Fig. 1) and assuming that its position does not change during flooding process, it can be defined a non-dimensional time-to-flood t_a to make the progressive flooding process independent from the room dimension as:

$$t_a = t_f \sqrt{\frac{g}{z_b}} = f\left(\frac{z}{z_b}, \frac{A}{S}\right) \tag{1}$$

where t_f is the time-to-flood measured in seconds, g is the gravity constant and z_b is the draught of the room bottom measured in earth fixed reference system having vertical axes z orthogonal to the free surface and positive upwards. The non-dimensional time-to-flood can be expressed as a function of two non-dimensional quantities: z/z_b and A/S, where z is the draught of damage centre, A its effective area including the reduction due to discharge coefficient C_d and S is the waterplane area in the flooded room, which is constant when considering a fixed parallelepiped room.

In the present study, the two-rooms case (Fig. 1) is composed of two parallelepiped rooms having the bottom at the same level. The first flooded room is connected with the

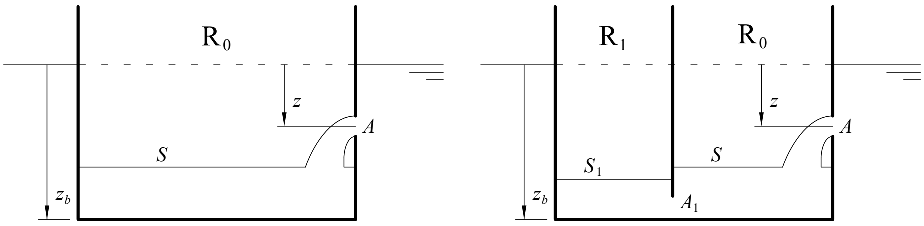

Figure 1. Sketch of the adopted one-room (R_0) and two-rooms (R_0, R_1) geometries

second one through an opening having area A_1 and being located on the floor of the first flooded room. Moreover, It is assumed that the second room has a constant free surface area equal to S_1.

With these assumptions, the Equation (1) can be used to evaluate the time-to-flood $t_{a_{min}}$ of the first room volume and $t_{a_{max}}$, i.e. the one related to the sum of the two rooms volumes. The filling time of the first room t_a in the two-rooms case cannot be lower than the time-to-flood $t_{a_{max}}$ related to the single room and cannot be lower than one-room case one $t_{a_{min}}$ and cannot be larger than the one required to fill a parallelepiped room having free surface equal to $S+S_1$. Thus, the following equation shall be satisfied:

$$t_{a_{min}} = f\left(\frac{z}{z_b}, \frac{A}{S}\right) \leq t_a \leq t_{a_{max}} = f\left(\frac{z}{z_b}, \frac{A}{S+S_1}\right) \tag{2}$$

Hence, a correction factor c_t can be defined as:

$$c_t = \frac{t_{a_{min}}}{t_a} = f_1\left(\frac{A_1}{A}, \frac{S_1}{S}\right) \tag{3}$$

where t_a is related to the time-to-flood of the first room connected to the second room. The correction factor has unitary value if one of the two parameters is null, otherwise it assumes values within the range $[1,0[$. Finally, if $A_1/A \to \infty$, the correction factor is:

$$c_{t_\infty} = t_{a_{min}}/t_{a_{max}} \tag{4}$$

2.2. Simulation Method

In the present work, the simulations on the considered simple geometries are carried out using a linearised method [14] applying an adaptive integration time step [15]. In the following, the method is briefly described. The progressive flooding process is governed by the conservation of mass applied to each room and the steady Bernoulli equation applied on all the openings connecting two rooms or a room to the sea. Considering an i-th room connected to other j rooms by N_i openings the governing equations are:

$$\dot{z}_i S_i \approx \dot{V}_i = \sum_{j=1}^{N_i} Q_{ji} \tag{5a}$$

$$Q_{ji} = K_{ji}\,\mathrm{sgn}\,(z_j - z_i)\sqrt{|z_j - z_i|} \tag{5b}$$

where Q_{ji} is the volumetric flowrate through an opening connecting j-th to i-th rooms, $\dot{V}_i$ is the time derivative of the floodwater volume inside the i-th room, S_i its waterplane area, z_i the level of floodwater in the earth-fixed reference system, $K_{ji} = A_{ji}\sqrt{2g}$ is a constant depending upon opening geometry and A_{ij} is the effective opening area (properly reduced via discharge coefficient).

