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4.1 Introduction

Sea ice is the key challenge to all human operations, such as those related to winter navigation or offshore wind energy harvesting, in cold sea areas (Figure 4.1a and b). Design of the vessels and other structures related to these operations requires insight on the mechanical behavior of sea ice at engineering scale, which can be said to reach from fractions of millimeters up to some kilometers. It is difficult to uniquely define when the ice engineering or ice mechanics research started, but ships meant for operations on ice-covered seas and structures such as bridges or peers, designed to withstand ice loads, have existed for centuries. One of the early scientific papers, if not the first, on ice engineering is the work by Runeberg (1889) on design of ice-breaking ships for the Baltic Sea. This chapter provides a short introduction to ice engineering research by describing some of its central topics and related mechanical phenomena occurring in sea ice. Thorough descriptions on ice engineering and ice mechanics, and the topics presented here, have been collected in textbooks by, for example, Sanderson (1988), Schulson and Duval (2009), or Palmer and Croasdale (2013).

Perhaps the most well-known ice engineering application is the design of ice-going ships. An engineer might need to estimate the total ice resistance on a ship to define the engine power it needs to advance in given ice conditions, or the goal could be to design a structural part of the ship so that it can withstand ice loads without failing. The applications in the focus of this chapter are, however, those related to bottom-fixed offshore structures. Such structures have traditionally included coastal and port infrastructure, offshore structures such as lighthouses, and platforms and support structures for hydrocarbon extraction. Currently, very topical ice engineering application is the design of offshore wind turbine foundations and other structures related to harvesting offshore wind energy. As will be described later, these are structures with special characteristics and their optimal design requires state-of-the-art ice engineering research.

Often the first focus of ice engineering is not the structural design but rather the mechanical behavior and failure of sea ice. It is the failure process of sea ice under various conditions that must be understood; structural design can only start after one is able to characterize the loads required to make the sea ice fail. The ice failure process includes

Sea Ice: Its Physics, Chemistry, Biology, Geology and Societal Importance, Fourth Edition. Edited by David N. Thomas.

(a) (b)

Figure 4.1 Two examples of structures requiring ice engineering research: (a) ice-breaking research vessel S.A. Agulhas II and (b) first offshore wind turbines meant for sea areas with annual ice cover located in Finnish waters in Tahkoluoto offshore windfarm at Northern Baltic Sea. *Source:* Photos by Jukka Tuhkuri, Suomen Hyötytuuli Oy.

all ice deformation and fracture processes, which occur as the ice fails against a structure. Owing to its focus on ice failure processes, the ice engineering research yields findings important for other disciplines related to sea ice as well. For example, geophysical-scale sea ice dynamics is dependent on the underlying engineering-scale mechanical phenomena, such as the ice ridge formation discussed later (Leppäranta, 2011). Ice failure processes are complex, and improving the accuracy of ice load estimates is still needed (Timco and Croasdale, 2006). Nevertheless, standards related to the ice engineering applications exist (ISO/19906, 2019). The standards include information on, and techniques for, estimating ice loads. Due to the uncertainty related to ice load estimates, standards are still far from a recipe for engineering design. Efficient design of offshore structures cannot be performed by solely relying on the standards, but thorough insight on the ice-loading processes and the data presented in the standards is needed.

The following is organized as follows. Section 4.2 provides a brief overview on most important engineering-scale material properties of ice. Section 4.3 describes some of the most central features of typical ice failure processes, presents models that are used to estimate ice loads related to them, and discusses the physical phenomena related to them. Since full-scale observations and laboratory-scale experiments form the basis for the validation of the ice engineering models, Section 4.4 gives examples of full-scale ice load measurements and describes how model-scale experiments are used in ice engineering. Section 4.5 focuses on numerical modeling and describes common techniques utilized in simulations of ice-loading processes. Section 4.6 concludes the chapter with remarks on future directions for ice engineering research.

4.2 Engineering properties of ice

General focus in ice engineering is in understanding the loads related to ice failure processes under various ice conditions. Models for these processes often rely on measurable material properties of ice. The material properties of first interest, on the other hand, depend on the engineering application. This section introduces the material properties of ice that are most important in many engineering applications. The following will not provide an exhaustive list of all engineering properties of ice, but an interested reader can learn more from, for example, the review by Timco and Weeks (2010).

4.2.1 Ice thickness

Ice thickness is a key measure related to the severity of the ice conditions and the magnitude of ice loads. Even if not a material property *per se*, thickness has a major role in engineering design, and it is practically always the first parameter considered, when estimating ice loads on a structure. Ice thickness is also one of the only descriptors for ice conditions, for which consistently recorded data exists over long periods for many sea areas. Ice thickness in ice engineering typically refers to the thickness of level ice and not to the thickness of deformed ice or ice ridges. This does not mean that the ice ridges would not be an important factor in the design of offshore structures. Rather, this division is made because the mechanical behavior and the failure of ice ridges, and modeling of the related loads, all differ drastically from those of the level ice.

