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A Comparison of Different Linearized Formulations for Progressive Flooding Simulations in Full-Scale

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Abstract

In the framework of Industry 4.0, simulation plays a key role in processing sensors data to predict the future behaviour of a complex system. Aiming to increase ship efficiency and safety, simulations can be used in normal conditions but also during an emergency. In this context, progressive flooding simulations can be applied onboard large passenger ships to support master decisions after a collision or grounding casualty. Among the methods present in literature, the techniques based on linearized differential equations have been recently proposed and tested in model-scale. Here, the effects of three different linearized techniques are studied on a large passenger ship. The main issues connected to different mathematical formulations are highlighted, to enhance the reliability of the onboard progressive flooding simulation and better exploit data collected by sensors to increase ship safety in the framework of Shipping 4.0.

Keywords: Progressive flooding simulation; Quasi-static; Linearized differential equations; Shipping 4.0

1. Introduction

The technologies encompassed by Industry 4.0 are expected to play a primary role in the future development maritime industry [1]. Digitalization is affecting all the sector ranging from ship design and construction [2] to

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shipping operations [3]. Industry 4.0 paradigm helps to move towards safer and more efficient vessels [4] thanks to the improved data collection, sharing and analyses capability [5]. In this environment, new digital technologies can help to improve the vessel automation [6], the fleet monitoring capabilities [7] and the prediction capability. Ship cohesive digital twin is becoming reality [8] by exploiting the data from sensors to increase ship safety and resilience by predicting its future state through the application of simulation techniques. Simulation is, in fact, one of the most significant Industry 4.0 enabling technologies. Simulation is essential not only during normal operations but can play an even more important role in emergencies. Thanks to Shipping 4.0 technologies, the consequences of a failure or a casualty can be forecasted to help the crew or the shipping company management in mitigating the risk for the crew, passengers and the ship itself. Hence, simulation-based scenarios improve ship safety by supporting critical decisions, such as the ship abandonment.

In this contest, one possible application is the response to a flooding emergency [9]. Data collected by onboard smart sensors can allow early damage detection [10, 11]. Then, the damage turns into the input condition for fast simulation algorithms capable to predict the progressive flooding of the ship in the time domain. These tools are of the utmost importance, especially on large passenger vessels. Such ships are fitted with very complex internal subdivision within the main watertight compartments and above the bulkhead deck. This complexity makes it hard to predict the final state (new equilibrium, capsize or foundering) and the time-to-flood of a given damage scenario without carrying out a simulation. Moreover, the status of internal non-watertight openings (especially B2 class fire doors) can have a very strong influence on the progressive flooding process introducing an additional challenge for time-domain predictions [12]. Hence, simulations shall be based on the actual opening status defined again with sensors, which could be changed to gain time or reduce ship heeling. In this context, the onboard simulation codes shall provide sufficiently accurate predictions, but, to be effective, the results shall be available to the decision-maker as early as possible after damage occurrence. For this reason, only quasi-static procedures have been directly applied onboard, since even the fastest dynamic methods still require too much computational effort [13]. Recently, a novel simulation technique has been proposed, based on the linearization of progressive flooding governing equations [14]. The methodology has been further improved through the application of a differential-algebraic formulation of the problem and through the application of an adaptive time step [15]. However, the validation has been performed only in model-scale and a comparison of the different proposed linearized formulation is lacking in full-scale.

The present work explores the effect of different linearized formulations on a large passenger vessel. The comparison is carried out on a significant test case including two watertight compartments in the forebody of the ship characterised by non-wall-sided hull forms and a quite large number of internal rooms and connections. Thus, the study allows to better understand the issues which might affect the reliability of linearized progressive flooding simulations in a very complex full-scale geometry. Hence, the progressive flooding simulation is here studied, being the base for properly exploiting smart sensors data and enabling further analysis of the emergency scenario in the framework of Shipping 4.0.

2. Materials and Methods

In the present study three different linearized formulations have been considered to model the progressive flooding process:

- Linearized Ordinary Differential Equation (LODE);
- Linearized Ordinary Differential Equation with Grouping of completely filled rooms (LODEG);
- Linearized Differential-Algebraic Equations (LDAE).

