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Preliminary FEM-DEM Study on Ice Encroachment

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ABSTRACT

Ice encroachment may cause damage on Arctic offshore structures and is one of the main considerations in the design of marine structures. Ice can ride up directly onto an inclined structure or it may accumulate on it as the broken ice pieces are pushed by the advancing ice sheet. Here we shortly present our study on ice encroachment on a wide inclined structure. The study is based on two-dimensional combined finite-discrete element method simulations. The paper examines how water depth and ice thickness influence the probability and severity of ice encroachment.

KEY WORDS: Ice encroachment; Finite-discrete element method; Ice-structure-interaction; Ice loads; Shallow water structures.

1. Introduction

Many Arctic offshore structures, such as ice barriers, artificial islands and platforms, are built in relatively shallow water. For this type of structures, ice encroachment is one of the important design considerations. Ice encroachment occurs when sea ice rides up on the top of a structure, or it may occur through pile-up, when the incoming ice is first broken into rubble and then pushed up on the structure. Intense ice encroachment may cause damage on the structure and the facilities on top of it. Ice encroachment is considered in the design of marine structures, for example, by building protective encroachment zones or by adding protective walls and ice barriers around the structure.

This paper studies the ice encroachment on top of a wide, sloping, structure in shallow water. The study is based on two-dimensional combined finite-discrete element (FEM-DEM) method (Munjiza, 2004; Paavilainen et al., 2009) simulations on ice-structure interaction process. FEM-DEM allows modelling the intact ice sheet and its failure based on FEM, while the interaction between the individual ice blocks is handled using DEM (Cundall and Strack, 1979). In the simulations of the paper, an intact ice sheet moves with a constant velocity against a sloping structure and fails into ice blocks, which form a rubble pile of ice in the vicinity of the structure (Figure 1). The ice blocks forming in the simulated process may interact with each other, the structure and the seabed, and they may ride and pile up on top of the structure.

The study focuses on examining how water depth and ice thickness affect the frequency and severity of ice encroachment. First, we describe the simulations and after this, we present our results on ice encroachment. After a brief analysis of the results we compare our work with earlier studies and conclude the paper.

2. Methods

In the numerical simulations conducted in this paper, an intact ice sheet was pushed with a constant velocity against a wide sloping rigid structure. When colliding with the structure, the initially intact ice sheet failed into separate ice blocks, which were able to interact with each other, the structure and the sea floor (Figure 1). The intact ice sheet and the separate ice blocks, when consisting of more than one discrete element, were modelled using visco-elastic non-linear Timoshenko beam elements. The ice beam failure was modelled using a cohesive crack model, which considered mixed mode failure due to bending and shearing. The interaction between the individual ice blocks, the structure, and the seabed were calculated using elastic-viscous-plastic normal and incremental Mohr-Coulomb tangential force models. The code is described in detail in Paavilainen et al. (2009) and validated against full- and model scale data in Paavilainen et al. (2011) and Paavilainen and Tuhkuri (2012).

Results of this paper are based on 120 simulated ice-structure interaction processes. The simulation parameters are presented in Table 1. In the simulations the ice thickness h, water depth D and seabed angle α (see Figure 1) were varied. The simulations were divided into sets 1-8 based on the parameter values as summarized by Table 2. Between the simulations in each set, the value of α varied (either 0, 10 and 20°), but otherwise the parameters were identical. Water depths were chosen so that the ratio D/h was equal for both ice thicknesses. Each set contained five replicate simulations with the same parametrization, but different initial velocity of the free end of the ice sheet v_0 (initial velocity was always a fraction of a mms^{-1}). This was enough to result in different ice loading processes in simulations with the otherwise same parametrization (see Ranta et al. (2017, 2018) for details). The ice sheet moved with a constant velocity of 50 mms^{-1} and each simulation ended when the length of ice pushed against the structure reached the value $L = 250$ m. Figure 2 shows the horizontal force record for both the structure and the seabed, as a function of L.