Considering a generic time instant t^*, when n rooms are partially filled with levels $\mathbf{z}^*$ and combining the equations (5a) and (5b), a system of non-linear ordinary differential equations can be written as:

$$\dot{\mathbf{z}} = f(\mathbf{z}) \tag{6}$$

As a level perturbation $\mathbf{z}' = \mathbf{z} - \mathbf{z}^*$ is defined, the system can be linearised in $\mathbf{z}^*$:

$$\dot{\mathbf{z}}' = \mathbf{J}(\mathbf{z}^*)\mathbf{z}' + f(\mathbf{z}^*) \tag{7}$$

where $\mathbf{J}$ is the Jacobean matrix of $f(\mathbf{z})$ evaluated in $\mathbf{z}^*$. According to [14], the Jacobean matrix can be decomposed through the single value decomposition as $\mathbf{J}(\mathbf{z}^*) = \mathbf{V} \times \mathbf{D} \times \mathbf{V}^{-1}$. Thus, introducing $\mathbf{u} = \mathbf{V}^{-1}\mathbf{z}'$, the Equation 7 becomes:

$$\dot{\mathbf{u}} = \mathbf{D}\mathbf{u} + \mathbf{V}^{-1} f(\mathbf{z}^*) \tag{8}$$

where $\mathbf{D}$ is a diagonal matrix. Therefore, the differential equations of the system (8) are decoupled obtaining an algebraic solution in the form:

$$z_i = z_i^* + \sum_{j=1}^{n} \frac{V_{ij} v_j \left(e^{D_{jj}(t-t^*)} - 1\right)}{D_{jj}} \tag{9}$$

The solution can be used to estimate the floodwater levels at the next time step dt, which is adapted at each step according to:

$$\mathrm{d}t = k_{\mathrm{d}t} \frac{z_b}{\max \dot{\mathbf{z}}^*} \tag{10}$$

where $k_{\mathrm{d}t}$ is a constant quantity governing the integration accuracy. Here, it is assumed equal to 0.01 based on an experimental tuning [15].

2.3. Definition of Coefficients

The explicit equations have been defined in order to reproduce the shape of the t_a and c_t obtained through the flooding simulations carried out on the tested geometries. Given an equation under investigation, it can be defined according to some coefficients $\mathbf{a}$. For each set of coefficients, it can be assessed the Sum of Squared Errors SSE as:

$$SSE(\mathbf{a}) = \sum_{i=1}^{N} \left(y_i - y_i^*(\mathbf{a})\right)^2 \tag{11}$$

where N is the number of progressive flooding simulations, y_i is the value of t_a or c_t estimated according to the i-th progressive flooding simulation and y_i^* is the value estimated with the explicit equation under analysis.

The coefficients are, then, defined as the ones minimising the SSE. The minimum is found using the Nelder-Mead simplex algorithm in the form defined by [16] assuming 10000 maximum iterations number and a proper set of initial guess values for the coefficients of the explicit equation.

The overall quality of the obtained equations is also reported in terms of coefficient of determination R^2, defined as:

$$R^2 = 1 - \frac{SSE}{\sum_{i=1}^{N} (y_i - \bar{y})^2} \tag{12}$$

where $\bar{y}$ is the data point mean value.

3. Application

In the following, the obtained explicit equations for the one- and two-rooms cases are presented along with the obtained values of the coefficients. The form of the equations has been inferred from a preliminary analysis of the progressive flooding simulations results, in order to best fit the simulated values. Then, coefficients values have been defined according to Section 2.3.