As mentioned, the three methods have been developed for direct onboard application where a fast response is extremely important, justifying the adoption of simplified formulations [16]. Hence, the methods are quasi-static, the sea free surface and the waterplanes inside flooded rooms are assumed flat and parallel. The following conservation of mass and conservation of momentum based on the steady Bernoulli equation have been adopted [15]:

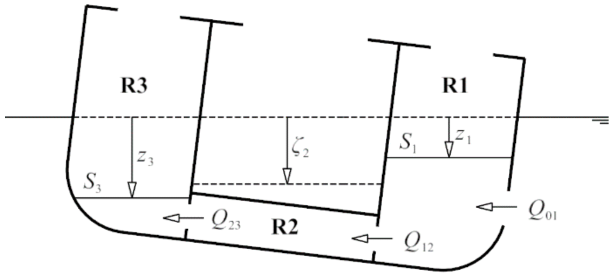

Fig. 1. Sketch of a simple three rooms geometry [15].

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

$$Q_{ji} = C_{dji} A_{ji} \, \mathrm{sgn}(\hat{z}_j - \hat{z}_i) \sqrt{2g \, | \hat{z}_j - \hat{z}_i |} \tag{2}$$

with:

$$\hat{z}_j = \max\left(z_j, z_{ji,min}\right) \tag{3}$$

where z_i, μ_i and S_i are the floodwater level (vertical distance from sea free surface), the permeability and the waterplane area in the i-th flooded room respectively, whereas Q_{ji}, C_{dji}, A_{ji} and $z_{ji,min}$ are the volumetric flowrate through opening connecting i-th and j-th rooms, its discharge coefficient, its effective area and the distance of its lower edge from sea free surface (Fig. 1).

The integration process is based on an adaptive time step dt that is a function of water level derivatives. Here, a non-dimensional coefficient k = 0.005 is applied for the time step computation [15]. At each iteration, a maximum time step is also evaluated to avoid late detection of new flooded rooms as well as too fast changing in ship's floating position, which is assumed as constant over a single time step. The simulation process is interrupted in case of ship capsize, foundering or if a new equilibrium position has been reached. The thresholds applied for the stopping algorithm are provided in Table 1.

Table 1. Applied thresholds of the stopping algorithm.

Description	Bounded Value	Threshold
Heel angle	$\vert \phi_n - \phi_{n-1} \vert / \mathrm{d}t$	0.00050 deg/s
Trim angle	$\vert \theta_n - \theta_{n-1} \vert / \mathrm{d}t$	0.00005 deg/s
Mean Draught	$\vert T_n - T_{n-1} \vert / (T_0 \mathrm{d}t)$	0.00001 1/s
Level	z_i / T_0	0.0001

2.1. LODE formulation

Combining Equations (1), (2) and (3) an ODE system can be obtained in the form:

$$\dot{\mathbf{z}}(t - t^*) = \widetilde{f}(\mathbf{z}(t - t^*)) \tag{4}$$

where t^* is a generic initial time instant during the progressive flooding simulation. The system can be linearized in order to obtain an algebraic solution, which predicts the floodwater level evolution in time domain [14] in the form:

$$z_i(t-t^*) = z_i(t^*) + \sum_{j=1}^{n} \frac{V_{ij} v_j \left(e^{D_{jj}(t-t^*)} - 1 \right)}{D_{jj}} \tag{5}$$

where **D** and **V** can be obtained applying the single value decomposition on the Jacobian matrix of the system (4):

$$\mathbf{J}_{\tilde{f}} = \mathbf{V} \times \mathbf{D} \times \mathbf{V}^{-1} \tag{6}$$

and

$$\mathbf{v} = \mathbf{V}^{-1} \tilde{f}(\mathbf{z}(t^*)) \tag{7}$$

The LODE formulation intrinsically assumes that all the flooded rooms are not completely filled. In fact, when a room is filled, the waterplane area S_i should be null. In a first approximation, it can be assumed equal to the room's top area and kept constant after the room's filling. However, in this case, the conservation of mass is no longer satisfied for the filled rooms.