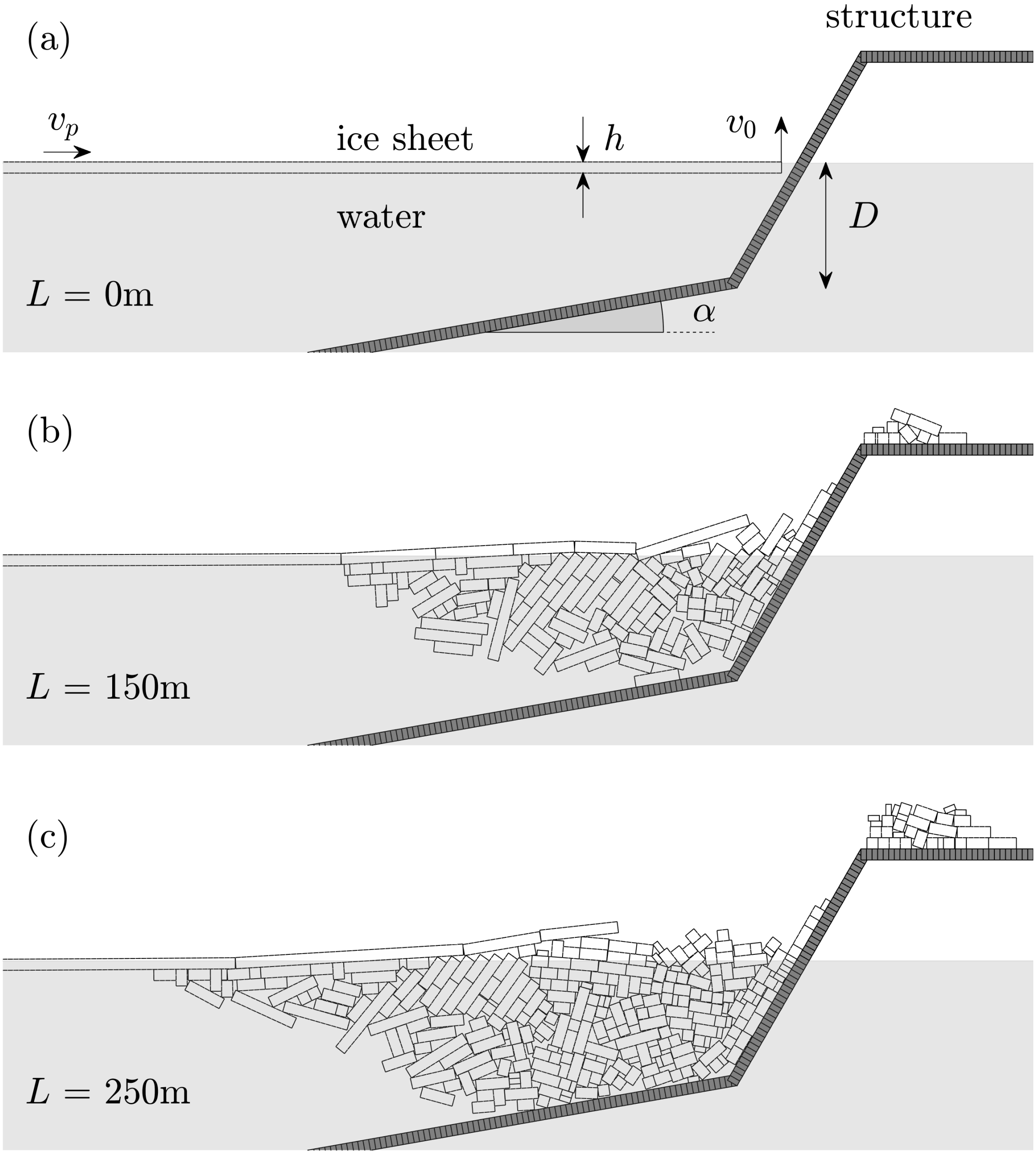

Figure 1: Snapshots from three different stages of a simulation, which had ice thickness h = 0.5m, water depth D = 5m and seabed angle α = 10°. L is the length of the of ice sheet pushed against the structure. First figure shows the initial vertical velocity v_0 used to generate different ice loading processes in simulations with the same parameterization.

3. Results

As this paper focuses on the effect of water depth and ice thickness on the frequency and severity of ice encroachment, we first studied how the probability of ice encroaching during the entire simulation was influenced by these factors. P(encroachment) is the probability of ice encroachment during the entire simulation and is obtained by calculating the fraction of all the cases that had any ice on top of the flat surface of the structure at the instance L = 250 m. The amount of ice is not considered here so as soon as the first piece of ice moves on top of the structure ice encroachment is occurring. Figure 3 shows P(encroachment) plotted against the relative water depth D/h. The probabilities for the ice thicknesses h = 0.5 m (simulation sets 1-4) and h = 1.25 m (sets 5-8) are presented with blue and red points, respectively.

