

TRAVISIONS

TRA VISIONS 2022

Final Project Template – This template is to be used for submitting the final version of the project. The final deliverable should be submitted by the 31st of December 2021

Idea Number:

C2022 - 19

PILLAR / TRANSPORT MODE				
ROAD ☐	RAIL ☐	WATERBORNE ☒	AIRBORNE ☐	CROSS MODAL ☐
Project Related to:	☐ RA1: Smart Solutions and Society ☐ RA2: Green Mobility and Decarbonisation ☒ RA3: Innovative Infrastructure for Europe 2030 ☐ RA4: Policies and Economics for a Competitive Europe			

Project Title:

A rapid assessment tool for the evaluation of ship hard grounding



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1. Introduction

According to (EMSA, 2020) ship navigational accidents attributed to collisions and groundings continue to dominate ship casualty statistics (Figs. Figure 1 and Figure 2). HELCOM (2021) reported that between 2000 and 2018 there have been 776 ship groundings in the Baltic Sea region (see Fig. Figure 3). These events primarily involved passenger ships and some cargo vessels. Recent examples are the groundings of the bulk carrier MV Wakashio in Mauritius on 25 July 2020 (see Fig. Figure 2) (MARINELINK, 2020) and the Ro-Ro passenger ship Amorella in Finland on 20 September 2020 (FleetMon, 2020).

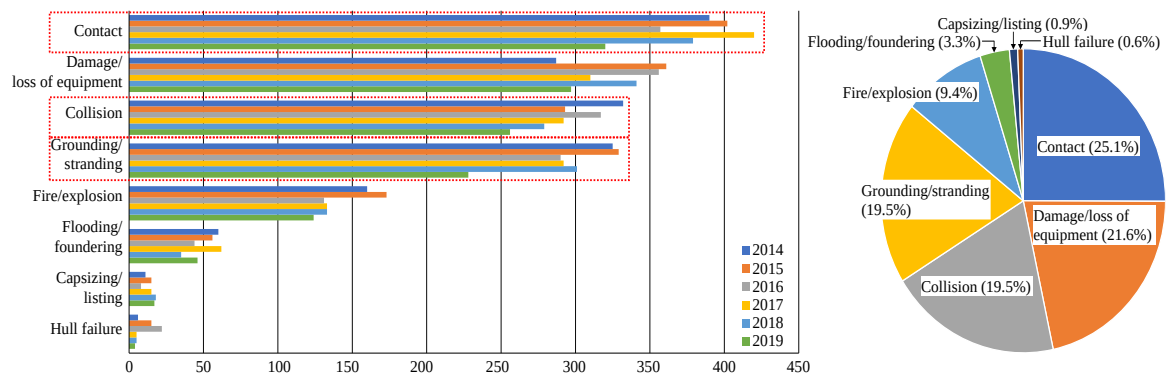


Figure 1. Distribution of maritime casualty events over 2014-2019 (EMSA, 2020).



Figure 2. Wakashio grounding accident at Mauritius on 25 July 2020 (MARINELINK, 2020)

Grounding accidents are naturally interlinked with manoeuvring in shallow waters, sea loads emerging from short waves, ocean currents and some increase of ship resistance. To mitigate such risks and enhance ship safety it is meaningful to understand the mechanics associated with hull damage extents. Such an approach can help update accident databases that form the backbone of future IMO Safety of Life at Sea (SOLAS) damage stability regulations and may suggest viable Risk Control Options for use in ship design and evacuation management (Conti et al., 2021; Zhang et al., 2021a,b)

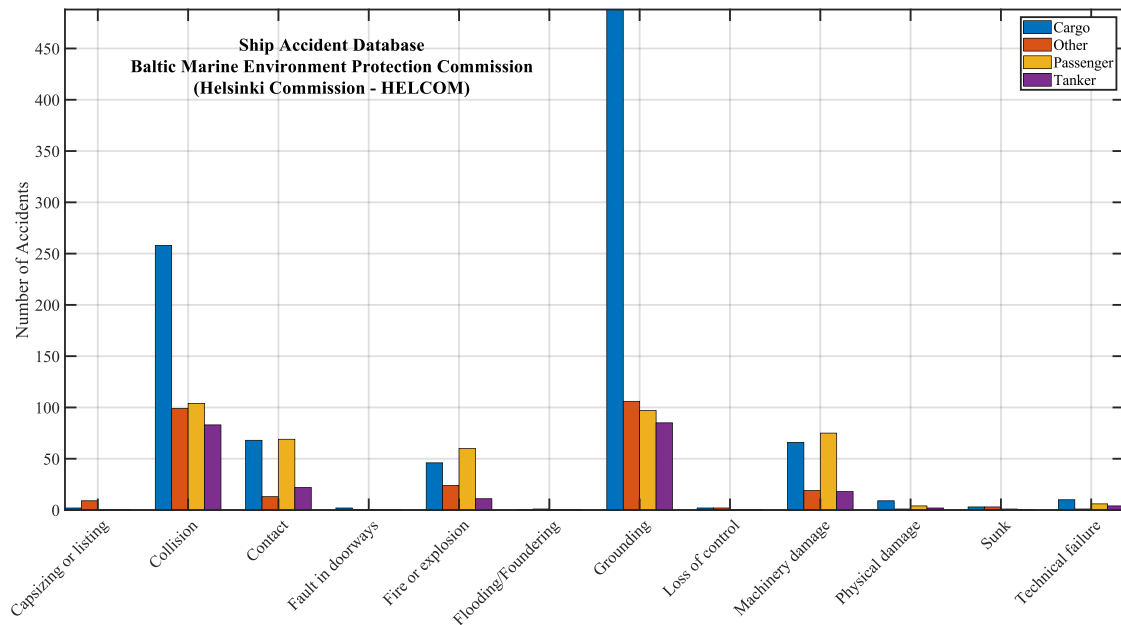


Figure 3. Baltic Sea maritime accidents database.