2.2. LODEG formulation

A viable solution to reduce the inconsistencies coming from ODE assumption is represented by the grouping of completely filled rooms [14]. In such a case, when a room is filled, it is removed from the system of equations and grouped with the previous one in the flooding chain. Hence, in the subsequent steps of the simulation, the rooms previously connected to the filled one are connected with the group, which is modelled by means of a single level z_i, waterplane area S_i and mean permeability μ_i.

This approach also reduces the dimension of the system, leading to a slightly faster assessment of the next step levels. However, it neglects the pressure loss on the opening connecting the two grouped rooms, that might be non-negligible, especially when the openings have the same shape and dimension (as likely happens in large passenger ships, where standard fire doors are fitted within a watertight compartment).

2.3. LDAE formulation

In order to consider all the internal rooms independently, including the completely filled ones, it is necessary to change the problem formulation. Considering *m-n* filled rooms, the related left terms in equation (4) are null. Hence the ODE system becomes a DAE system [15]:

$$\begin{cases} \dot{\mathbf{z}}(t-t^*) & = & f(\mathbf{z}(t-t^*), \boldsymbol{\zeta}(t-t^*)) \\ \mathbf{0} & = & g(\mathbf{z}(t-t^*), \boldsymbol{\zeta}(t-t^*)) \end{cases} \tag{8}$$

where ζ_i is the waterhead inside the *m-n* completely filled rooms expressed as height of water column (Fig. 1). The differential part of the system (8) can be still linearized and solved separately according to the process exposed in Section 2.1, keeping constant the waterheads $\boldsymbol{\zeta}$. Once the levels $\mathbf{z}(t+\mathrm{d}t)$ have been defined, the waterheads can be evaluated by solving in $\boldsymbol{\zeta}$ the algebraic part of the system (8). Here, the system is solved by means of Levenberg-Marquardt algorithm.

2.4. Internal openings modelling

The discharge coefficient C_d of all the internal connections is assumed constant and equal to 0.6 [17]. Some additional assumptions are necessary to model the closable openings. In fact, when a non-watertight opening is closed and subject to a waterhead z_{ji} its effective area A_{ji} should be properly reduced. The area is assumed null for $z_{ji} < z_l$, being z_l the leakage minimum waterhead. During leakage, the opening area is modelled according to [18] as:

$$A_{ji} = A_{ji,o}\left(\alpha_{ji} + \beta_{ji}\left|\hat{z}_j - \hat{z}_i\right|\right) \tag{8}$$

where $A_{ji.o}$ is the area of the open connection whereas α and β are two coefficients related to the opening type and waterflow direction (into, out). Under a critical effective waterhead, a closed opening might collapse. Means that the effective area is assumed to equal $A_{ji.o}$ for $z_{ji} < z_c$, where z_c is the collapse waterhead. The applied coefficients and critical waterheads are reported in Table 2 for Hinged (B2 H) and Double Leaf (B2 DL) fire doors [18] and for Elevator (E) doors [19].

Table 2. Assumed leakage and collapse particulars for closed opening modelling.

Particular		E	B2 H	B2 DL	Particular		E	B2 H	B2 DL
α into	(-)	0.090	0.000	0.025	z_l into	(m)	0.000	0.000	0.000
α out	(-)	0.090	0.000	0.025	z_l out	(m)	0.000	0.000	0.000
β into	(1/m)	0.000	0.020	0.000	z_c into	(m)	1.000	2.500	2.000
β out	(1/m)	0.000	0.030	0.000	z_c out	(m)	1.000	2.500	2.000

3. Test Case

The three methods have been applied on a large cruise ship in a significant area in order to study the behaviour of different simulation methods. In the present section, the modelling assumptions are presented together with the selected damage scenario.

3.1. Cruise ship model

The test ship is a large cruise vessel having the main characteristics reported in Table 3. The ship has 21 watertight compartments arranged in 7 main vertical zones. Figure 2b shows a sketch of the general arrangement of the test ship. The ship hull and internal rooms are modelled by means of non-structured meshes (e.g. Fig. 2b) in order to apply an in-house built hydrostatic code based on pressure integration to evaluate the ship floating positions and the water volumes inside flooded rooms [20].