The magnitude of the ice loads always increases with an increase in ice thickness. It is likely intuitive that the maximum load transmitted by a thick ice sheet before its failure is higher than the load transmitted by a thin ice sheet. Thickness may also influence how the ice failure occurs, that is, what the failure mode of the ice is. The detailed relation between the thickness and the load depends on the failure mode. In addition, the failure process of a thick ice sheet results in larger ice rubble piles than that of thin ice, which may influence the magnitude of the ice loads. Ice thickness also affects ice ridges, since the loads needed for ridge formation and the size of the ridges both increase with the ice thickness.

For the sea areas where detailed observations on ice thickness do not exist, ice thickness can be estimated by using freezing degree days (FDDs) described in Chapter 1. Standards instruct estimating the level ice thickness by using semiempirical equations that rely on the FDDs and field observations from various sea areas (ISO/19906, 2019). The observations are needed as, for example, snow damps the effect of cold atmospheric temperatures on ice growth (Weeks, 2010). In any case, relying on the FDDs is very likely to lead to conservative estimates on the ice thickness. This is positive from the aspect of the safety of offshore structures but poses a disadvantage for the structural optimization. Another challenge related to use of FDDs relates to the drift ice. In the regions where the ice does not move, estimating the level ice thickness based on FDDs is justified, while the sea areas with drift ice could have thick ice entering them from other colder sea areas.

4.2.2 Ice strength and contact pressure

In addition to the ice thickness, compressive and flexural strength of the sea ice are often considered as important material properties in ice engineering. Chapter 1 already described how compressive and flexural strength of the sea ice are defined and measured by using uniaxial compression experiments and flexural strength experiments. To summarize, the compressive strength is the maximum compressive stress that an ice specimen can sustain before it fails, while the flexural strength indicates how much out-of-plane loading an ice specimen can withstand before its failure. In both cases, the higher the strength, the higher the load-bearing capacity of the ice. Hence, it appears intuitive that the ice strength affects the ice loads on a structure, and it often does, but it is at least difficult, usually impossible, to define the magnitude of the ice load based on the ice strength and geometrical parameters of the ice only as will be discussed later.

The compressive strength of sea ice is often regarded as one of its most important engineering properties, particularly because ice tends to fail under compression in various engineering applications. Due to this, a relatively vast body of research has focused on this material property. Several factors influence the measured values of the compressive strength of ice. These factors can be related either to the intrinsic properties of ice or to the experiments used to measure the strength. The latter factors include, for example, the rate of applied loading, boundary conditions during testing, and sample preparation (Schulson & Duval, 2009b; Timco & Weeks, 2010b). When compressive strength values of ice are reported, they are of little use, if they do not include information on these factors. From the aspect of ice engineering, an important feature is the so-called ductile-to-brittle transition. In brief, when ice is subjected to a slow loading, it behaves in a ductile manner, whereas under rapid loading, it tends to go through a brittle failure.

It has also become common to measure the flexural strength of sea ice as already described in Chapter 1. The flexural strength is not a fundamental material property of ice. When an ice specimen is forced to fail due to out-of-plane deformation, the failure initiates due to tensile stresses. The experiments conducted to accurately measure the tensile strength of sea ice remain sparse, likely due to the challenging and time-consuming nature of such tests (Timco & Weeks, 2010). Experiments on flexural strength, on the other hand, are relatively easy to perform even on large ice specimens *in situ*. In a typical field experiment, a cantilever ice beam is cut off from the ice field and pressed down until the beam fails. Results from flexural strength experiments are used in several applications of ice engineering. Flexural failure is one of the governing modes of ice failure, when moving ice sheet fails against an inclined structure. Also, the loads related to ice-breaking process are related to the flexural failure of ice.

4.2.3 Ice fracture

Fracture mechanics is a branch of applied mechanics studying fracture processes dominated by cracks. The application of fracture mechanics to ice initiated in the 1970s through measurements of fracture toughness, K_{IC}, of ice. Fracture toughness is a parameter used in linear elastic fracture mechanics (LEFM) and is the critical value of stress intensity factor, a parameter describing the stress state near a crack tip. As the name states, LEFM assumes both elasticity and linearity, and its application should be limited to such cases. Ice is linearly elastic only when cold and when loaded at high rates, but LEFM is still often used in ice studies.

A more general theory that has been used for ice is the fictitious crack model, also called cohesive zone model. In that model, a fracture process zone (FPZ) is assumed in front of a crack tip and the softening behavior inside the FPZ is described by a stress-separation law. The material response outside the FPZ is governed by a constitutive relation of the bulk material. Mulmule and Dempsey (1997) have developed a viscoelastic fictitious crack model for ice.

The fracture properties of ice are sensitive to scale. The fracture toughness of sea ice has been shown to increase with size of the specimen tested, until the dimensions are of the order of several meters (Mulmule & Dempsey, 1999; Dempsey et al., 2018). This makes the interpretation of small-scale laboratory data challenging. In addition, these dependencies are interrelated. At least for warm columnar freshwater ice, a scale effect was observed only for slow loading; at fast loading there was no scale effect (Gharamti et al., 2021b). Similarly, no rate effect was observed, if the specimen size was 0.5 m, but a rate effect was observed for specimen with a size of 3 m. The fracture energy of ice has been measured to increase with decreasing strain rate. In experiments with warm columnar freshwater ice, when the time to failure increased from 2 to 2000 seconds, the fracture energy increased from about 2 to 12 $N\ m^{-1}$. For sea ice, fracture energies in the range of $10 - 15\ N\ m^{-1}$ have been measured.