Table 1: Main simulation parameters. Ice properties are mostly based on Timco and Weeks (2010)

	Parameter	Symbol	Unit	Value
General	Time step	Δt	s	$2.0 \cdot 10^{-5}$
	Element length	L_0	m	0.25
	Gravitational acceleration	g	m/s^2	9.81
	Ice sheet velocity	v_p	m/s	0.05
	Drag coefficient	d_c	-	2.0
Ice	Thickness	h	m	0.5, 1.25
	Effective modulus	E	GPa	4
	Poisson's ratio	ν	-	0.3
	Density	ρ_i	kg/m^3	900
	Tensile strength	σ_f	kPa	600
	Shear strength	τ_f	kPa	600
Contact	Plastic limit	σ_p	MPa	2.0
	Ice-ice friction	μ_i	-	0.3
	Ice-structure friction	μ_s	-	0.3
	Ice-bottom friction	μ_b	-	0.3
Water	Density	ρ_w	kg/m^3	1010
	Depth	D	m	$2 \ldots 20$
Structure	Structure angle	α	$^\circ$	60
	Seabed angle	β	$^\circ$	0, 10, 20

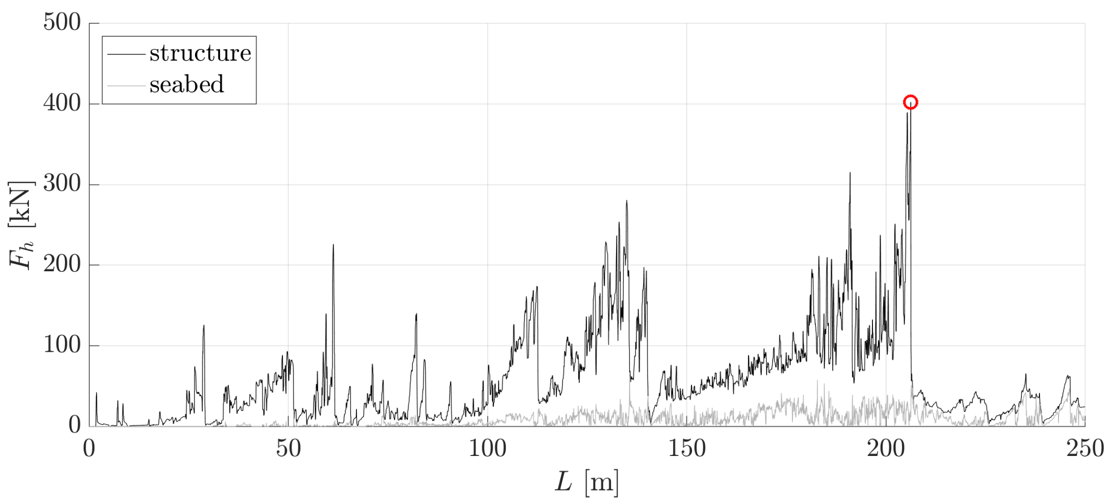

Figure 2: The horizontal ice load F_h on the structure and the seabed as a function of the ice pushed against the structure L. The maximum peak load applied on the structure is marked with red circle. The force data of the figure is filtered with a median filter. The simulation parameters are $h = 0.5$ m, $\alpha = 0^\circ$and $D = 4$ m.

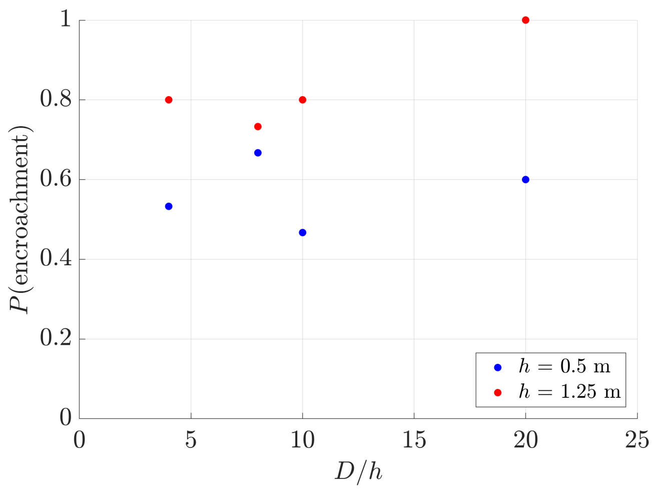

Figure 3: The probability of ice encroachment P(encroachment), plotted against D/h. The blue points stand for h = 0.5 m and the red points for h = 1.25 m.