Table 3. Test ship main particulars in intact condition.

Particular	Symb.	Value		Particular	Symb.	Value	
Length between perp.	L_{BP}	285.380	m	Displacement	Δ	57760.68	t
Length overall	L_{OA}	315.600	m	Long. centre of mass	LCG	130.380	m
Beam	B	36.700	m	Trans. centre of mass	TCG	0.000	m
Draught	T	8.300	m	Vertical centre of mass	VCG	18.840	m
Depth	D	11.200	m	Metacentric height	GM	2.109	m
Volume	∇	56351.88	m^3				

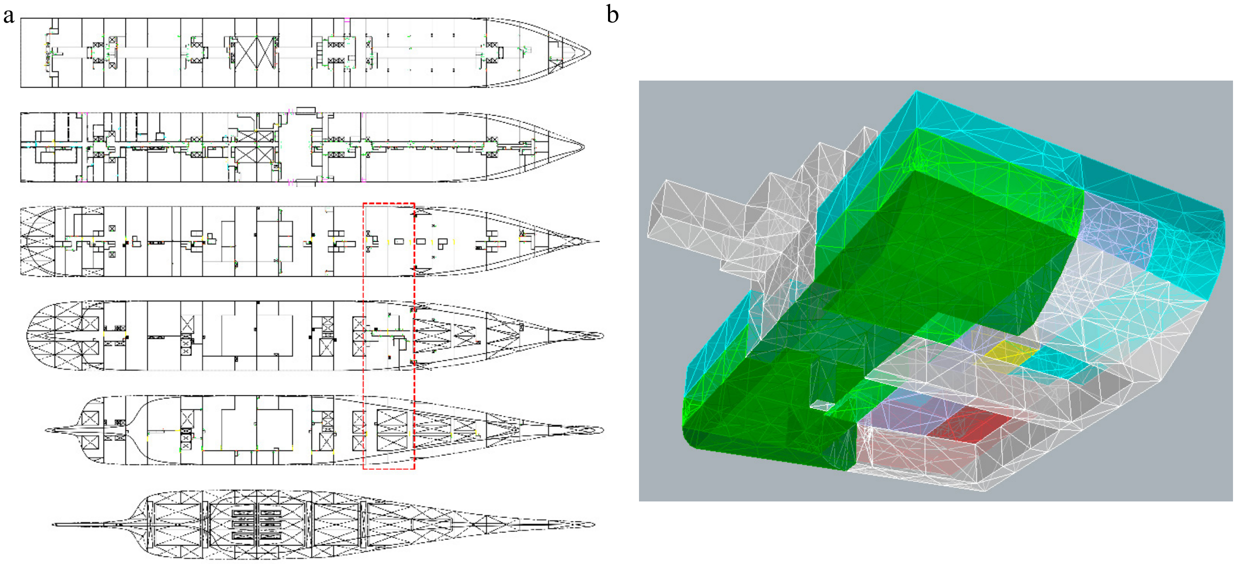

Fig. 2. (a) Test ship general arrangement; (b) 3D model of CMP14 and CMP15.

3.2. Damage Scenario

Here one damage scenario has been analysed. A medium-size damage located on starboard side affects two consecutive watertight compartments (CMP14 and CMP15). In these compartments three decks are fitted under the bulkhead deck: D -1 (8.4 m above B.L.), D-2 (5.6 m above B.L.) and D -3 (2.2 m above B.L.). At the lower deck are located the sewage treatment room and one void space, embracing three freshwater tanks. The tanks are not included in the model, being watertight and intact (since are inside B/5 line). Above the main laundry and housekeeping spaces are arranged to create a very complex internal subdivision interconnected by two corridors. On D -1 in both compartments are fitted crew accommodation. A complete list of internal spaces is provided in Table 4 including the room capacity V_e and its permeability μ. Finally, Figure 3 shows a detail on the internal arrangement in CMP 14 and CMP15.