4.2.4 Other properties

In addition to the above-described main engineering properties of ice, there are also several other properties commonly determined for sea ice, such as ice salinity, grain size, ice temperature, and ice density. From the perspective of ice engineering and ice load estimates, it is common to focus on the effect of these properties to ice strength, since this is a property that can be connected, even if in a complicated manner, to the ice loads. It is, for example, known that the flexural strength of ice increases with decreasing ice salinity and grain size. It is also known that the mechanical behavior and fracture process of sea ice change with temperature. Even if many of the ice properties do not have direct application in ice engineering, it is important to emphasize that all well-defined properties of sea ice contribute to our understanding of sea ice as a material.

4.3 Sea ice failure and ice loading

Ice loading on an offshore structure is a result of an ice failure process, during which the ice load varies as a function of time. Roughly, given the driving forces moving the ice sheet are large enough, the magnitude of the ice load depends on the failure mode of ice and sometimes on the amount of ice piled-up against the structure. The failure mode, on the other hand, mainly depends on the ice velocity and on the size and the geometry of the structure. From these aspects, the ice-loading processes can be divided into two categories (Figure 4.2): (i) processes where the flexural failure of ice is the governing failure mode with ice rubble having an important role and (ii) processes where the crushing failure and dynamic interaction of the ice and the structure dominate the ice load on the structure (Sanderson, 1988). One could roughly say that an ice sheet will fail in bending against an inclined structure and by crushing against a vertical structure. Overall, during an ice–structure interaction process, the ice fails into a myriad of fragments of various sizes and shapes, which may accumulate against of the structure, and affect the subsequent failure events (Daley et al., 1998). The processes leading to ice loads are, thus, much more complicated than the ice failure in typical material tests, which partly explains the above-described fact that the ice load on a structure cannot be obtained directly from the material properties, say compressive strength of ice, for example.

4.3.1 Bending-dominated ice-loading process

When an ice sheet is pushed against an inclined structure, it must start to ride up the structure and initially fails due to bending failure (Figure 4.2a). Perhaps the simplest analytical model for this scenario is that of a beam on an elastic foundation (Hetenyi, 1946), where the elastic foundation is due to the buoyant force of the water. When compared to compressive ice failure, the ice load related to bending failure is small in magnitude. This is why the offshore structures designed for ice-covered waters often have inclined structural parts near the water line; port structures may have wide sloping faces, while narrow structural members may be furnished with ice cones at their waterline. Also, the ice-breaking vessels have hull shapes, which make them press the ice downward to make it fail in bending. The force related to the bending failure is vertical, but has a horizontal component, which depends on the inclination angle of the structure and on the friction between the ice and the structure (Sanderson, 1988). This horizontal ice load component is often of first interest in engineering applications.

When the ice sheet continues its motion toward the inclined structure, it keeps on gradually failing into a rubble pile of ice blocks. The ice rubble forming in the process usually consists of initially fairly large ice pieces that have their dimensions depending on the characteristic breaking length of the ice sheet. The ice rubble may significantly affect the magnitude of the ice load on the structure, which has to support the weight of the ice mass. Depending on the width of the structure, the rubble pile may eventually clear due