3.1. One-Room Case

To define the explicit equation for t_a in the one-room case, 10000 progressive flooding simulations have been carried out with z/z_b and A/S randomly selected in $]0,1[$ range through the Monte Carlo method. The equation that best fits the records reads:

$$\begin{aligned} \frac{1}{t_a} =& a_0 + a_1 \ln\frac{z}{z_b} + a_2 \left(\ln\frac{z}{z_b}\right)^2 + a_3 \left(\ln\frac{z}{z_b}\right)^3 + a_4 \left(\ln\frac{z}{z_b}\right)^4 \\ &+ \frac{A}{S}\left[a_5 + a_6 \ln\frac{z}{z_b} + a_7 \left(\ln\frac{z}{z_b}\right)^2 + a_8 \left(\ln\frac{z}{z_b}\right)^3\right] \end{aligned} \tag{13}$$

Using the coefficients provided in Table 1, an $R^2 = 0.9999$ has been obtained. Figure 2 shows the results of the explicit equation for the one-room case.

Table 1. Coefficients of multivariate regression for single room geometry

a_0	a_1	a_2	a_3	a_4
-3.21E-03	-2.45E-02	-3.10E-02	-1.28E-02	-1.64E-03
a_5	a_6	a_7	a_8	
7.88E-01	3.75E-02	-8.39E-02	-1.40E-02	

3.2. Two-Rooms Case

Considering the two-rooms case, in a preliminary analysis it was observed that, taken a generic S_1/S value, $c_t = 1$ for $A_1/A = 0$. As $A_1/A = 0$ grows, c_t decreases fast reaching a local minimum, than c_t slightly increases up to an horizontal asymptote. As previously mentioned, for $A_1/A \to \infty$, $c_t \to c_{t_\infty}$.

It is worth noticing that, for the considered two-room geometry, the position of the minimum is independent by the value of S_1/S. Thus, two different approaches have been adopted to mimic the c_t before and after the minimum. To define the explicit equations, 20 values of S_1/S have been separately investigated ranging between 0 and 40. For each value 10000 progressive flooding simulations have been carried out. The damage cases

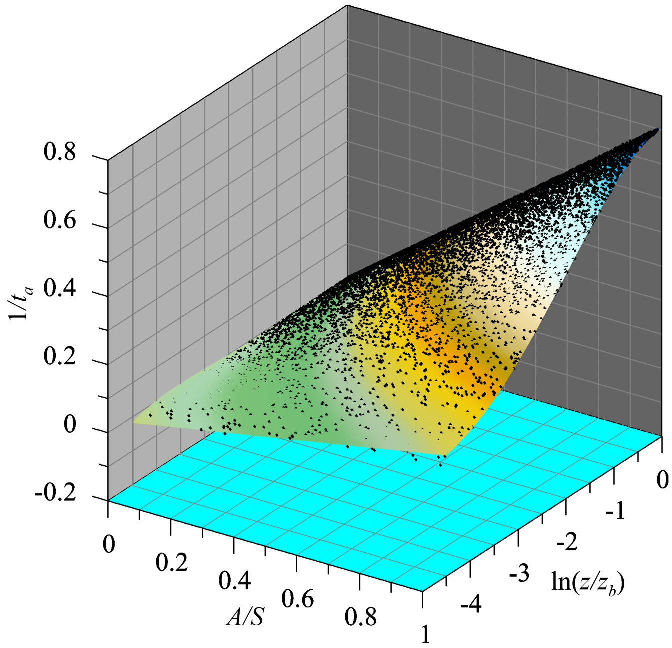

Figure 2. Comparison of the surface resulting from the equation and the simulated points in the one-room case

have been generated with Monte Carlo sampling assuming z/z_b and A/S in $]0,1[$ range and A_1/A in $]0,2]$ range. As the simulated c_t values have been defined, the position of the minimum of c_t as been computed as $(A_1/A)_{min} = 0.2024$. Furthermore, the value of the minimum can be estimated with the following explicit equation (coefficients provided in Table 2) based on the 20 values of S_1/S, having $SSE = 2.39E-04$ and $R^2 = 0.9998$:

$$c_{t_{min}} = 1 + a_1 \exp\left[-b_1\left(\frac{S_1}{S}\right)^{c_1}\right] + a_2 \exp\left[-b_2\left(\frac{S_1}{S}\right)^{c_2}\right] - a_1 - a_2 \tag{14}$$

