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Multi scale modelling of interaction between pack ice and offshore structures

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Abstract: Several offshore wind farms are planned for installation in the Gulf of Bothnia, Baltic Sea. As the sea is at least partially frozen every year, wind turbine foundations must be designed accordingly. However, the related forces and ice conditions now and decades into the future remain unknown. Here, we present a working technical concept by combining modelling in continuum mechanics based large scale sea ice dynamics model and discrete element model that can be used to simulate interaction between drifting pack ice and offshore structures.

Keywords: sea ice; modelling; multi scale; discrete element method; offshore wind farm

1. Introduction

There has been a growing interest in offshore wind energy development projects in freezing sea areas such as the Northern Baltic Sea. One of the main challenges hindering the projects is the uncertainty of the ice conditions in potential development sites. Turbine foundations need to be designed to withstand the additional load due to ice, thus accurate estimates of ice conditions are crucial. Moreover, there are also concerns from maritime navigation authorities that the offshore wind farms would significantly alter the ice conditions in the surrounding areas, which in turn affect the winter navigation. To address these potential issues, numerical tools capable of modelling large sea areas with high resolution are needed. However, existing sea ice dynamics simulation tools are not able to address aforementioned requirements, which motivates us to investigate alternative approaches to model sea ice dynamics in high resolution.

Traditionally, sea ice dynamics in large sea areas has been studied by using continuum mechanics based finite difference method simulation tools (Hunke et al., 2023; Vancoppenolle et al., 2023). However, the smallest grid cell resolution that can be achieved in these models is about 500 m. On the other hand, nominal diameter of an offshore wind turbine foundation is about 10 m, and the foundations are about 1 km apart in a wind farm. Thus, application of continuum mechanics based simulation tools to investigate ice conditions in offshore wind farms is not possible.

Discrete element method (DEM) based sea ice dynamics simulation tools have had significant developments in recent years. In this method, pack ice is modeled as a collection of distinct ice floes interacting with each other. Thus, DEM is capable of simulating ice deformations in meter scale. DEM has been used previously to investigate ice floe dynamics (Herman, 2016; Manucharyan and Montemuro, 2022), formation of aggregate structure in pack ice (Hopkins et al., 2004; Wilchinsky et al., 2010), development of internal forces in pack ice (Herman, 2013) and sea ice dynamics in specific geographical areas (Damsgaard et al., 2018; West et al., 2022). However, DEM simulations are computationally heavy due to complex search algorithms utlized to detect interacting ice floes, thus, modelling large sea areas of kilometer scale is not feasible.

In the present paper, we explore the possibility of combining continuum mechanics based finite difference method sea ice dynamics simulation tool NEMO-SI^3 and DEM sea ice fracture simulation tool HiDEM to model the interaction between an offshore structure and pack ice. HiDEM is used for modelling meter scale ice dynamics of ice-structure interaction processes, while NEMO-SI^3 is used to model the large scale drift of pack ice. The aim of this research is to develop a preliminary framework for high resolution modelling of large scale sea ice dynamics. The method developed in the present paper can be applied to modelling interaction between pack ice and an offshore wind farm to estimate the ice conditions within the wind farm. In what follows, we introduce the theoretical background of NEMO-SI^3, HiDEM and the coupling approach in Section 2. Section 3 presents the results of HiDEM simulation and combined HiDEM-NEMO-SI^3 simulations. We end the paper with a discussion on the proposed methodology.

2. Methods

2.1 NEMO-SI^3

NEMO [Nucleus for European Modelling of the Ocean (Madec et al., 2023)] is a widely used numerical modelling framework for research and operational forecasting in ocean and climate sciences in regional and global scales. It is developed by a European consortium aiming for reliability and sustainability in the long run. NEMO's physical ocean component solves for example ocean currents, sea surface height, temperature and salinity in three dimensions down to about a kilometer resolution. A curvilinear orthogonal grid is used in the horizontal direction, while in the vertical, the user can choose from full or partial step z-coordinate, s-coordinate, or a mixture of them. An Arakawa C grid is used for variable distribution. The model is designed for supercomputer environments.