Table 4. List of the test ship flooded rooms in CMP 14 and CMP 15

Id	Type	V_e (m3)	μ (-)	Id	Type	V_e (m3)	μ (-)
E1401	VOID	55.026	0.95	R1501	VOID	476.942	0.95
E1402	VOID	55.026	0.95	R1502	VOID	105.296	0.95
R1401	MACHINERY	695.207	0.85	R1503	VOID	71.209	0.95
R1402	VOID	64.798	0.95	R1504	ACCOMODATIONS	228.328	0.95
R1403	VOID	428.501	0.95	R1505	MACHINERY	27.608	0.85
R1404	MACHINERY	445.699	0.85	R1506	ACCOMODATIONS	180.238	0.95
R1405	MACHINERY	408.543	0.85	R1507	ACCOMODATIONS	57.855	0.95
R1406	STORES	10.231	0.60	R1508	ACCOMODATIONS	124.042	0.95
R1407	ACCOMODATIONS	1016.614	0.95	R1509	STORES	206.080	0.60
T1401	VOID	10.576	0.95	R1510	ACCOMODATIONS	1100.951	0.95

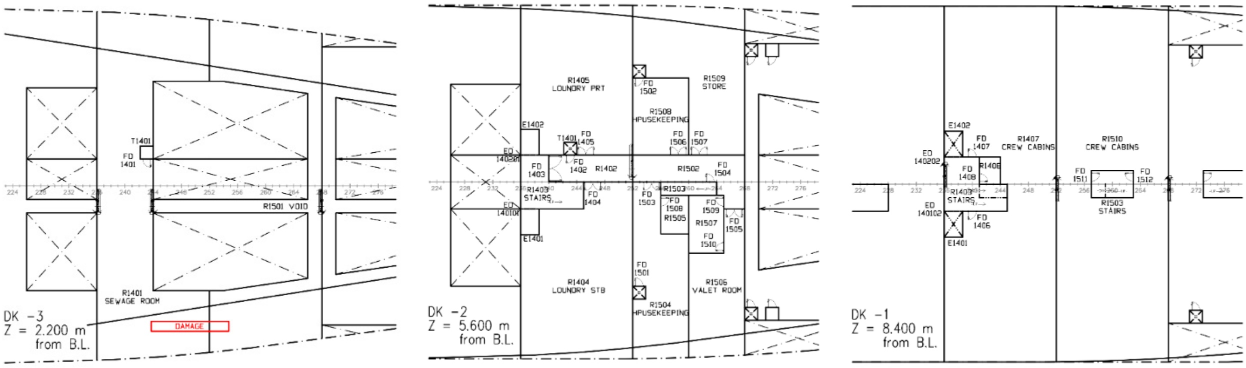

Fig. 3. Detail of the general arrangements in damaged compartments (CMP14 and CMP15).

4. Results and Discussion

The simulated flooding scenario lasts about four hours but it is characterised by a fast pace during the first 20 minutes and very slow propagation of floodwater on the upper deck due to the closed doors FD1408 and FD1504, which withstands the waterhead without collapsing. The relevant events (leakage, collapse of non-watertight openings and free outflow through open openings) are summarised in Table 5. Figures 4 and 5a show the time evolution of heel, trim and sinkage, during the initial phase of progressive flooding.