As part of work carried under EU Horizons 2020 project FLARE (Flooding Accident Response - <https://flare-project.eu/>) this paper presents a time-domain mathematical model and computational tool for the rapid evaluation of ship grounding dynamics. The model incorporates the 6-DoF dynamics of a conventional rudder propeller configuration of a twin-screw ship manoeuvring in shallow seas under calm waters, short waves and ocean currents (Taimuri et al., 2020). Structural deformation is modelled using the simplified FSI method (Taimuri et al., 2022). The computational tool developed allows for accurate modelling of ship geometry, structural particulars, and rock shapes. Following crashworthiness analysis, the damage extents, deformation energy, structural component forces, ship motions, and evasive manoeuvres can be rapidly analysed. The methods developed push forward the state of the art in ship structural crashworthiness. They can help shipyards and operators mitigate risks and accordingly suggest risk control options for use in ship design development and ship operations (e.g. development of improved criteria for implementation in novel decision support systems).

The idea and justification for selecting the study topic are described in Section 2. State of the art research in ship grounding is reviewed in Section 3. Section 4 discusses details of the concept with a focus on external mechanics (see Section 4.1), internal mechanics (see Section 4.2) and their coupling (see Section 4.3). A numerical validation study is illustrated in Section 5. Conclusions and future research studies are given in Sections 6 and 7 respectively.

2. Research Topic

The world economy is based on 90% of the world's trade transported by sea. Notwithstanding this, grounding ship accidents potentially leading to a loss of life and cargo, and detrimental impacts on the environment persist.

To date, because of the lack of practical tools and methods grounding accidents are understood on the basis of limited statistical datasets, probabilistic grounding scenarios and deterministic computational crashworthiness methods (i.e. Nonlinear Finite Element Methods under LS-DYNA or closed-form empirical formulations). The implementation of structural crashworthiness based criteria in the IMO SOLAS regulations for passenger ship damage stability assessment has not been possible. This is because existing methods are computationally expensive and the overall influence of multiphysics surrounding hydrodynamic interactions, evasiveness and seabed obstacle obstructions are not well understood. Statistical models accounting for historical data records are used to idealize the geometrical distributions of vessel traffic profiles. However, those are naturally limited in terms of accounting for the influence of ship evasive actions (Mazaheri and Ylitalo, 2010) or the geometrical distribution of damage extents (Bulian et al., 2020, 2016). As an alternative way forward, suitable use of big data analytics (e.g. AIS and GEBCO data streams) could allow for precise determination of traffic distributions in specific regions of interest. Yet, the conceptualization of these methods is still limited by the availability of regional data records and technology readiness (Zhang et al., a,b).

The focus of this research is to introduce a practical rapid tool for the assessment of ship grounding. The method idealises ship dynamics under realistic operating conditions while accounting for the influence of structural crashworthiness in way of contact. The research impacts upon ship science, maritime safety and the society at large. Ship science is advanced because of improvements in our fundamental knowledge to understand the physics of fluid-structure interactions for the idealisation of ship grounding. The research also allows for the combination of ship manoeuvring, seakeeping and structural crashworthiness methods for use in the assessment of ship damage stability. This is the reason why the suggested concept and methodologies may contribute to the development of future goal-based ship safety regulations that account for the influence of extreme events (e.g. serious flooding following grounding) on ship safety. The multidisciplinary nature of the methods used could help in the development of new generation decision support systems for use by conventional and future autonomous vessels. In this sense, the work presented contributes to improved safety standards for the benefit of people, the protection of the maritime environment, and the preservation of floating assets.

3. Literature Survey

Costs resulting from ship asset damages associated with collision and grounding events may be significant. This is well justified by the recent example of the grounding of Costa Concordia that is worth over \$2 billion, (Allianz Global and Corporate Speciality, 2021). The risks of ship grounding events are particularly significant in inland waterway areas, near harbours and in shallow waters. In such areas, the complicated action of hydrodynamic forces and moments on the ship hull and her controlling devices influence manoeuvrability (Elloot et al., 2015; Liu et al., 2015; Rotteveel, 2013; Vantorre, 2001; Vantorre et al., 2017).

Although developments in marine hydrodynamics appear optimistic, research on evasive ship dynamics relevant to unintentional events (collisions, groundings, etc.) remains relatively constrained and liable to both computational uncertainties and costs. Ståhlberg et al. (2013) emphasized the significance of ship velocity and time history in determining vessel evasive measures in the event of a collision. Matusiak, (2002) and Varsta et al. (2004) presented a 6-DoF ship dynamics model accounting for simplified hard grounding. Yu and Amdahl (2016), provided a coupled technique for estimating structural damage and 6-DoF ship motions in ship collisions. None of these researchers concentrated on the development of rapid evaluation methods that take into consideration the combined effect of ship manoeuvrability on vessel behaviour during both grounding and collision situations.

Modelling grounding dynamics consists of two processes namely external mechanics and internal mechanics. The consideration of the influence of hydrodynamics on the contact path (e.g. added inertia and damping effects due to ship motions, evasive movements following a manoeuvring path) is referred to as external mechanics. Internal mechanics is mainly concerned with the responses and deformation of the structure due to energy dissipation following grounding.

Several approaches can be used to evaluate the ship's structural deformation (internal mechanics). Examples are empirical methods (Minorsky, 1958), the FEA method (Kim et al., 2020; Liu et al., 2021), the super element method (Buldgen et al., 2012; Kim et al., 2022; Le Sourne et al., 2012), experimental approaches (e.g. Calle et al., 2020; Rodd, 1996; Rodd and Sikora, 1995), and simplified analytical models (Zhang et al., 2019). External dynamics are generally modelled by the decoupled approach. This means that the loss of energy due to the impact is estimated using an analytical expression. In turn, this is used to estimate structural deformations using FEA (Liu et al., 2017; Yu et al., 2019).

Coupled approaches are required to realistically model the influence of local structural deformation since the decoupled approach does not capture the dynamic effects on a ship surrounded by fluid (Ehlers, 2011; Liu et al., 2018). In the analysis of ship collisions, simplified coupled approaches are used to idealize the influence of added masses and contact forces. Such models typically ignore the effects of ship hydrodynamics, restoring forces, damping forces and out-of-plane motion (Pill and Tabri, 2011).

Grounding scenarios are usually modelled using FEA software, where the penetration damage is investigated in terms of material fracture and plastic distortion (Abubakar and Dow, 2013). Several authors constructed the analytical equations representing the resistance forces of hull bottom structure using experiments and FEA software. Analytical equations have been formed for the rapid estimation of the structural response, where the different structural resistance of components (plate, stiffeners, bulkheads, girders and

floors) are evaluated individually and summed up to idealise the total deformation (Hong and Amdahl, 2012, 2008; Simonsen, 1997; Sun et al., 2017; Zeng et al., 2016).