The additional SI^3 [Sea Ice modelling Integrated Initiative (Vancoppenolle et al. 2023)] module is of particular interest here. It models ice dynamics, thermodynamics, brine inclusions and subgrid-scale variations in ice thickness. Simplifications are made according to relevance: ice drift is assumed horizontal only, while heat can only be exchanged in the vertical direction. Subgrid variability in sea ice properties is accounted for via using multiple categories of ice and snow. The momentum equation is

$$m\frac{\partial u}{\partial t} = A(\tau_a + \tau_w) + \tau_b - mfk \times u - mg\nabla\eta + \nabla \cdot \sigma \qquad \textbf{[1]}$$

where m is the ice and snow mass per area, u is the ice velocity, A is the ice concentration, τ_a and τ_w are the air and ocean stresses, respectively, f is the Coriolis parameter, k is a unit vector pointing upwards, g is the gravitational acceleration, η is the ocean surface elevation, and σ is the internal stress tensor. The terms on the right-hand side represent atmospheric and ice-ocean stresses, the Coriolis force, sea-surface tilt and internal stress respectively.

2.2 HiDEM

HiDEM [Helsinki Discrete Element Model (Åström and Herrmann, 1998; Åström and Benn, 2019)] is a discrete element method tool that can be used to model fracture of sea ice. In HiDEM, an ice floe is modelled as a lattice of spheres connected by Euler Bernoulli beam elements. Contact between spheres are modeled by using a soft contact model. Beams can fail in the simulation due to high strains which leads to forming micro-cracks within the ice floe. Coalesce of these micro cracks will eventually form large cracks and ice rubble formation. Ice rubble can then interact with each other forming features such as rubble fields and ridges. Equation of motion of a particle in HiDEM can be written as,

$$m_i\ddot{x}_i + C_1\dot{x} + \sum_j C_2\,\dot{x}_{ij} + \sum_j K\,x_{ij} = F_i \qquad \textbf{[2]}$$

where m is the mass of the particle, C_1 is the drag from water and air (viscous drag), j is the neighboring particle of the particle in consideration, K is the stiffness matrix of beam connecting particle with neighbor j, C_2 is the damping matrix of the beam connecting particle with neighbor j and, F_i is the external forces such as gravity, buoyancy and boundary forces.

HiDEM uses central difference time integration to explicitly solve the equation of motion of a particle in small time steps. Time steps are in the order of 10^{-4} to 10^{-5} s for ice thickness of 0.5 to 1.0 m. Solving 1 x 1 km^2 ice floe takes about 8 hours on a high-performance computing facility using 32 AMD MI250X GPUs.

In HiDEM, it is also possible to simulate an ice floe interacting with a structure. Structure is modeled by using a point mesh. Contact force between an ice particle and the mesh is calculated by using a soft contact model and added to the equation of motion of the particle similar to contact forces between ice particles. Moreover, resultant ice load on the structure is calculated by summing-up contact forces acting on the mesh.

2.3 Coupling methodology

The momentum equation of NEMO-SI^3, Equation 1, and the equation of motion of a particle in HiDEM, Equation 2, can be compared to identify the corresponding terms. The acceleration term $m\frac{\partial u}{\partial t}$ in Equation 1, is identical to $m\ddot{x}_i$ of Equation 2. The divergence of internal stress tensor of ice in Equation 1, $\nabla \cdot \sigma$, corresponds to the terms $\sum_j C_2\, \dot{x}_{ij} + \sum_j K\, x_{ij}$ of Equation 2 describing the rheology of ice. The external stresses acting on ice are represented by $A(\tau_a + \tau_w)$ and F_i, respectively in Equation 1 and Equation 2. The Coriolis force and the sea-surface tilt terms also correspond to F_i in Equation 2, nevertheless they are neglected in this study since the effects of these forces are infinitesimally small in the scale of ice floes used in HiDEM.

In this paper, we test two methods to couple the above equations. Firstly, we consider that the HiDEM is providing an estimation of ice pressure parameter P of the viscous plastic rheology instead of traditional parametrization where P is related to ice thickness and concentration. The benefit of this method is that, P is increasing in compressive situation but can also be considerable low or near zero if case of very fractured but thick pack ice. An offshore structure in pack ice would increase internal stress of the ice field due to the force exerted by structure on ice. Force exerted on the sea-ice from structure can be obtained from HiDEM and then, the pressure increase can be calculated by dividing force with the contact area of the ice edge. Therefore, presence of an offshore structure in one of NEMO-SI^3 grid cells can be mimicked by altering $\nabla \cdot \sigma$ of the momentum equation of the cell based on the pressure increase calculated from HiDEM results.