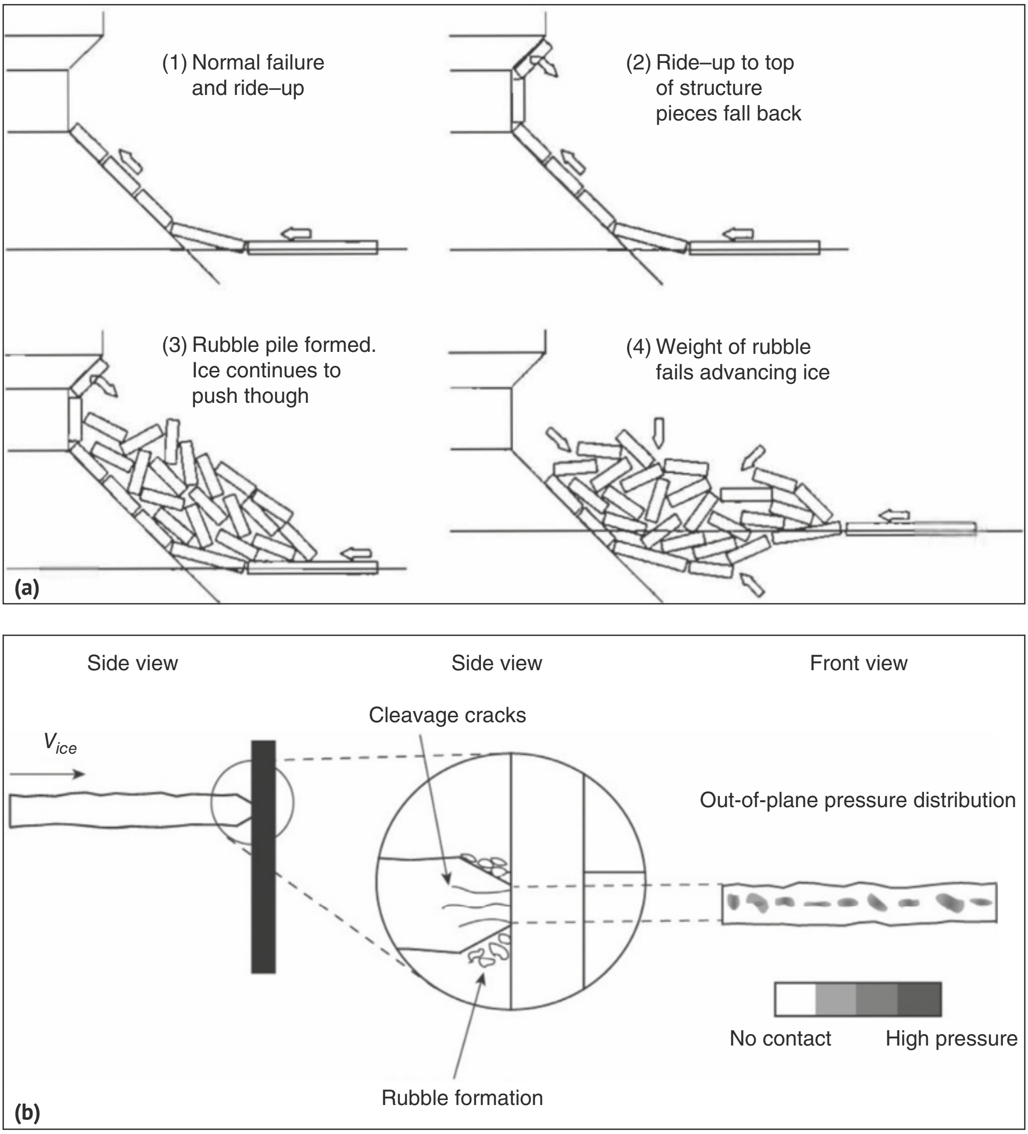

Figure 4.2 Two types of ice-loading processes: (a) ice failing against an inclined structure in a process, where the main failure mode of ice is bending and the ice rubble pile-up has an important role Adapted from (Croasdale, Cammaert and Metge, 1994), and (b) ice interacting with a vertical structure in a process where the governing ice failure mode is crushing and where the dynamic interaction between the structure and the ice is important (Hendrikse, 2017) / Delft University of Technology.

to moving around the structure or due to the failure of the advancing intact ice (Figure 4.2a). This leads to a drop in the magnitude of the ice load. The ice rubble pile is also assumed to affect the loading process by, for example, hindering the flexural failure of the ice sheet and by resisting the motion of the ice sheet toward the structure (Croasdale et al., 1994). Further, the governing failure mode may occasionally transform from bending into a compressive failure due to confined conditions inside the rubble pile. The intact ice may also start to fail against the rubble in compression or by buckling (Paavilainen & Tuhkuri, 2013; Ranta et al., 2018; Ranta & Polojärvi, 2019).

ISO/19906 (2019) standard suggests treating the bending-dominated ice-loading processes by using a so-called plastic method for cones (Ralston, 1977) and an elastic method for other inclined structures (Weeks, 2010). Both of these methods yield an upper bound solution for the ice load. The main variables assumed to affect the ice load include the inclination angle and the width of the structure, the thickness, the yield strength, the flexural strength of ice, and the coefficient of friction. In addition, the elastic method uses material properties of the ice rubble, which are challenging to determine (Liferov & Bonnemaire, 2005). In a bending-dominated ice-loading process, the structural response is usually assumed to not affect the response of the incoming ice. This assumption simplifies the analysis, as there is no need to couple the structural response with the ice behavior.

4.3.2 Crushing-dominated failure process

Assume an idealized failure process where an ice sheet comes into a compressive contact with a vertical structure. In this case the load applied on the structure is transmitted through the contact pressure at the ice–structure interface, and the magnitude of the load can increase until the ice fails under compression. Why does it remain a challenge to estimate the ice load based on compressive strength of ice? One important reason is a nonintuitive feature related to the contact pressure of ice: The maximum nominal contact pressure appears to decrease when the scale of the interaction process increases, as depicted by the so-called pressure-area curve presented in Figure 4.3 (Sanderson, 1988). The figure shows data on the global contact pressure, $P = F/A_n$, where F is the magnitude of the ice force on a structure (or measured in an experiment) and A_n is the nominal contact area, often defined by multiplying the ice thickness by the width of the structure. The data of the figure shows wide scatter, which is not surprising as it collects data from various sources and includes various ice types and structural geometries. Nonetheless, P shows a clear decreasing trend with increasing A_n.