The dynamics of ship grounding can be studied by model tests, or fully coupled fluid-structure interaction (FSI) methods. The former is expensive and scaling of model results to full-scale may be difficult to interpret (Simonsen, 1997; Sun et al., 2017). The advancement of computational technology allows for FSI simulations using advanced FEA-based and ALE methods (Rudan et al., 2019; Song et al., 2016). The usage of non-linear finite element methods with coupled fluid-structure interaction models assures a very high degree of accuracy. However, the major constraint of using FEM and FSI models is time. Notwithstanding this, the implementation of simplified approaches such as the Super Element method is essential (Conti et al., 2021; Kim et al., 2022) for use in regulatory development or operational management.

Most of the existing ship grounding models are prone to many simplifications in terms of modelling the combined influence of environmental, seakeeping and manoeuvring effects. Whereas modern Fluid-Structure Interaction (FSI) techniques (e.g. Lee et al., 2017) may help with understanding the influence of simulations due to accidental loading, a significant knowledge gap is evident in terms of explicitly modelling the influence of grounding accidents on serious ship flooding. Detailed models are also time-consuming to generate and computationally expensive. Recently, Kim et al., (2021) proposed a 3D FSI model that combines explicit FEA structural dynamics with seakeeping, manoeuvring, and calm water resistance. This study reaffirmed the need to establish accurate tools with the goal of implementing the effects of multiphysics modelling assumptions on ship structural crashworthiness.

The rapid assessment of ship grounding dynamics can be achieved by coupling the super-element method with rigid body dynamics Le Sourne et al., (2012). In the super element method, the ship structure is divided into several macro-elements (e.g. plates, intersection, transverse, and longitudinal members) having different closed-form analytical formulations of the structural resistance force. These elements deform individually, and the contribution is added to give total energy of deformation. The work by Kim et al. (2022), confirmed the validity of this approach in terms of suitably idealising the physics of ship collision and grounding. It also demonstrated that only 4 minutes are required to simulate a grounding scenario. Notwithstanding this, the approach presented in this paper is rapid (i.e. of the order of seconds) and also accounts for the influence of ship manoeuvring and sea loads in realistic to ship grounding environmental conditions (e.g. shallow waters, wind, short waves and currents).

4. Methodology

A computationally fast and simplified two-way coupled 6-DoF rapid grounding dynamics model is used to investigate the deterministic damage extents following a grounding event. Structural deformations are modelled by simplified analytical approaches (Simonsen, 1997; Sun et al., 2017) that are enhanced to account for the influence of plate tearing (plate splitting angle) associated deformations in the time domain (i.e. under the influence of ship motions). This is combined with the 6-DoF manoeuvring dynamics model of Taimuri et al. (2020), which ultimately models the consequences of ship groundings. The methodology of the rapid two-way coupled 6-DoF time-domain FSI simulation for grounding dynamics is illustrated in Figure 4. The structural deformation load from the rock and ship bottom interaction changes the 6-DoF motion of the ship considering the effect of the surrounding hydrodynamic actions. This coupled FSI methodology results in the contact forces, penetration of rock into the hull, damage extent, ship motions, and individual structural component forces. Utilizing the developed rapid assessment tool, probabilities of damage extents was constructed for a modern cruise vessel for use in damage stability calculations.

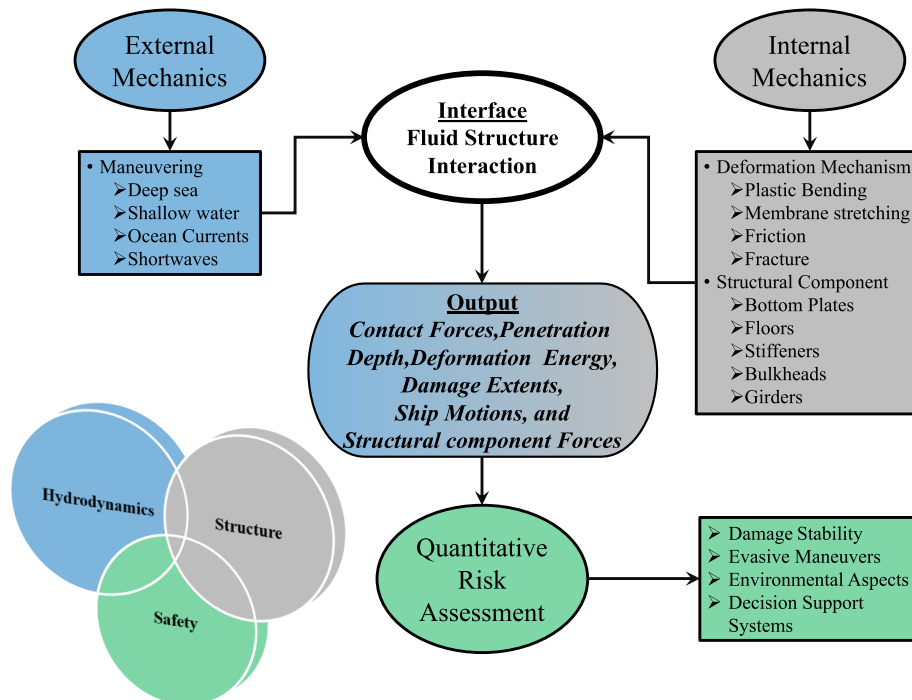


Figure 4. Methodology of a rapid Fluid-structure interaction model for quantitative risk assessment of ship grounding and evasiveness.