Alternatively, an offshore structure can also be accounted in NEMO-SI^3 as an additional external stress component. This approach is analogous to parametrization of fast ice formation due to grounding of pressure ridges. External stress exerted on the sea-ice by the structure is added to the momentum equation of the NEMO-SI^3 grid cell containing the structure. Stress due to offshore structure can be calculated by using the ice load results from HIDEM.

We start the coupled study by simulating the drift of an ice floe in NEMO using 500 m resolution, which is known to be a reasonable limit for the parameterization of SI^3. We set up an idealized scenario of a 200 km by 60 km cyclic channel closed from the south and north with free-slip boundary conditions. A 500 m by 500 m “island” is placed in the channel, and a large ice floe is set in motion towards it by a constant wind of 10 m/s as well as the induced current. Here, the island represents the location of an offshore structure. As the ice flow collides with the island, the velocity and thickness of ice in a small area around it is used as input for the HiDEM model. Then, a HiDEM simulation of ice flow with that thickness and velocity interacting with a square offshore structure is initiated. HiDEM is run until the ice load on the offshore structure reaches steady state. Following that, the nominal pressure excreted on the offshore structure by the ice floe is calculated by dividing the steady state ice load by the nominal contact area. Then, the nominal pressure on the offshore structure calculated in HiDEM is fed back to NEMO-SI^3 momentum equation as increased ice strength in internal stress tensor around the location of the offshore structure (the island is removed from the domain as a boundary). Then the NEMO-SI^3 simulation is continued for 60 timestep (one hour), the result is fed back into HiDEM, and the loop continues. For simplicity, SI^3 thermodynamics is disabled i.e. there is no formation or melting of ice. Figure 1 presents a flow diagram of the coupling scheme.