The general features of the ice behavior leading to pressure-area effects are empirically relatively well understood. The first detail to understand is that there are only very few conditions, where the ice load becomes transmitted over the whole nominal contact area A_n. Usually, the true contact area is much smaller than A_n, as it has been observed that the pressure is transmitted to the structure through a line-like contact and distinct zones of high pressure. In other words, ice failure occurs at distinct locations independently, not simultaneously across the width of the structure. This phenomenon is known as nonsimultaneous failure and it occurs when the ice velocities are at least moderate and ice behaves as a brittle material. Perhaps only in a well-controlled compression experiments the contact area is truly equal to A_n. Further, the contact areas related to scenarios where the ice moves very slowly, and creeps may be approximately A_n. It is due to this effect that ice loads of very high magnitude may be measured when the ice velocities are slow. Another important detail to realize is that P in Figure 4.3 is limited by different types of failure processes in different scales. In a typical laboratory-scale experiment, ice specimens are limited in size and P is limited by the specimens failing due to shearing or splitting (Schulson & Duval, 2009). On the largest scale of Figure 4.3, on the other hand, the values of P are related to those used in geophysical-scale ice dynamics simulations. As will be described later, it is often assumed that the strength of the sea ice sheet is limited in this case by the ice ridge formation process.

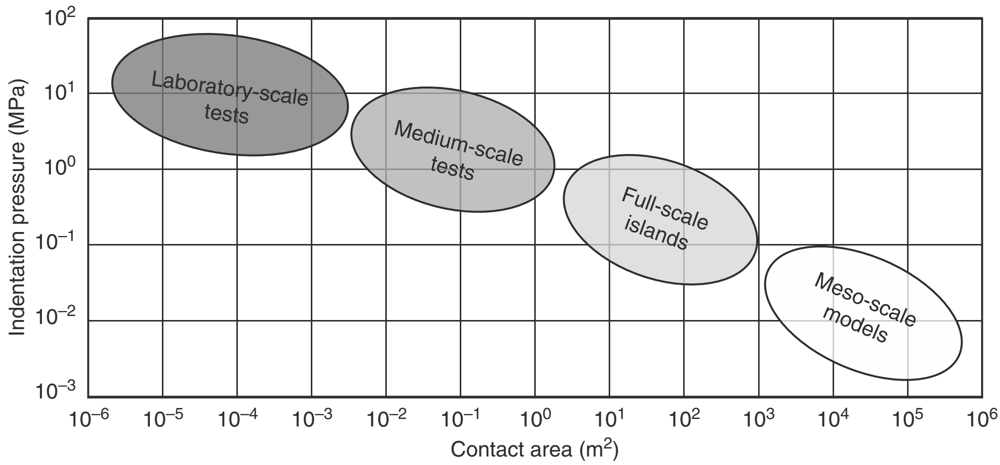

Figure 4.3 Nominal indentation pressure is scale dependent as described by pressure-area curve. The graph shows the maximum compressive pressure ice can transmit as the function of contact area. The data source for each group of data is given. The figure is adapted from Sanderson (1988) / Office of Scientific and Technical Information / Public Domain.

When estimating ice loads on vertical structures for engineering purposes, the strength of ice is not explicitly included in the recommended equations found from standards. Instead, typically, a dependence of the design pressure, p_g, on aspect ratio, w/h, where w is the width of the structure and h ice thickness, is included. The design pressure in ISO/19906 (2019) is defined as

$$p_g = C_R\left[\left(\frac{h}{1}\right)^n\left(\frac{w}{h}\right)^m + e^{\frac{-w}{3h}}\sqrt{1+5\frac{h}{w}}\right]$$

with m an empirical coefficient equal to -0.16, n an empirical coefficient equal to $-0.5 + h/5$ for $h < 1.0$ m and -0.3 for $h \geq 1.0$ m, and C_R an ice strength coefficient. This type of dependence captures, besides the above-described pressure-area effect, the observation that the global ice pressure is typically larger for thin than thick ice and that there is some dependence on ice exposure, which basically can be understood as ice failure being a stochastic process for which the expected maximum value depends on the duration of the process. The effect of ice exposure is very poorly understood and the coefficient C_R appears to lump the variability in actual strength of the ice together with the loading-rate or velocity effects (Hendrikse & Owen, 2023). As such, the results from uniaxial compression tests can only be used, if the effect of the exposure and the velocity are also separately defined, but this has not been achieved yet.

4.3.3 Dynamic ice-loading process

Structural vibrations are oscillations of a structure subjected to dynamic loading. It is common to experience structural vibrations, for example, when feeling a slight motion of a bridge as cars pass over it, caused by the dynamic interaction between the car and the bridge. The ice loads are inherently time dependent, and they fluctuate with the frequencies associated with the local and global ice failure processes of ice. The frequency content of a typical ice load signal does not generally cause severe concern for the design of offshore structures, since the crushing frequencies exceed the common natural frequencies of an offshore structure. It has, however, been observed that significant ice-induced vibrations of offshore structures can occur, when the ice adapts its deformation and failure behavior to the structure it meets. The vibrations are usually related to a continuous crushing failure process of ice. Violent vibrations have been observed to lead to structural damage and even near-failure of offshore structures, but even moderate vibrations, when repeated sporadically over long periods of time, cause fatigue damage to structures (Määttänen, 1975). Engineering research on dynamic ice–structure interaction focuses on explaining when ice-induced vibrations occur and on determining the corresponding magnitude of ice loads.