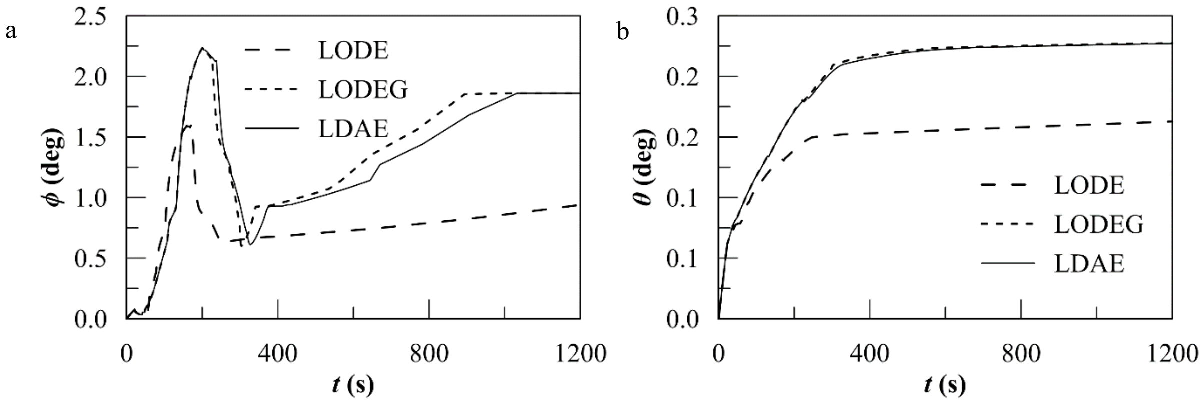

Fig. 4. Comparison of heel angle (a) and trim (b) simulation with the three methods.

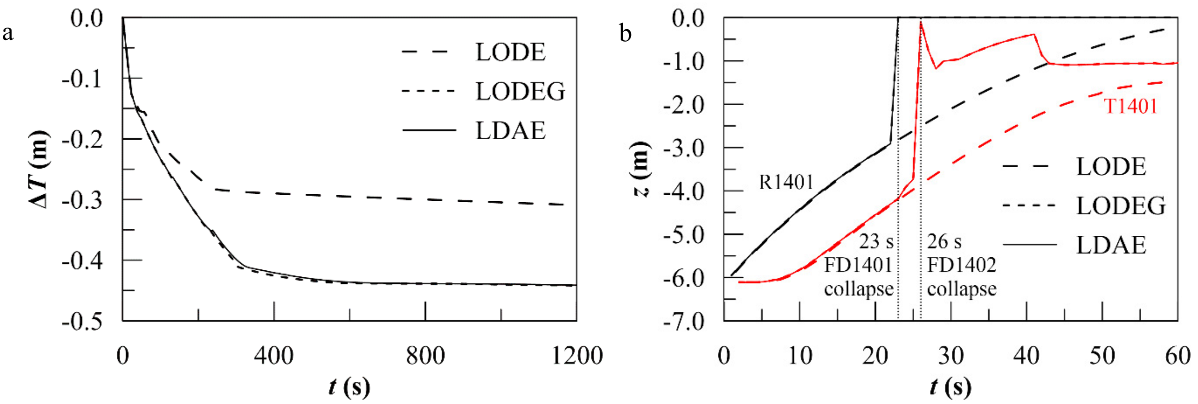

Fig. 5. Comparison of trim angle (a) simulation and floodwater levels in earth-fixed reference system within rooms R1401 and T1401 (b).

Table 5: Comparison of occurrence of main events during progressive flooding of CMP14 and CMP15

Id	event	t (s) LODE	LODEG	LDAE	Id	event	t (s) LODE	LODEG	LDAE
FD1401	leakage	1	1	1	FD1508	leakage	59	50	50
FD1401	collapse	n.a.	23	23	FD1506	leakage	63	50	50
FD1402	leakage	36	26	26	FD1505	leakage	62	70	70
FD1402	collapse	36	26	26	FD1509	leakage	75	71	71
FD1405	leakage	62	27	27	FD1504	leakage	75	72	72
FD1404	leakage	60	27	27	FD1507	leakage	77	74	74
FD1403	leakage	56	27	27	FD1506	collapse	78	108	108
ED140101	leakage	114	38	38	FD1510	leakage	92	116	116
ED140201	leakage	186	39	39	FD1505	collapse	99	129	129
FD1405	collapse	n.a.	41	41	FD1507	collapse	168	223	235
FD1404	collapse	n.a.	41	41	FD1406	open	15086	294	312
FD1403	collapse	n.a.	41	41	ED140102	leakage	n.a.	294	313
FD1501	leakage	45	44	44	FD1408	leakage	16453	299	317
FD1502	leakage	45	44	44	FD1407	open	15086	301	321
FD1501	collapse	50	48	48	ED140202	leakage	n.a.	301	322
FD1502	collapse	50	48	48	FD1512	open	n.a.	374	410
FD1503	leakage	59	50	50					