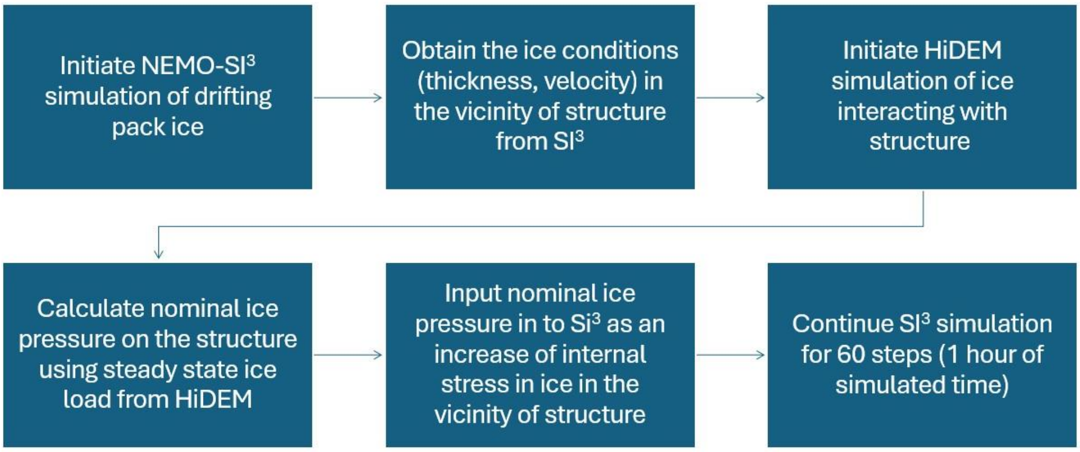
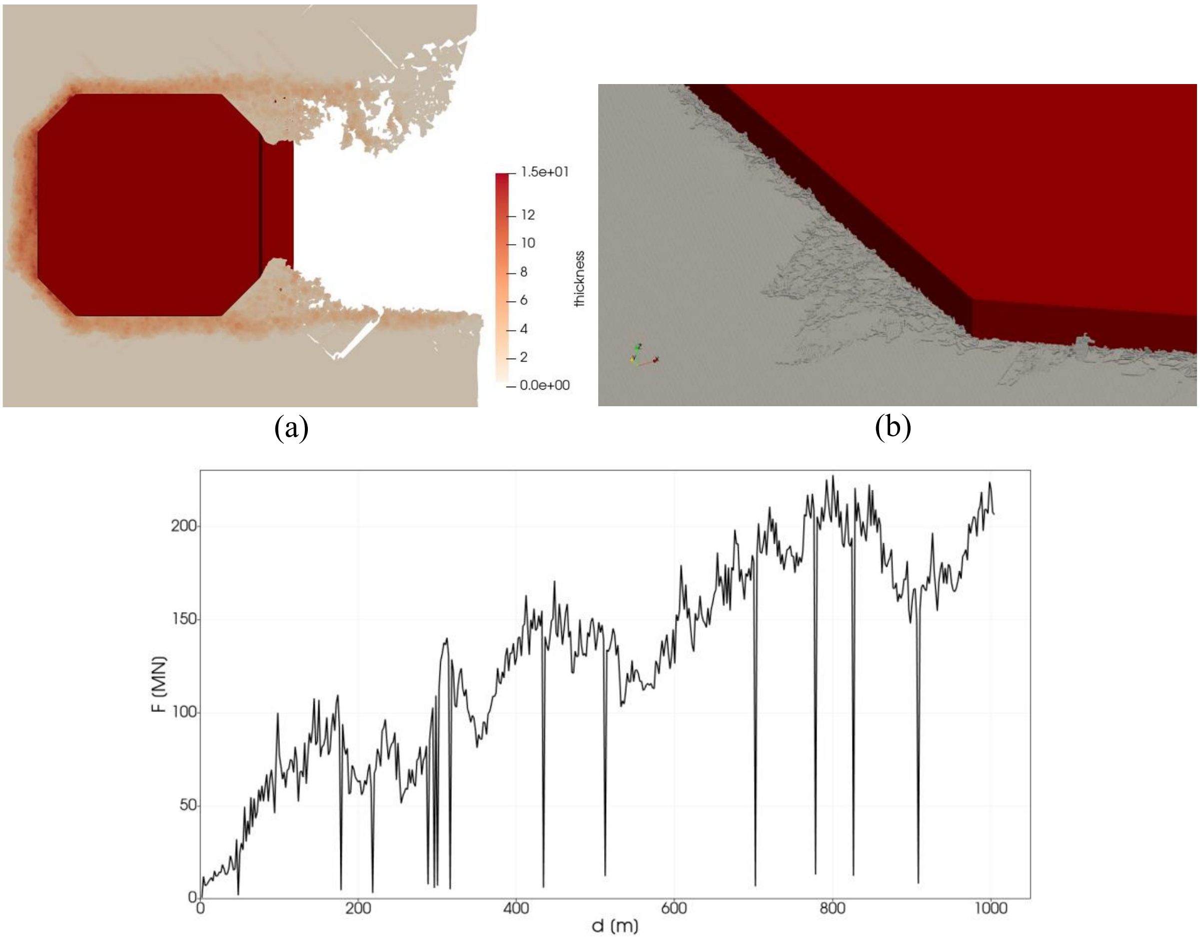


Figure 1. Flow diagram demonstrating the coupling scheme between NEMO-SI^3 and HiDEM.

3. Results

3.1 HiDEM

Figure 2 summarizes the HiDEM simulation results of an ice floe interacting with a 500x500 m octagonal shaped offshore structure. Figures 2a and b show the ice thickness around the structure and ice rubble pile forming in front of the structure, respectively, after about 1 km of ice had pushed against the structure. As seen in Figure 2a, rubble accumulation is about 15 m thick and 10 m horizontally-wide, in front of the structure. Moreover, an ice-free open water channel has formed behind the structure. The figure also shows ice accumulating in the channel walls. Rubble piled up in the channel walls, eventually get washed back into the open water area as ice drifts further away from the structure. Simulation results are in agreement with field observations of ice dynamics around large offshore structures such as Molikpaq. It is worth noting here that ice rubble get washed back in to the channel behind the structure as there is no refreezing in HiDEM. Figure 2c presents the nominal ice load on the structure, F, against ice pushed, d, obtained from HiDEM. As seen in the figure, F-d record shows a distinct saw-tooth pattern of peak loads. F builds up as the ice floe interacts with the structure and drops eventually due to the global failure of the edge of the ice floe, which in turn causes peak load events. F record shows an increasing trend with d and seems to be plateauing at about 200 MN after 750 m of ice had pushed against the structure.