Figure 4.4 describes three dynamic ice–structure interaction regimes commonly distinguished (ISO/19906, 2019). The first regime is called intermittent crushing, named after the observation that a typical ice load record in this regime shows a period of ice load buildup, during which the structure deforms and moves together with the ice at the ice–structure interface, followed by a short period of rapid ice failure, during which the structure moves toward the ice as it returns toward its undeformed state. The magnitude of peak ice loads reached at the end of the load buildups are very high in intermittent crushing. The second regime is named frequency lock-in. This regime is characterized by nearly harmonic motion of the structure, with a period close to one of its natural periods, and a periodic ice failure, during which brittle crushing of ice is interrupted by a short moment of no ice failure and a load peak. The third regime is called continuous brittle crushing, where the effect of the structure on the interaction is minimal; ice load records for rigid and flexible vertical piles are very similar during brittle crushing.

What causes one structure to experience only quasi-random high-frequency loads and others periodic loading and response in similar ice conditions? The answer to this question

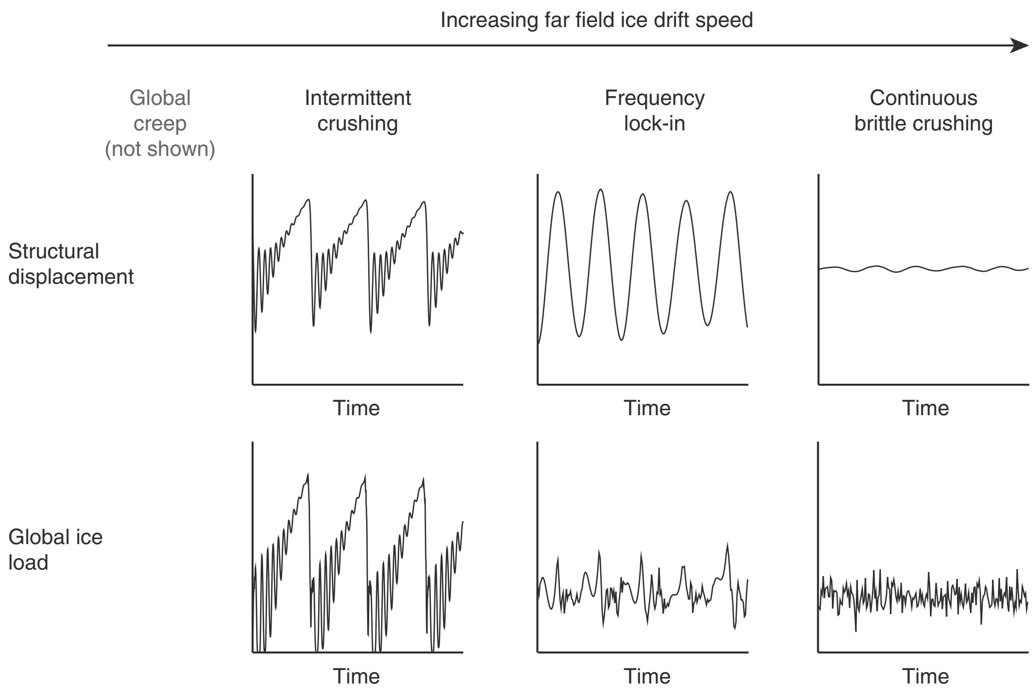

Figure 4.4 Three regimes of the dynamic ice–structure interaction: intermittent crushing, frequency lock-in, and continuous brittle crushing (Hendrikse, 2017) / Delft University of Technology. The graphs describe typical records for structural displacements at the ice–structure interface and the ice load histories for the three regimes. There is a drastic change in the ice load magnitude between the regimes.

has, since the first observations in the 1960s (Peyton, 1968), been sought mainly in two directions: (i) ice possesses a characteristic failure frequency that can synchronize with a natural frequency of the structure (Matlock et al., 1969) or (ii) ice exhibits a strain-rate-dependent deformation and failure behavior that results in an apparent ice strengthening at low loading rates (Määttänen, 1978). The second approach can explain how the energy required for sustained structural vibrations can be introduced to the system formed by the structure and the ice. More recently, it has been proposed that the apparent ice strengthening is not instantaneous but develops after some duration of loading at a specific rate and is lost upon ice failure (Owen et al., 2023). Details related to the "strengthening" remain unclear, but potential explanations include a change in the ice–structure contact area at low speeds or an actual inherent material strengthening mechanism within ice. Nevertheless, this type of strengthening can predict the development of the three regimes of ice-induced vibrations, and it allows for models, where the ice behavior can be defined independent of the structure it meets.