It is worth to notice that the LDAE and LODEG methods provide a similar trend, whereas the LODE method shows a completely different time prediction. This is caused by the too simplistic assumptions. As mentioned, applying the LODE formulation when the room R1401 is completely filled, the conservation of mass is no more respected. Means that the waterhead in the room rises with the same slope of the partially filled condition, instead of reaching almost the seawater level in about 2 s, as happens in the LODEG and LDAE simulations (Fig. 5b). In general, when the waterplane area S_i is assumed to equal the top area of a completely filled room' only a delay was experienced in LODE formulation, driving to an optimistic estimation of the time-to-flood. However, in the studied test case, the LODE method also fails in recognising the collapse of FD1401, which connects the damaged room R1401 to the escape trunk T1401. In fact, the slower rising of floodwater in R1401 does not overtake the required collapse waterhead of 2.5 m. This issue implies a strong distortion in all the subsequent phases of the simulation, which lasts over 12 hours (three times the time-to-flood estimated with the other formulations. Hence, in the selected damage scenario the LODE method is not capable to obtain even a qualitative simulation of the progressive flooding process.

Considering the LODEG and LDAE formulation, they provide comparable results at the beginning of progressive flooding process. Both are capable to model properly the FD1401 collapse and predict qualitatively the same time evolution. Only a small delay can be noted in LDAE prediction after 200 s. Figure 6 shows the comparison of water levels inside the flooded rooms simulated with LDAE and LODEG formulations. It can be noted that the delay is again related to room-filling.

In fact, in LODEG method the filled rooms are grouped, leading to discarding some pressure losses. As R1504 is filled, it is grouped with the room R1501. The same happened to R1508. A similar situation is observed also in CMP14 at about 270 s, where again LODEG pace is faster than LDAE one. Such a distortion is reduced as the level in grouped rooms approaches the sea free surface. Menes that the pace in the subsequent phases is mainly due to the already mentioned closed doors FD1407 and FD1504 and their higher pressure losses. In fact, the discarded pressure losses related to collapsed openings are negligible compared to the closed ones, restabilising a similar slope of LODEG and LDAE simulations until the end.