(a) (b)

(c)

Figure 2. a) Ice thickness around the structure. b) A snapshot from the simulation showing ice ruble pile in front of the structure. c) Ice load on the structure, *F*, plotted against the amount of ice pushed, *d*.

3.2 NEMO-SI^3

The initial results of our coupling paradigm seem promising. Figure 3 displays the initial state in terms of thickness of the ice floe, which was set to 0.5 m with 0.99 ice concentration (as NEMO-SI^3 does not allow fully rigid ice).

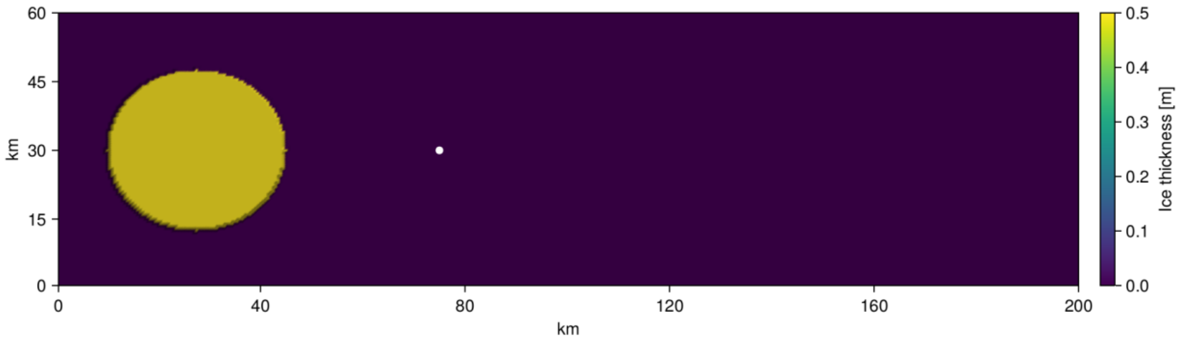


Figure 3. Initial ice thickness. The location of the offshore structure is also shown as a white spot at (75km, 30km).

In Figure 4, the situation one week after the large ice floe collided with the offshore structure, and in 4-hour intervals until the floe has passed it. Here, the effect of the offshore structure is taken into account by modifying the internal stress of sea ice in the location of the offshore structure (note that the “structure” was removed as a bathymetric boundary condition after the initial collision). As expected, the ice floe breaks around the offshore structure. There is no refreezing, as thermodynamics was switched off for simplicity. The slight decrease in ice concentration around the circular ice floe is due to numerical diffusion.

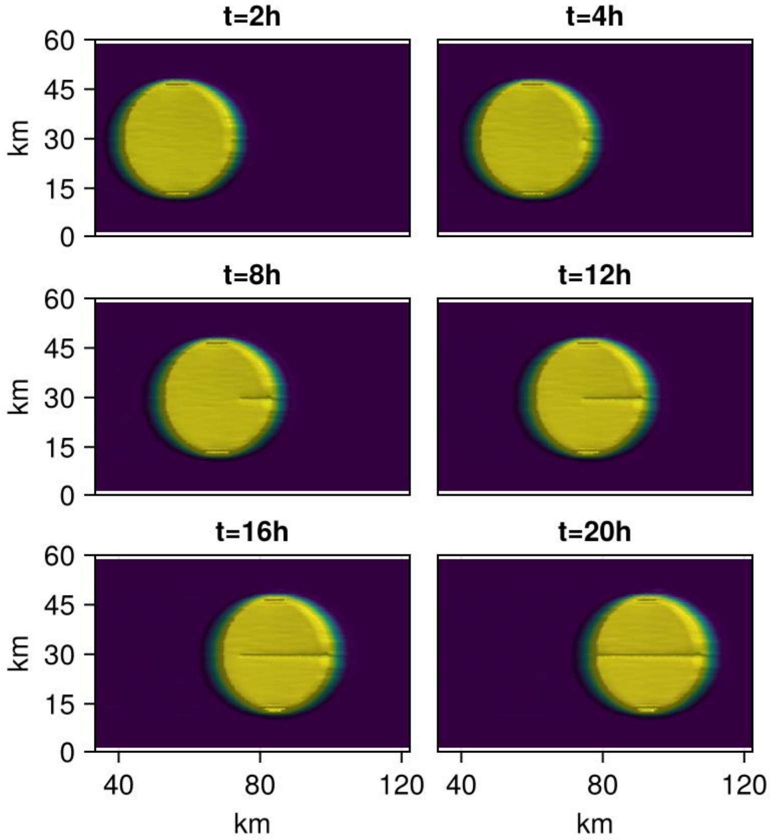


Figure 4. Ice concentration during collision with the offshore structure in 4-hour intervals. The ice floe is moving to the right. In this simulation, the coupling was accomplished via modifying the internal stress in ice.