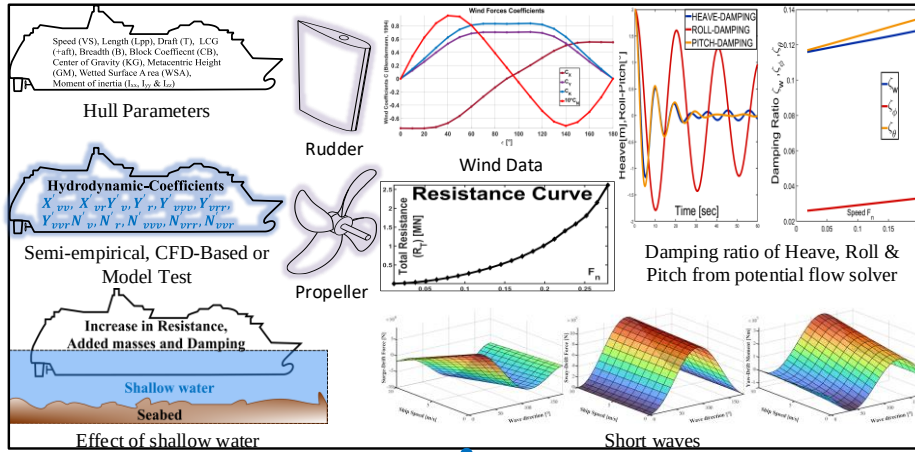
4.1. External Mechanics

A detailed explanation of the model developed for the idealisation of 6-DoF ship dynamics is presented in Figure 5 (Taimuri et al., 2020). The model uses as an input the hull form and general particulars, a simplified calm water resistance curve (Holtrop and Mennen, 1982; Matusiak, 2021), ship propulsion thrust and rudder forces (Brix, 1993; Lewandowski, 2004; Söding, 1982). Wind loads account for the aerodynamic coefficients of (Blendermann, 1994) as implemented by (Matusiak, 2017). The forces acting on a ship during manoeuvring account for the velocity and acceleration of the ship and are expressed by hydrodynamic

derivatives. Accelerations related terms are designated as added mass and inertia. Velocity related derivatives are termed added damping. Based on the assessment of the hydrodynamic assumptions on ship manoeuvring (Taimuri et al., 2019) a combination of hydrodynamic derivatives are presented in (Taimuri et al., 2020). The radiation damping of out of the plane heave, roll and pitch motion is estimated linearly based on the natural period of the ship, where the assumption of small amplitude roll, pitch and heave motions made it possible to have a linear approximation. Additionally, a reference technique is introduced. This accounts for the change in hydrodynamic assumptions of hull forces for a twin-screw vessel.

The presence of the bottom close to the ship keel in shallow waters increases the forces and moments acting on the ship and may result in grounding extreme scenarios (Newman, 1979). The approach introduced in this work utilises the correction factors of Raven, (2019) that accounts for the changes in viscous resistance, wave resistance and squat due to shallow water. This change in the resistance coefficients allows adequate prediction of the shallow water effects. Hydrodynamic damping is also influenced by shallow water conditions, and these are accounted based on Ankudinov et al. (1990) and Kijima et al. (1990). Hydrodynamic derivatives used are derived from semi-empirical formulations, model tests, CFD and/or their combinations. The model considers only short waves ($\lambda/L_{pp} \leq 0.5$) of certain heading and speed, where the intended purpose is to manoeuvre ship shallow water before grounding impact. It is based on the methodology of predicting added resistance of ship in short waves presented by Faltinsen et al., (1980), Sakamoto and Baba, (1986) and Faltinsen, (1990).

The mathematical model of external dynamics has been intensively verified and validated using different environmental conditions (e.g. shallow and calm waters, shortwaves) and ship propulsion configurations (e.g. single and twin screw vessels) as presented in Taimuri et al. (2020).



6-DOF Maneuvering Mathematical Model					
$(m - X_{\dot{u}})\ddot{u} + (mz_G - X_{\dot{u}}z_G)\ddot{q} = mrv + mx_G(r^2 + q^2) - mwq - mz_Gpr + \rho g A_{WP}(\Delta z) \sin(\theta) + X_{Hull} + X_{Res} + X_{Prop} + X_{Rud} + X_{Wind} + X_{Waves}$	$(m - Y_{\dot{v}})\ddot{v} - (mz_G + Y_{\dot{v}})\ddot{p} + (mx_G - Y_{\dot{v}})\ddot{r} = m(pw - ru - z_Gqr - x_Gpq) - \rho g A_{WP}(\Delta z) \sin(\phi) \cos(\theta) + Y_{Hull} + Y_{Rud} + Y_{Wind} + Y_{Waves}$	$(m - Z_{\dot{w}})\ddot{w} - (mx_G + Z_{\dot{w}})\ddot{q} = m(uq - vp + z_G(p^2 + q^2) - x_Grp) - \rho g A_{WP}(\Delta z) \cos(\phi) \cos(\theta) - 2\xi_{\phi}\omega_{\phi}w$			
Surge-E.O.M	Sway-E.O.M	Heave-E.O.M			
$-(mz_G + K_p)\ddot{v} + (I_x - K_p)\ddot{p} = (mx_Gz_G + K_p)\ddot{r} = m(z_Gur - z_Gwp + x_Gz_Gpq) + (I_y - I_z)qr - mgGM_T \sin(\phi) \cos(\phi) \cos(\theta) + K_{Hull} + K_{Rud} + K_{Waves} - 2\xi_{\phi}\omega_{\phi}p$	$(mz_G - X_{\dot{u}})\ddot{u} - (mx_G + Z_{\dot{w}})\ddot{w} + (I_y - M_q)\ddot{q} = m(z_Gvr - z_Gwq + x_Gvp - x_Guq - x_Gz_G(p^2 - r^2)) + (I_z - I_x)pr - mgGM_L \sin(\theta) \cos(\phi) \cos(\theta) + M_{Rud} - 2\xi_{\theta}\omega_{\theta}q$	$(mx_G - N_p)\ddot{v} - (mx_Gz_G + K_p)\ddot{p} + (I_z - N_p)\ddot{r} = m(x_Gwp - x_Gur - x_Gz_Gqr) + (I_x - I_y)pq - \rho g V(-GM_L \cos(\theta) + GM_T) \sin(\phi) \sin(\theta) + N_{Hull} + N_{Rud} + N_{Wind} + N_{Wave}$			
Roll-E.O.M	Pitch-E.O.M	Yaw-E.O.M			
Inertia Matrix	Coriolis and centripetal force	gravitational and buoyancy force	Damping Terms	Control Forces	External Forces

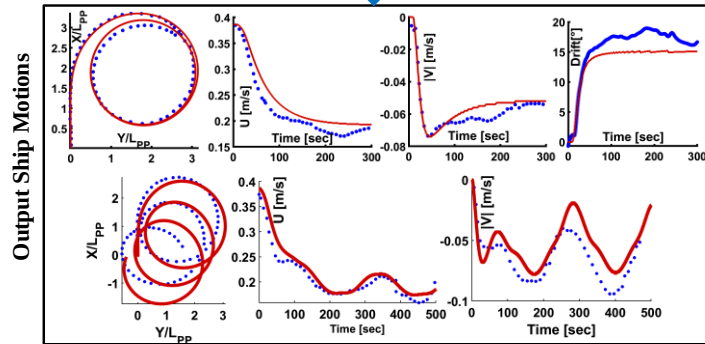


Figure 5. Methodology and simulation of 6-DoF ship dynamics model.