Figure 3 shows that the probability of ice encroachment for all values of D/h is higher for the thicker than the thinner ice. Accounting for all of the data in the figure, ice encroachment for ice having the thickness h = 0.5 m occurred with the probability of about 60 %, whereas the probability of the ice having the thickness h = 1.25 m to encroach was about 80 %. This difference could be expected, as the thicker ice has a greater load bearing capacity, which allows it to push larger volumes of ice up along the structure and on top of it. Figure 3 further shows that P(encroachment) does not show any clear trend with changing relative water depth D/h, which means that the water depth does not appear to have an effect on P(encroachment) according to our simulations.

We also examined the severity of the encroachment by studying how much ice had encroached on top of the structure at the end of the simulation. Figures 4 and 5 show the volume of encroached ice V_E and the encroachment length L_E as functions of the relative water depth D/h for each simulation and the mean values of these parameters for each D/h. The values are shown separately for h = 0.5 m and h = 1.25 m in Figures a and b, respectively. The length of encroachment L_E describes how far from the inclined face of the structure ice fragments have advanced (see Figure 6). Figure 6 shows a snapshot from the end of a simulation with severe encroachment.

Table 2: Simulations sets of this paper. Five replicate simulations for each combination of parameters were conducted.

Set	h [m]	D [m]	D/h [-]	α [°]
1	0.5	2	4	0, 10, 20
2	0.5	4	8	0, 10, 20
3	0.5	5	10	0, 10, 20
4	0.5	10	20	0, 10, 20
5	1.25	5	4	0, 10, 20
6	1.25	10	8	0, 10, 20
7	1.25	12.5	10	0, 10, 20
8	1.25	20	20	0, 10, 20

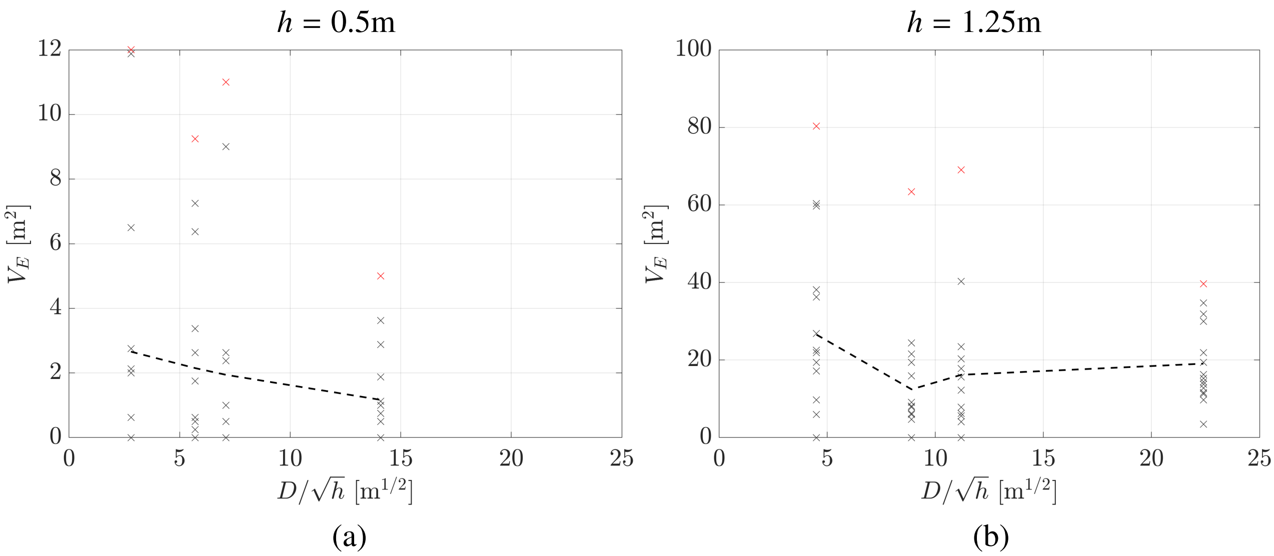

Figure 4: The volume of encroached ice V_E on top of the structure at the end of the simulation as a function of D/h for each simulation and the mean value of V_E for each D/h-value. The volumes and their mean values are presented (a) for ice thicknesses $h = 0.5$ m and (b) for $h = 1.25$ m. The maximum values of V_E for each D/h are marked with red. The reader should notice that the scale of vertical axis is different for the two figures.