Table 2. Coefficients of multivariate regression for $c_{t_{min}}$

a_1	b_1	c_1	a_2	b_2	c_2
5.38E-01	2.02E+00	1.27E+00	4.46E-01	6.80E-01	6.87E-01

In the range $A_1/A = [0,(A_1/A)_{min}]$, considering the Equations (4) and (14), the correction factor has been estimated with a 7^{th}-order Fourier expansion passing through (0,1) and the minimum point:

$$c_t\left(\frac{A_1}{A},\frac{S_1}{S}\right) = 1-(1-c_{t_{min}})\left[a_1\sin\left(\omega\frac{A_1}{A}\right)+a_2\sin\left(3\omega\frac{A_1}{A}\right)+ + a_3\sin\left(5\omega\frac{A_1}{A}\right)+a_4\sin\left(7\omega\frac{A_1}{A}\right)\right] \tag{15a}$$

$$
\begin{aligned}
a_1\left(\frac{S_1}{S}\right) &= a_{11}\exp\left[-a_{12}\left(\frac{S_1}{S}\right)\right]+1-a_{11}+a_{13}\left(\frac{S_1}{S}\right)^{a_{14}-1}\exp\left[-a_{15}\left(\frac{S_1}{S}\right)^{a_{14}}\right]\\
a_2\left(\frac{S_1}{S}\right) &= a_{21}\exp\left[-a_{22}\left(\frac{S_1}{S}\right)^{a_{23}}\right]-a_{21}\\
a_3\left(\frac{S_1}{S}\right) &= \min\left(0,\, a_{31}\exp\left[-a_{32}\left(\frac{S_1}{S}-a_{33}\right)\right]-a_{31}\right)\\
a_4\left(\frac{S_1}{S}\right) &= a_1\left(\frac{S_1}{S}\right)-a_2\left(\frac{S_1}{S}\right)+a_3\left(\frac{S_1}{S}\right)-1\\
\omega &= \frac{\pi}{2\left(\frac{A_1}{A}\right)_{min}}
\end{aligned}
\tag{15b}
$$

The values of the coefficients have been defined with a two-step approach. First, the coefficients a_1, a_2, a_3 have been evaluated to fit the simulated values of c_t at each constant value of S_1/S. Then, the methodology described in Section 2.3 has been again applied to obtain explicit equations to compute the coefficients a_1, a_2, a_3 as a function of S_1/S. The results are provided in Table 3 along with the obtained SSE and R^2.

Table 3. Coefficients of multivariate regression up to $(A_1/A)_{min}$

i	a_{i1}	a_{i2}	a_{i3}	a_{i4}	a_{i5}	SSE	R^2
1	3.46E-02	2.76E+00	-1.65E-01	1.32E+00	3.90E-01	1.80E-03	9.71E-01
2	2.07E-01	2.24E+00	1.45E+00	-	-	0.0007	0.9850
3	1.15E-01	3.71E-01	9.01E-01	-	-	0.0013	0.9311

In the range $A_1/A =](A_1/A)_{min}, 2]$, a process has been applied similar to the previous one. In this region the following formulation of the explicit equation has been defined:

$$
\begin{aligned}
c_t\left(\frac{A_1}{A}, \frac{S_1}{S}\right) &= (c_{t_\infty}-c_{t_{min}})\arctan\left(\frac{2a}{\pi}\frac{A_1}{A}\right)-c_{t_{min}}\\
a\left(\frac{S_1}{S}\right) &= a_1\left(\frac{S_1}{S}\right)^{-a_2}+a_3\left(\frac{S_1}{S}\right)^{-a_4}+a_5
\end{aligned}
\tag{16}
$$

Such a formulation imposes the passage through the minimum point with a horizontal tangent, assuring the continuity of the function and its first derivative, and presents the horizontal asymptote at c_{t_∞} value. The explicit equation, assuming the coefficients provided in Table 4, lead to $SSE = 0.8644$, $R^2 = 0.9998$.