From the aspect of engineering design, the main challenge related to the dynamic ice–structure interaction is that there are no simple formulas, nor other straightforward means, to define under which ice conditions the three interaction regimes may develop for a structure with specific geometry and size. Because of this, the guidance provided by the standards on design for dynamic ice–structure interaction remains very basic (ISO/19906, 2019). Due to this, direct application of the standards may lead to, for example, very conservative fatigue damage estimates for a structure. In short, structures expected to be prone for dynamic loading must be overdesigned. Even moderately conservative designs can impose limitations for implementing such offshore structures as wind turbines, which demand thorough optimization for sustainability and cost. While numerical models can be used to assess the dynamic behavior of such structures in ice, the scarcity of full-scale data required for model validation still often limits their use.

4.3.4 Ridge loads

Chapter 1 already described how winds and currents cause the sea ice to move and form ice ridges (Figure 1.2). Ridges are very common ice features on sea areas with drift ice and of crucial importance from the ice engineering perspective. Ice ridges yield the most challenging ice conditions that an ice-going vessel encounters in first-year ice. Further, the ice loads due to ice ridges often define the design load on an offshore structure. This is rather intuitive considering that the thickness of ice ridges may reach values of even tens of meters. Amundrud et al. (2004) suggest that the ridge depth on a given sea area relates to the level ice thickness through $20h^{0.5}$ [m].

The part of a ridge that is above water is called a sail, and the underwater part is called a keel (Figure 4.5). Over some time in freezing temperatures, the sea water between the ice blocks within a ridge starts to freeze and forms a solid ice nucleus into the ridge. This frozen nucleus is called a consolidated layer, and it is located below the waterline, between the sail and the keel. Most of the ice volume within a ridge is in its keel, which consists of ice rubble, a pile of ice blocks formed in a ridging process. Immediately after the ridge formation, the keel is a collection of loose ice blocks, but after some time, at least the upper part of keel becomes partly consolidated, that is, it consists of ice blocks bonded together by freeze bonds. Due to the importance of ice ridges, it has become common to study their morphology and to derive relations between the sizes of the various parts of ridges (Timco & Burden, 1997; Strub-Klein & Sudom, 2012).

Which physical processes contribute to ridge loads? When an offshore structure or a ship penetrates a ridge, it must first break the consolidated layer, while simultaneously

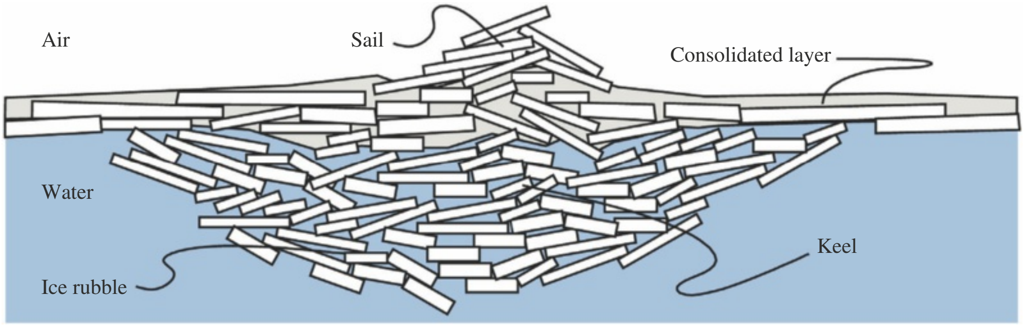

Figure 4.5 Cross section of an ice ridge. The three main parts of the ridge are the sail above the waterline, the consolidated layer close to the waterline, and the ridge keel underwater. Consolidated layer is a refrozen layer of rafted ice and ice fragments. The keel is a rubble pile of freeze-bonded and loose ice blocks, and it can reach tens of meters of depth (Polojärvi, 2013) / Aalto University.

deforming the sail and the keel. The loads related to each process are usually treated as independent contributions to the ridge load (ISO/19906, 2019). Effect of sail on the load is always assumed negligible. Consolidated layer is treated similarly to level ice, with its thickness typically estimated to be approximately 1.6–2.0 times of the thickness of the ice surrounding the ridge, while its strength is assumed somewhat lower than that of the level ice. Analogous to level ice thickness having a major contribution on the ice load, the load related to breaking the consolidated layer is often estimated to be of high magnitude, even sometimes governing the ridge load depending on a type of the structure.

Ridge keel may also cause a significant contribution to the ridge load, not least due to its extensive size but also due to its strength, often attributed the freeze-bonded rubble. The freeze bonds form a cohesive-type of skeleton structure that must be first broken when the keel starts to deform (Heinonen, 2004). The load required for failure of this skeleton is assumed to determine the initial cohesive strength of the ridge. It remains somewhat unclear, how the cohesive strength varies through the ridge keel thickness, but the standards suggest assuming the keel strength is at its maximum immediately under the consolidated layer and vanishes at bottom of the keel (ISO/19906, 2019). It is only after the failure of the freeze bonds that the ice blocks in the keel start to move in relation to each other, and the frictional resistance of the deforming rubble is mobilized. In contrast, the standards suggest a conservative approach for calculating ridge keel loads by assuming that the cohesion and the frictional resistance act simultaneously (ISO/19906, 2019). In addition, especially in the case of the ice-going ships, the force needed to accelerate the ice mass within the ridge may form a significant part of the total ridge keel load (Gong et al., 2019). It has become common to model ridge keels by adopting material models similar to Mohr-Coulomb model (Heinonen, 2004; Serré, 2011), based on approaches related to soil mechanics. It still remains unclear when the continuum assumptions required for such modeling apply (Polojärvi & Tuhkuri, 2009).