Figure 5 shows the normal and shear stresses as output by NEMO-SI^3 during the collision event in 2-hour resolution. As in Figure 2c from HiDEM, there is build-up of stress until it plateaus, although time scales are very different.

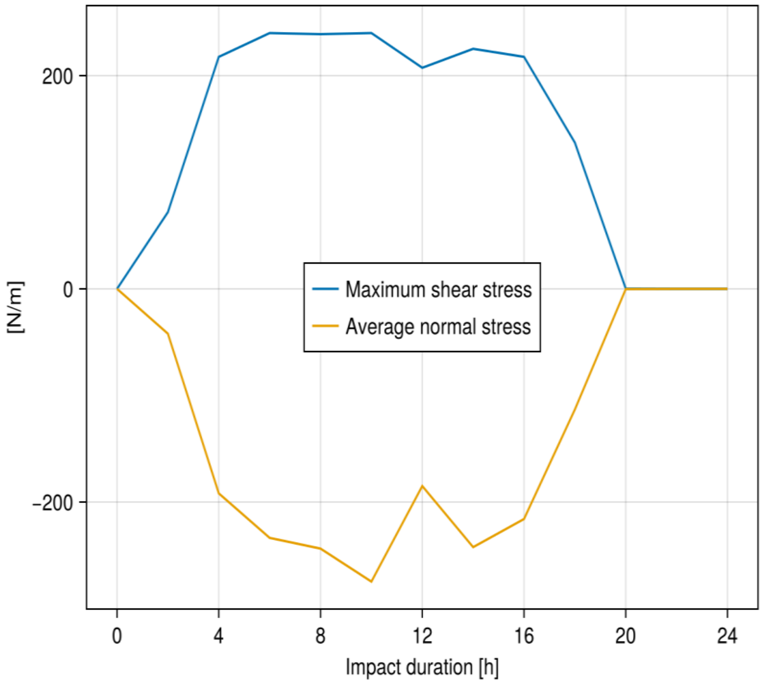


Figure 5. Stresses in sea ice at the location of the offshore structure during impact. Coupling via modified internal stress.

Figures 6 and 7 correspond to figures 4 and 5, but with the coupling accomplished by introducing an additional external stress term in the grid cell of the offshore structure. The general behavior is similar in both scenarios. Coupling via additional stress terms produces higher internal stresses in sea ice because the additional stress term was concentrated in one grid cell resulting higher stress concentrations.