Table 4. Coefficients of multivariate regression above $(A_1/A)_{min}$

a_1	a_2	a_3	a_4	b_5
1.34E-06	1.22E+01	9.79E+00	9.57E-01	1.67E+00

3.3. Discussion

Considering the one-room case, the proposed equation captures very well the behaviour of the non-dimensional time-to-flood. In detail, $1/t_a$ is a linear function of A/S. The slope and intercept of this linear relation is a function of the natural logarithm of the z/z_b. In detail, third- and fourth-order polynomials provide good results for the slope and intercept respectively. The ranges of the equation's parameters cover all the possible configurations that might arise in a real environment.

Regarding the two-rooms case, it has been studied in terms of correction coefficient c_t. In Figure 3, the results from the simulations and derived equations are compared for three different values of S_1/S. It is worth noticing that the proposed equations reproduce well the simulated values of c_t. Considering the corrected t_a obtained by reversing Equation (3), the maximum value is always located at $(A_1/A)_{min}$. The relative dimension of the rooms, expressed by the ration S_1/S, only affects the magnitude of the maximum, i.e. the non-dimensional time-to-flood increases with S_1/S. Regarding the ranges of the

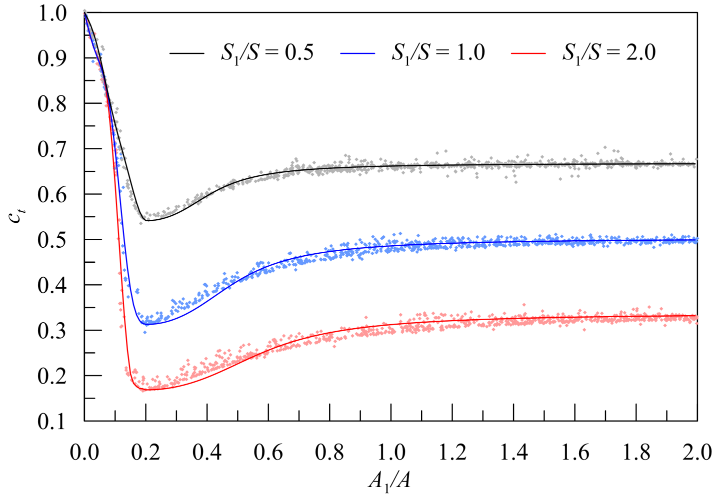

Figure 3. Comparison of the results from explicit equations and the simulated points in the two-rooms case

equations' parameters, it is worth to notice that the considered range of A_1/A up to 2 is sufficient to allow the function tail to converge towards c_{t_∞}, as can be seen in Figure 3. The chosen range of S_1/S up to 40 lead to a value of $c_{t_{min}} = 1.54E-2$, which is very close to the theoretical $\lim_{S_1/S \to \infty} c_{t_{min}}(S_1/S) = 1.53E-2$. It was observed that further increasing S_1/S does not change significantly the results of the progressive flooding simulations.

4. Conclusions

This study provides a better understanding of the physical basis of the phenomenon of progressive flooding. In the case of a single-room case, it is possible to understand the connection between the main non-dimensional quantities describing the geometry and the non-dimensional time-to-flood. This approach makes the developed model independent from the scale of the studied problem.

Moreover, the applicability of the model in the case of two rooms can be extended in a very simple way by considering only some additional parameters. Thus, the two models together ensure instantaneous estimation of the time-to-flood for a very wide range of cases, which are very common in the subdivision of real ships.

In the present work, the flooded rooms were assumed to extend vertically above the waterline. Thus, it cannot deal with spaces that are vertically bounded by an upper deck below the waterline. Since this is the case on many cruise ships, future work could address such cases by introducing a new correction coefficient. This could greatly extend the applicability of the explicit equations derived in this study to a wider range of geometries.

Acknowledgements

This work was fully supported by the Croatian Science Foundation under the project IP-2018-01-3739.

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