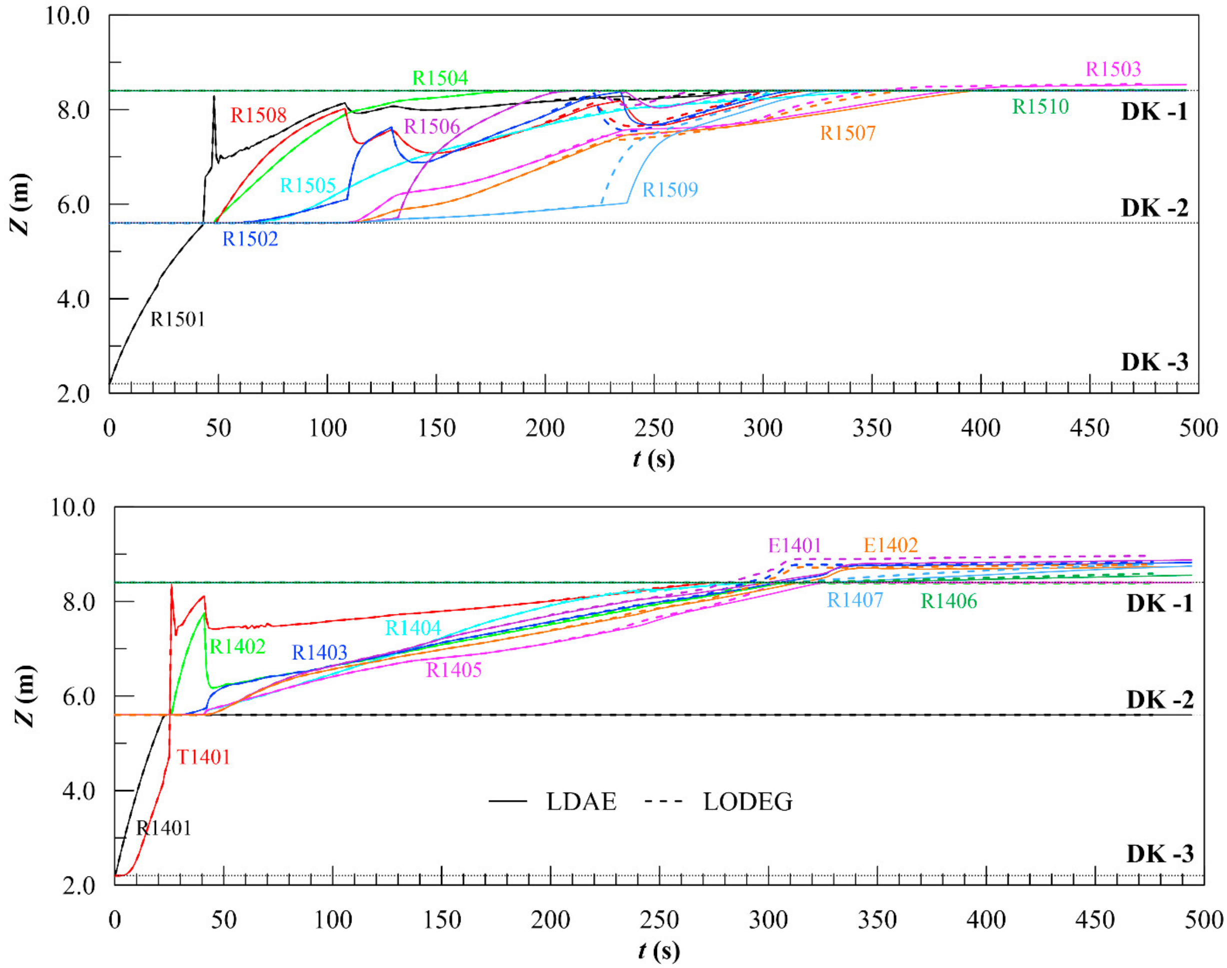

Fig. 6. floodwater level in ship-fixed reference system within CMP14 and CMP15.

However, the choice of the LODEG or the LDAE method has a very limited impact on floating position prediction in the studied test case. In particular, they might be negligible when compared to the uncertainties that might affect the definition of the discharge coefficients [21], the room permeabilities, the initial loading condition [22] or the critical waterheads that usually are only roughly estimated in a real operative environment.

5. Conclusions

As a primary driver within Industry 4.0, simulation can play a key role in providing accurate data and forecasts not only during the design process and ordinary operations but also during emergencies. The present work show in a full-scale environment the effects on progressive flooding simulation connected to the application of different linearized formulations. The choice of the proper simulation technique is essential to obtain reliable data to be processed for decision making and monitoring processes. Progressive flooding simulation can allow the exploitation of data from sensors to mitigate the consequences of a flooding emergency, contributing to increasing navigation safety in the framework of Shipping 4.0.

It can be concluded that the LODE formulation is not suitable for the onboard application. The simplistic assumptions on completely filled rooms can easily lead to optimistic time-to-flood estimation or even to completely erroneous predictions, especially in presence of closed fire doors. In fact, during an emergency situation, time-to-flood overestimation cannot be accepted, especially if ship abandonment is required. The LODEG and LDAE methods, both already validated against model-scale tests, provide very similar prediction in the considered test case. The assumptions in LODEG formulation totally justify the small underestimation of time-to-flood. Moreover, such a pessimistic prediction could be more acceptable from an operative perspective, provided that it does not lead to rush the evacuation procedure, increasing the risk for passengers and crew.

Finally, in the considered flooding scenario, in several occasions, multiple opening collapsed in some instant due to critical waterhed overtaking. Since the effective waterheds applied on same-deck openings are likely very similar with small heel and trim angles, defining a realistic order for collapsing in not an easy task. Collapsing order might be governed by uncertainties and dynamic phenomena. Therefore, considering the strong effect of opening status on progressive flooding, further research is still advisable on this topic to soften potentially critical issues.

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