4.2. Internal Mechanics

Internal mechanics are explained in Taimuri et al., (2022). The structural topology considered, comprised of the inner and the outer shell of the hull as well as longitudinal girders, bulkheads, stiffeners and transverse floors. Forces generated by the individual structural components were summed up to produce the resultant contact force at a particular position of the rock within the hull of the ship.

The impact loads from the rock were obtained based on the bottom structural deformation model presented by Simonsen (1997) and Sun et al. (2017). In these formulations, the energy dissipation was obtained by integrating the stress and strain field over the volume

of the structure to form an analytical equation. A rigid-plastic structure, neglecting the effect of elastic deformation is assumed for the theoretical model of deformation (Simonsen, 1997). Grounding over a rigid object is idealized by a conical rock having a rounded tip defined by tip radius R_R and semi-apex angle ϕ (see Figure 6).

The plate split angle θ , which is unknown in the problem of structure deformation represents the extent of the plate deformation ahead of the conical rock. Approximating the deformation zone of the structure ahead of the rock was the major uncertainty in the approach by Simonsen (1997), where he opted for a constant plate split angle θ and computed in a way that it gives minimum total resistance of the structure. Taimuri et al. (2022) highlight the importance of properly evaluating the plate split angle by demonstrating a comparison of the plate split angle obtained from the FEM solver against the theoretically minimized resistance force approach introduced by Simonsen (1997). It was noted from FEM computations that the minimized resistance approach by Simonsen (1997), for identifying the length of plate splitting zone ahead of rock (see Figure 6) is not suitable.

To achieve a reasonable formulation of plate split angle, several FEM computations were conducted Taimuri et al. (2022). The range over which various plate split angles were acquired from LS-DYNA FEM simulations depend on the combination of penetration of the rock into hull and cone semi-apex angle. Based on the simulated data from LS-DYNA, a curve fitting of the plate split angle as a function of penetration into the hull and width of the cone base (cone base-radii) was proposed. The proposed equation idealises the dynamic behaviour of the ship structure as a function of conical rock geometry. This implementation of varying plate tearing angles provided different horizontal and vertical forces depending on the rock penetration into the hull and ship motions in 6 DoF. Furthermore, with the revised formulation, the ship's inner and outer bottom plates now have distinct plate split angles, which was not the case according to Simonsen (1997)

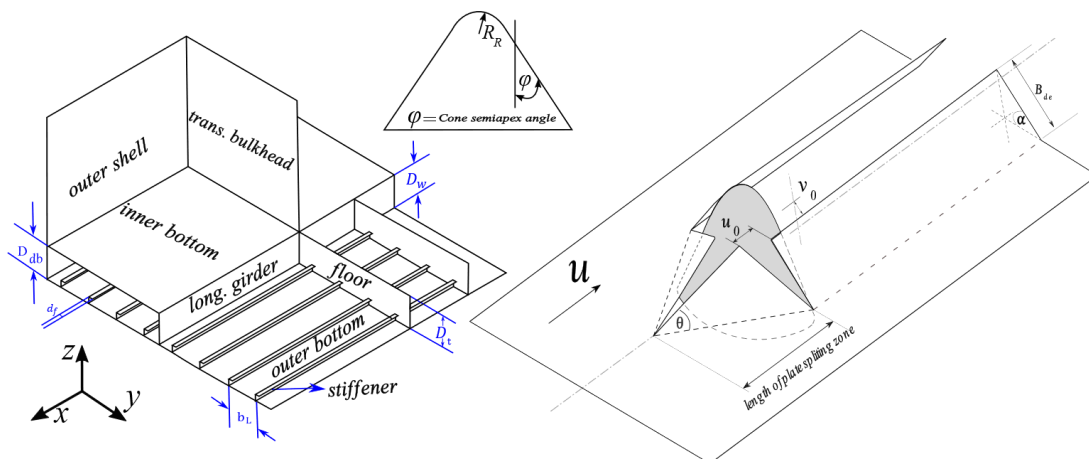


Figure 6. idealization of ship bottom structure, conical rock, and plate failure mode.

4.3. Interface capturing

The contact between the rock tip and hull panels in presence of hydrodynamic actions actuate the mechanism responsible for structural deformations during contact. To idealise

physics a fast contact detection algorithm was developed to locate the interface between the ship panel hull and the tip of a rock (Taimuri et al., 2022). The hull model was initialized by triangular panel coordinates. Figure 7, illustrates the following steps :

- 1a) A grid is generated based on the main dimension of the hull and number of blocks;
- 1b) Panel IDs corresponding to specific blocks are stored;
- 2) The rock tip is defined as a vector pointing from the tip to the base of the ship;
- 3) The relative distance between the ship origin and the tip location helps identify the sub-block containing the rock;
- 4) The intersection between the tip vector and the hull panel is obtained using a ray-tracing algorithm (Badouel, 1990; Moller and Trumbore, 1998);
- 5) Based on the rock tip position and ship motion, the relative displacement is output in way of the intersection detected.