According to Figures 4 and 5, the mean values of both, V_E and L_E, are significantly higher for the thicker ice than for the thinner one. On average, V_E and L_E for $h = 1.25$ m are, respectively, approximately five and two times higher than for $h = 0.5$ m. With small values of the relative water depth D/h, the differences are even higher. Even if the standard deviations are large, Figures 4 and 5 suggest that the mean values of both V_E and L_E seem to decrease with increasing D/h ratio and reached their highest average value with the shallowest water. Thus, the water depth appears to have an effect on the severity of the encroachment while not having a noticeable effect on the probability of it (Figure 3).

Table 3 summarizes the extreme cases of encroachment in our simulations by showing the maximum values of V_E and L_E for all simulation sets. These values are presented with red markers in Figures 4 and 5. These maximum values behave very similar to V_E and L_E and decrease with both, increasing relative water depth D/h and decreasing ice thickness. The smallest values of V_{Emax} and L_{Emax} are reached with $h = 0.5$ m and $D/h = 20$, whereas the largest values of V_{Emax} and L_{Emax} are reached with $h = 1.25$ m and $D/h = 4$. With $h = 1.25$ m and $D/h = 4$, the length of encroachment reached up to approximately 22 m along the flat surface of the structure and up to 80 m^2 of ice was pushed onto the structure (Figure 6).

Table 3: The maximum encroachment levels shown for different values of D/h and ice thicknesses h. V_{Emax} stands for maximum volume of encroachment and L_{Emax} signifies the maximum length of encroachment for each set of simulations. These maximum values are marked with red in Figure 4 and 5.

	h = 0.5 m		h = 1.25 m	
D/h	V_{Emax} [m^2]	L_{Emax} [m]	V_{Emax} [m^2]	L_{Emax} [m]
4	12.0	7.9	80.3	22.0
8	9.3	7.0	63.4	21.9
10	11.0	6.9	60.1	20.4
20	5.0	5.7	39.7	16.4