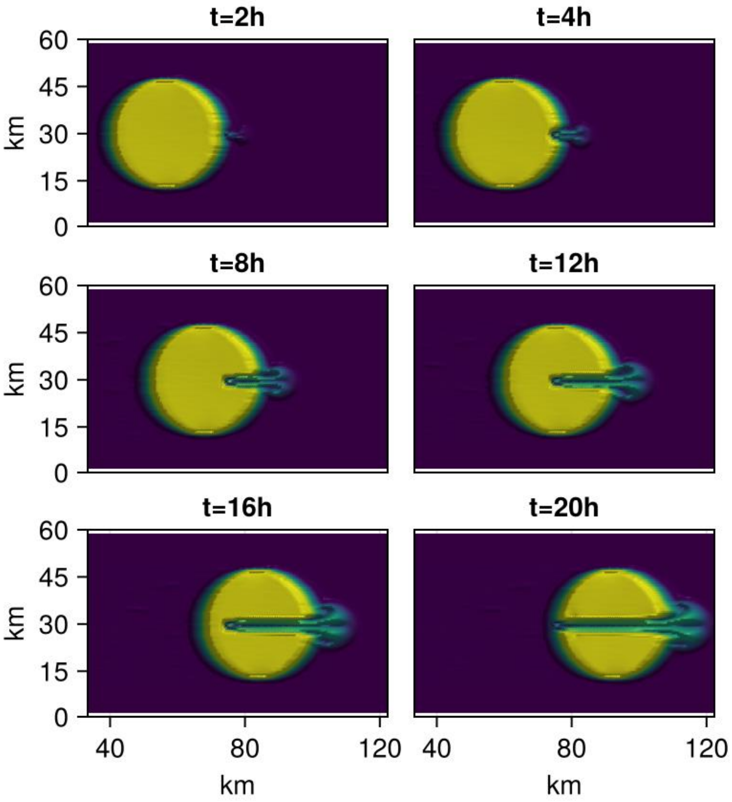


Figure 6. Ice concentration during collision with the offshore structure in 4-hour intervals. The ice floe is moving to the right. In this simulation, the coupling was accomplished via an additional stress component.

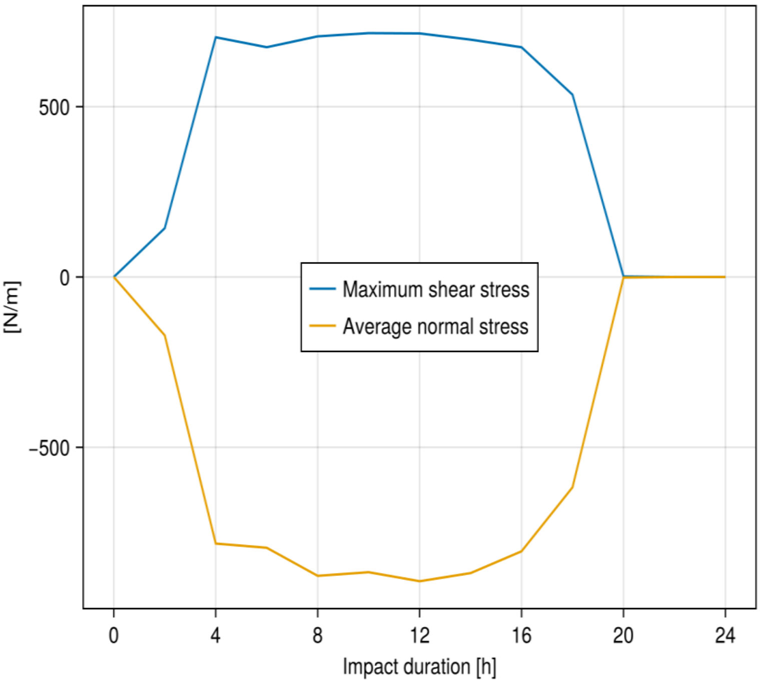


Figure 7. Stresses in sea ice at the location of the offshore structure during impact. Coupling via additional stress term.

4. Discussion and Conclusions

The present paper developed a theoretical framework for modelling interaction between pack ice and offshore structures, by combining discrete element method and finite difference method simulations. Combined simulations seem to produce sound results providing a proof of concept for the framework. We proposed two different methods for coupling the two models, and both approaches seem to produce similar results for the studied case. Nevertheless, the applicability of each method is dependent on the relative size of the offshore structure compared to the NEMO-SI^3 grid cell size. For an offshore structure which has nominal dimensions in the order of NEMO-SI^3 grid cell size, coupling simulations by modifying the internal stress tensor is preferable. This is because the presence of a large structure will affect the ice dynamics significantly in several grid cells close to the structure. On the other hand, an offshore structure which has significantly smaller dimensions compared to NEMO-SI^3 grid cell will only cause local effect on that particular grid cell. Therefore, coupling by using additional stress term is preferable in such a case.

Combined HiDEM-NEMO simulations presented in this paper were simulated by manually transferring data and initializing simulations. Thus, further work is needed to develop a fully coupled simulation scheme capable of running both tools simultaneously and communicate with each other. One of the main challenges for such setup is the substantial difference of computational times between two codes. HiDEM simulations take about 8 hours to simulate 1000 m of ice being pushed against the structure while in NEMO-SI^3 this corresponds to only two grid cells and computes practically instantaneously. Therefore, having full-length HiDEM simulations for ice drift is computationally not feasible. A plausible workaround here could be running multiple HiDEM simulations in parallel with shorter domains created based on the average ice conditions obtained from NEMO- SI^3.

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