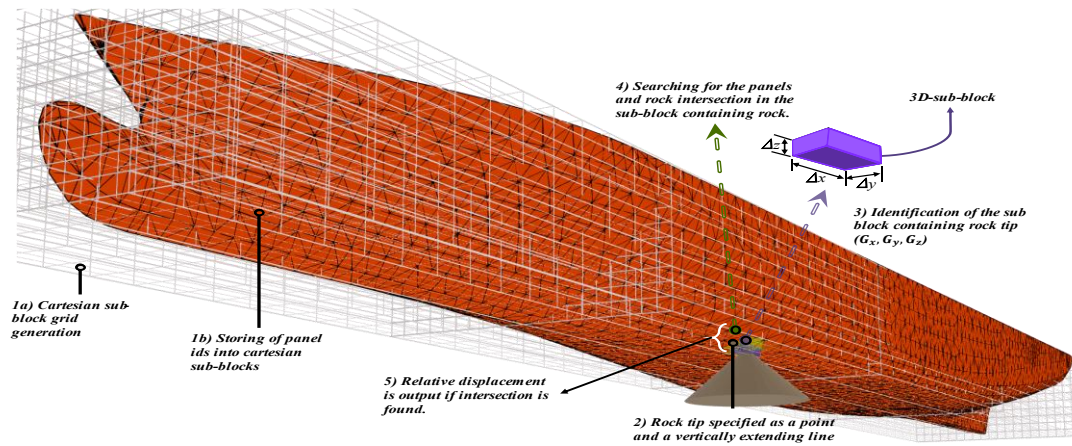


Figure 7. Representation of the ship, rock, cartesian domain, intersection between the rock and panel and the steps followed for rapid evaluation of contact detection

The displacement outputs from the contact search algorithm are utilized to estimate the structural deformation forces, which are subsequently employed as an external force in the 6-DoF equation of motion.

5. Findings and Discussion

5.1. Study Vessel Details

The rapid FSI grounding dynamics model was validated numerically against LSDYNA-MCOL simulations for the case of the passenger vessel. The structural arrangement of the passenger vessel is shown in Figure 8. Other general particulars are available in (Kim et al., 2022, 2021; Taimuri et al., 2022, 2020).

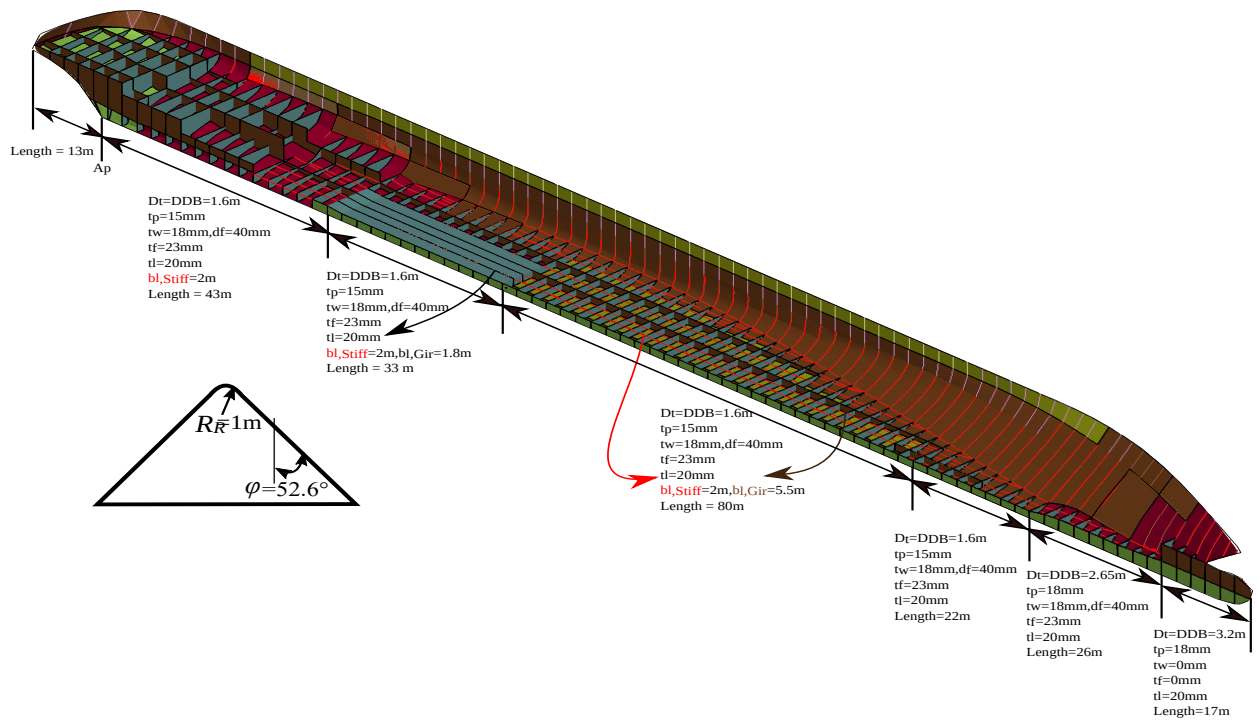


Figure 8. Main parameters of grounding simulation setup for passenger vessel.

5.2. Validation Results Off-Center (B/4) Grounding

Results for the case of the off-center (B/4) grounding of the passenger vessel are shown in Figure 9. The results of the surge, heave, and pitch motions match well with the values available from the validation study. The total damage length of the ship is the same as the ship entirely passes over the rock. Surge velocity from LS-DYNA MCOL simulation and rapid FSI model shows that the contact between ship and rock separates after 30.6 sec and 33.2 sec respectively (see results depicted in Figure 9a after 30 seconds). The difference in the surge velocity corresponds to the lower estimation of the horizontal force. For the validation case of Figure 9c in average horizontal resistance has 8.5 % lower values. For this case the vertical force is within 3%, and the trend of the force fits well with the simulations. The total deformation energy and sliding energy are within 10% and 4% respectively (see Figure 9c). The influence of lower vertical forces is also realized in heave motions of marginally lower heave amplitude.

The roll response discrepancies between LS-DYNA and the simplified model are noteworthy. According to LS-DYNA simulations, when the rock is positioned in between two longitudinal girders (see Figure 9b-dotted red line and Figure 10), roll motion grows steadily but is delayed in comparison to the values anticipated by the basic FSI model. Simplified models overestimate the roll motion and yawing of the ship, this is most likely due to the underestimation of the lateral force. The lateral force tries to keep the rock in between two girders in LS-DYNA simulation, however, the smaller lateral force from the simplified approach allows a ship to yaw and roll considerably.