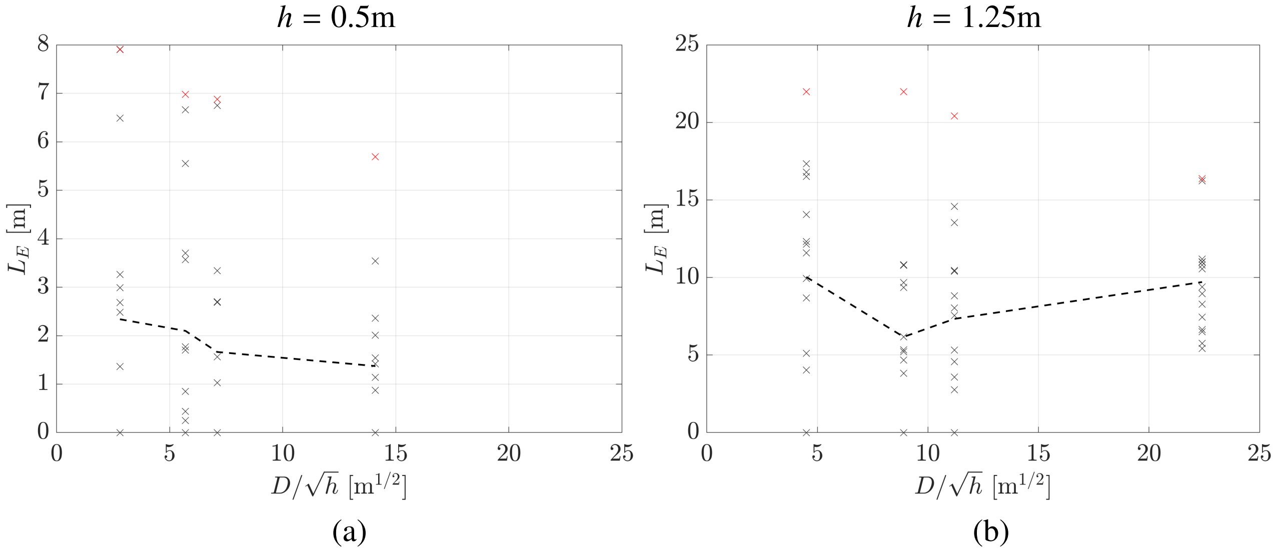

Figure 5: The lengths of encroached ice L_E at the end of the simulation as a function of D/h. L_E describes how far to the right the ice has moved on the flat top surface of the structure. The encroachment lengths and their mean values are presented for $h = 0.5$ m and $h = 1.25$ m in (a) and (b), respectively. The maximum L_E values for each D/h are marked with red. The reader should notice that the scale of vertical axis is different for the two figures.

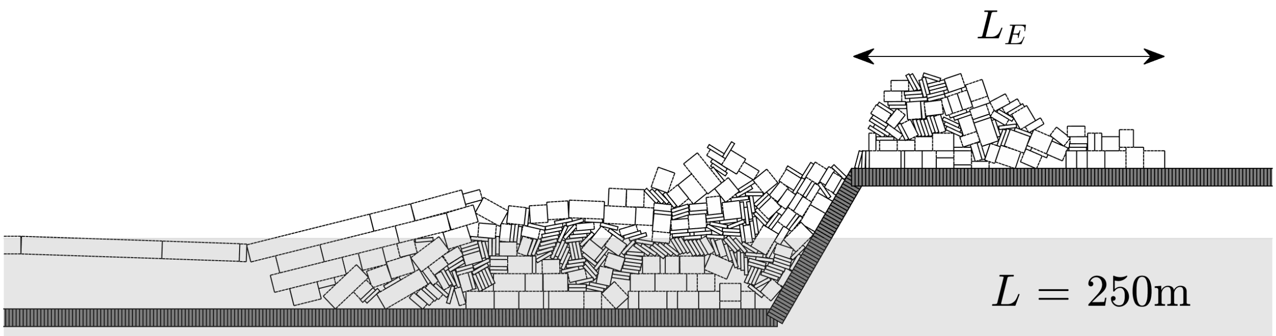

Figure 6: A snapshot from the end of a simulation simulation with severe ice encroachment. Here the ice thickness was $h = 1.25$ m and water depth $D = 5$ m and the length of the encroached ice L_E reached 22 m along the flat surface of the structure.

4. Discussion

Our simulations suggest that ice encroachment becomes more severe when the ice thickness increases. This was shown by both, the volume of encroached ice and the distance of the encroachment, being significantly higher for thick than thin ice (Figure 4 and 5). This result is in line with Li et al. (2009) and McKenna et al. (2011) who, based on full-scale ice encroachment events and physical model tests, reported that thick ice is more prone to produce ride-up, which leads to high encroachment lengths. On the other hand, according to them, thin ice tends to produce a pile-up.

Also according to Li et al. (2009) and McKenna et al. (2011), ice encroachment occurs more frequently for thin than thick ice. Our simulations yield somewhat different outcome as the probability of encroachment was about 10 . . . 20 % higher for thick that thin ice. One potential reason for this discrepancy could be in the driving force. Assuming constant driving force, the thin ice is in nature more easily moved by winds and currents than the thick ice. Also, encroachment with thicker ice requires higher driving force than encroachment with thinner ice. Here the ice sheet was moved towards the structure with a constant velocity, which effectively means that the driving force was unlimited. Thus, there can be no effect related to the magnitude of the driving force.

Ice encroachment is often associated with shallow water structures. However, our simulations did not show a clear effect of water depth on the probability of ice encroachment (Figure 3). Even if not strongly affecting the probability of encroachment, the severity of encroachment appears to be influenced by the water depth in our simulations. This differs from the observations by McKenna et al. (2011), who did not find a clear effect of water depth on encroachment heights or lengths in full-scale. The full-scale events, however, might have varied a lot and the data related to them was from vertical structures. A different result could be obtained in full-scale for inclined structures.

5. Conclusions

This paper focused on ice encroachment and on how the water depth and ice thickness influence it. The study was based on 2D FEM-DEM simulations on the ice loading process against a wide sloping structure in shallow water. Our simulations showed that both the probability and the severity of ice encroachment increases with increasing ice thickness. Further, we did not observe the water depth to have an effect on the probability of ice encroachment, but significantly more severe ice encroachment seems to occur when the water is shallow.

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