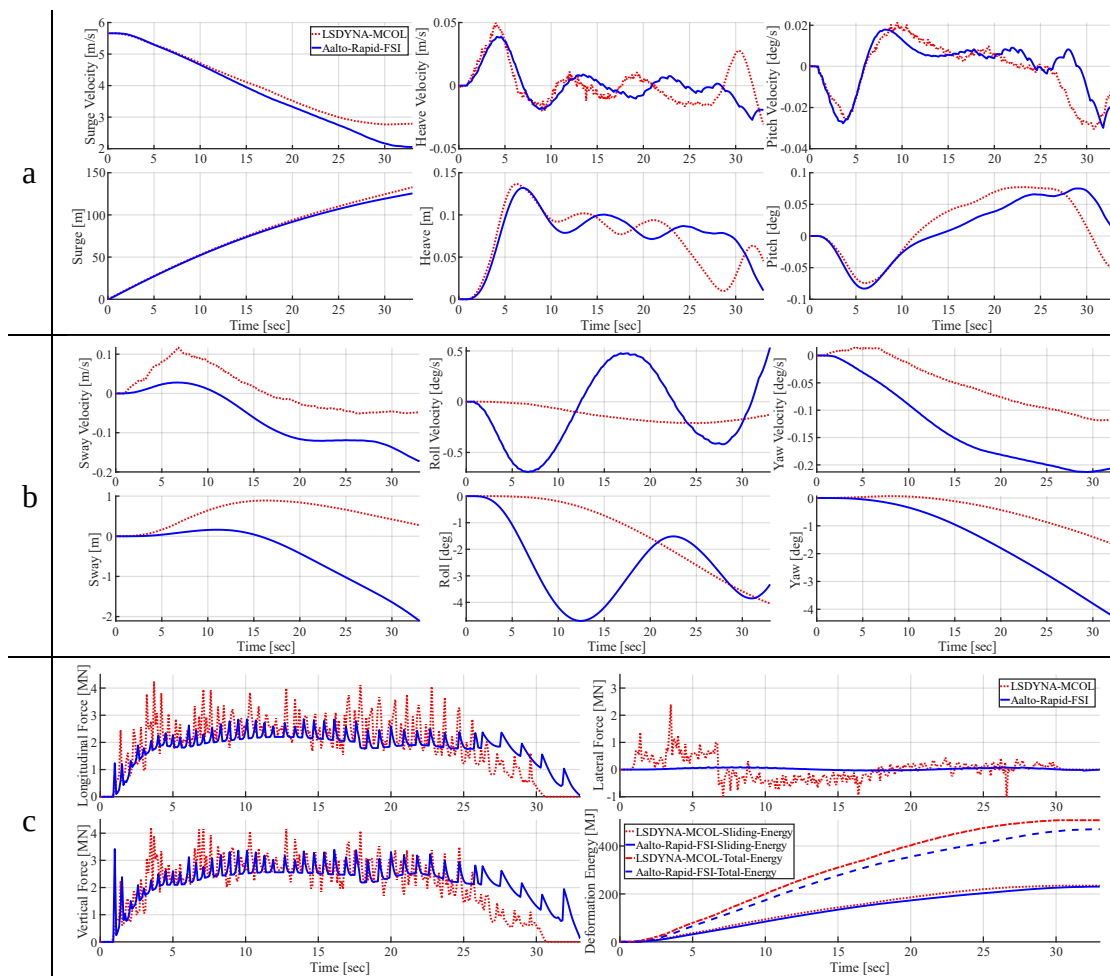


Figure 9. Side (B/4) grounding of a passenger ship. Velocities, displacements, forces and energy . a) Surge, heave and pitch motions and b) Sway, roll and yaw motions c) Sliding forces and deformation energy of side (B/4) grounding of a passenger ship.

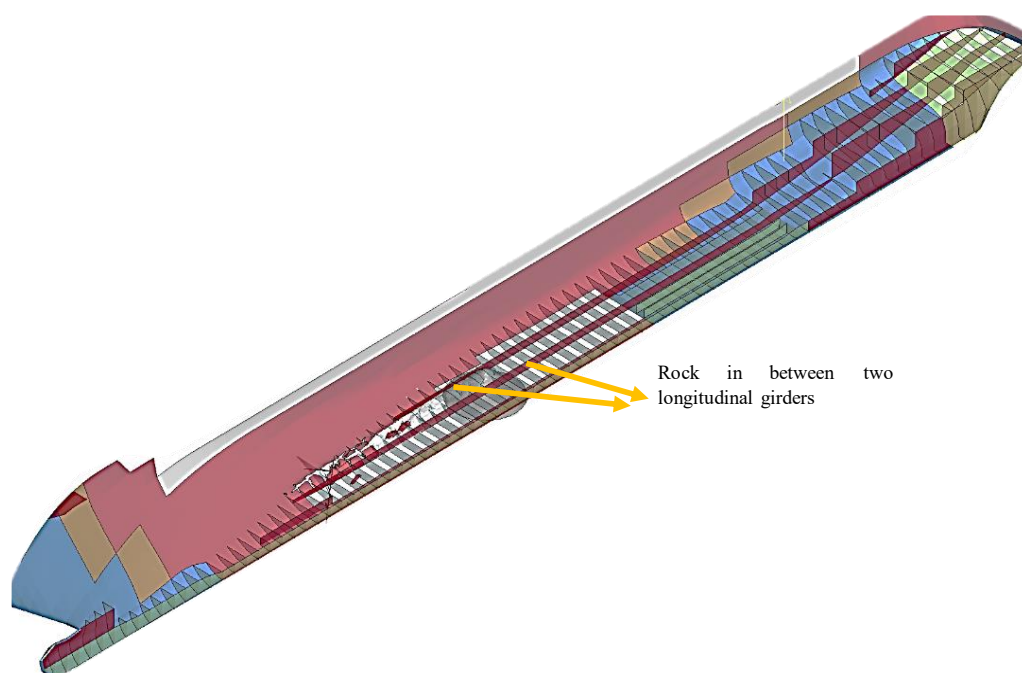


Figure 10. Off-centre grounding LSDYNA-MCOL validation study, rock fastened in between two longitudinal girders.

5.3. Grounding Dynamics during ship operation (Application)

In a real scenario, the captain will try to evade the obstacle by turning the ship. Performing an evasive manoeuvre to avoid grounding will lead to different types of damage characteristics. It is also debatable whether during an evasive manoeuvre the ship will avoid contact or crash with the rock, and what will be the result of bottom plate rupture.

The method presented can assess grounding dynamics in different environmental and operating conditions. Using the ship's manoeuvrability tool, the significance of timely actuating controlling devices and determining the required speed for avoiding an accident may be assessed. Figure 11, depicts the case of turning manoeuvre with a 35° rudder angle towards the starboard side. The distance of the rock from the ship in the global coordinate system is shown in Figure 11, at a location of $(x, y) = (655, 380)$ m, as a red dot. The geometry of the rock is shown in Figure 8, and the distance of the rock tip from the keel line is 2m.

During a turning manoeuvre (see Figure 11), the ship avoided the obstacle at a speed of 4 knots. However, manoeuvring at the design speed of 15 knots ruptures the bottom of the ship. One of the key findings of this task was the prediction of lateral force, which is significantly greater than the longitudinal force. The rolling and yawing of the ship increased during a turning manoeuvre, which allows higher penetration on the port side of the ship due to roll and larger lateral force due to yaw motion. The maximum roll angle after grounding was roughly 4° (see Figure 11). The maximum heave and pitch during grounding were 0.2 m and 0.15° respectively Figure 11. After the rock passes the ship domain, the ship does not stop as the velocity is higher and the ship continues the turn.

The damage to the hull is severe as the inner plate ruptures. The extent of the damage ranges from amidships to the aft section in way of the engine section (see Figure 8 and Luhmann, 2009). The maximum penetration into the hull is 2.5 meters. The resistance forces of the structural component can be seen in Figure 11. This illustrates the longitudinal variation of how the components are contributing to the total deformation of the ship structure. This analysis confirms that the method can be used for the preliminary rapid assessment of structural crashworthiness.

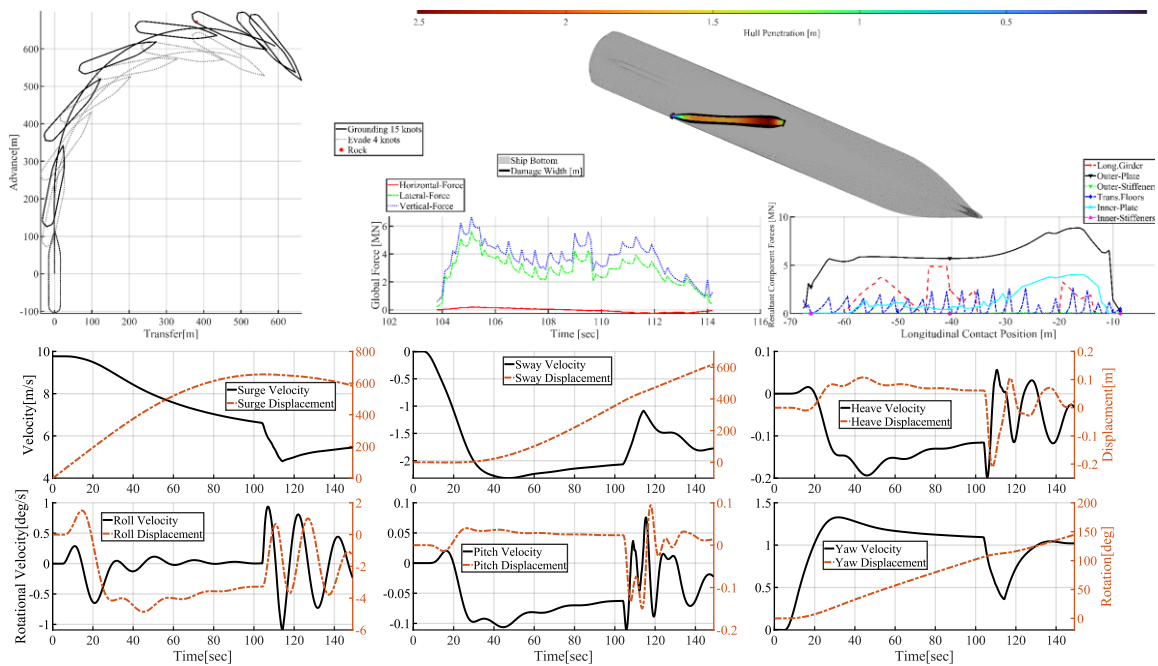


Figure 11. Results of ship operation. Ship turning manoeuvre, representing grounding and evasive action at different speeds. Evasive speed 4 knots and grounding speed 15 knots, both with 35° starboard turn. Top left evasive and grounding trajectory. The remaining plots are of grounding damage extent, resistance forces, and 6-DOF translational and angular ship motion.

6. Summary

The simplified model presented provides insight into the grounding response and damage characteristics, by significantly reducing the computation time. Moreover, the influence of manoeuvring dynamics and environmental conditions can be considered to quantitatively assess the structural crashworthiness and/or evasive actions. In simulations using the rapid FSI model, the computation time is less than 1 sec when the time step is 0.01 sec. This drastically reduces the computation in comparison to the fully coupled FSI model of LS-DYNA, where LSDYNA-MCOL simulation time is roughly around 3-4 days for passenger ship on supercomputers or even Super Element idealisations that may be carried out over 4 mins for a selected scenario (Kim et al., 2002).

The paper proposes a simplified and rapid multibody fluid-structure interaction model, for the realistic assessment of grounding dynamics. Validation of the model is conducted through a non-linear LSDYNA-MCOL coupling. Results show good agreement with the damage length, width, penetration into the hull and deformation energy. Horizontal and vertical forces match well. The lateral force in an idealized straight course operation is to some extent underestimated. However, the demonstration of the real ship operation shows that these uncertainties will be overshadowed during the evasive manoeuvring operation of the ship. As the approach accounts for the influence of evasive manoeuvres it could potentially serve as a more reliable alternative to blind safety domain simulations.

This research benefits the science, the maritime industry and society. This is because it develops our fundamental understanding of FSI for grounding events, it considers the combination of manoeuvring, seakeeping and crashworthiness in grounding scenarios and the combined effects on ship damage stability. The proposed model and methods may contribute toward new ship safety regulations under the hospices of performance-based ship stability standards introduced by the IMO. Understanding the influence of serious flooding events will help better regulations to ensure people safety, protect the environment and

maintain floating assets. This will bring to light the potential mechanisms responsible for avoiding contact with the seabed, improving ship safety, evaluating oil outflow and approximating the real-time of passenger evacuation.

7. Future work

Future work will focus on the development of a probabilistic model accounting for the influence of structure crashworthiness and ship hydrodynamics for grounding events. This could help estimate probabilistic grounding damage extents in stochastic environmental conditions and eventually improved methods (non-zonal assessment methods (Bulian et al., 2020, 2016)) for ship damage stability assessment following serious flooding events.

Acknowledgements

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