4.3.5 Ice ridge formation

Ice ridges start to form when two ice floes come into contact and start to fail against each other or when the compressive or shear stress within an ice sheet meets a threshold, at which the ice sheet starts to fail. Latter phenomenon makes the ice ridge formation important for ice engineering. It is the process that defines the ultimate strength of an ice sheet in the horizontal direction, or in other words, ridging defines the upper limit for the stresses transmitted through an ice sheet: Similarly to the continuous crushing process at the ice–structure interface, ridge formation can define the upper limit for the magnitude of the ice load on a structure. Since the ridge formation is a process where an ice sheet is broken into ice blocks, which then accumulate to form an ice rubble pile, it is very similar to the process of an ice sheet failing and piling up against a wide marine structure. The knowledge on ridge formation can be applied to ice problems related to wide offshore structures. Finally, ice ridge formation is an ice failure process of interest, since it is one of the central processes that connects ice engineering to geophysical-scale sea ice modeling as will be discussed later.

4.4 Experiments and observations

Using the measured sea ice properties to estimate ice loads on full-scale offshore structures is extremely challenging as described earlier. Due to this, there is a long ice engineering tradition to perform full-scale and model-scale ice load measurements. While new measurements are constantly needed for improved understanding of ice loading on various structure types, the measurements are often challenging to perform. The following first describes a selection of well-known full-scale campaigns on a general level before describing how model-scale experiments are used in ice engineering. Palmer and Croasdale (2013) provide a more thorough list of experimental campaigns and description of the techniques commonly used in experimental ice engineering work.

4.4.1 Full scale

Full-scale ice load measurements have been usually performed on existing structures or structures modified for measurements, but full-scale structures dedicated to solely measure ice loads have not been implemented. One reason for this is the high cost of implementing offshore structures and the challenges related to performing reliable ice load measurements. The motivation for the measurements has been a need for new design criteria for improved and more efficient structures or the loss of earlier structures. One noteworthy story related to the latter case is that of the early version of the Kemi-I lighthouse, which was designed according to a new economical slender steel structure design in 1974, only to experience severe vibrations throughout its first season of deployment leading to failures of lamps and secondary components due to fatigue damage. The lighthouse further collapsed during that first season, most likely due to an ice ridge (Määttänen, 1975).

Notable field studies on ice loading on conical structures include those performed at the second version of the Kemi-1 lighthouse in the Gulf of Bothnia during the 1980s and the measurements at piers of the Confederation Bridge starting in the late 1990s. In addition, there exists full-scale ice-loading data from production platforms in the Bohai Sea and the Kulluk floating caisson in the Beaufort Sea. All of these measurements have provided insights into ice loading under diverse ice conditions, including level ice, ice ridges, and ice rubble fields. While findings from these field programs have been since used in model validation and for establishing design criteria for conical or sloping structures, the data remains sparse for the engineering purposes.

The earliest full-scale observations related to vertical structures and ice-induced vibrations date back to the studies aimed at understanding ice loads on vertical piles. These studies were initiated in the late 1960s and conducted throughout the 1970s. An important outcome from these studies was, for example, the ice load recordings included in the early paper by Peyton (1966). These recordings showed ice loads changing from nonsimultaneous to synchronized, with the corresponding saw-tooth load pattern as an ice floe came to a stop against a flexible pile. The measurements showed that the peak loads increased as the ice velocity decreased, something which was seen two decades later in the case of a 90-meter-wide Molikpaq platform in the Beaufort Sea (Jeffries & Wright, 1988), which experienced severe vibrations when a multiyear ice floe with thick inclusions came to a slow stop against the side of the platform. Severe vibrations were also later experienced on the four-legged concrete gravity-based platform Lunskoye-A at offshore Sakhalin and on the Norströmsgrund lighthouse in the Bay of Bothnia (Nord et al., 2018). Even if some data on ice-induced vibrations in full scale exists, there is a well-recognized need for new full-scale measurements related to modern offshore structures, such as wind turbines, where this phenomenon has an important role (Hammer et al., 2023).

4.4.2 Laboratory scale

Similarly to the full-scale measurements, model-scale experiments have been used in ice mechanics and ice engineering for decades. Compared to full-scale measurements, laboratory-scale experiments allow better control on ice properties and other variables, and they are less expensive and more straightforward to perform. Further, the measurements and the subsequent analysis of the laboratory-scale experiments can be more detailed than those related to their full-scale counterparts. Laboratory-scale experiments can be performed in cold rooms or in ice basins, the focus here being on the latter (Figure 4.6).

Experimentation in model scale also has its challenges. It should first be ensured that the ice

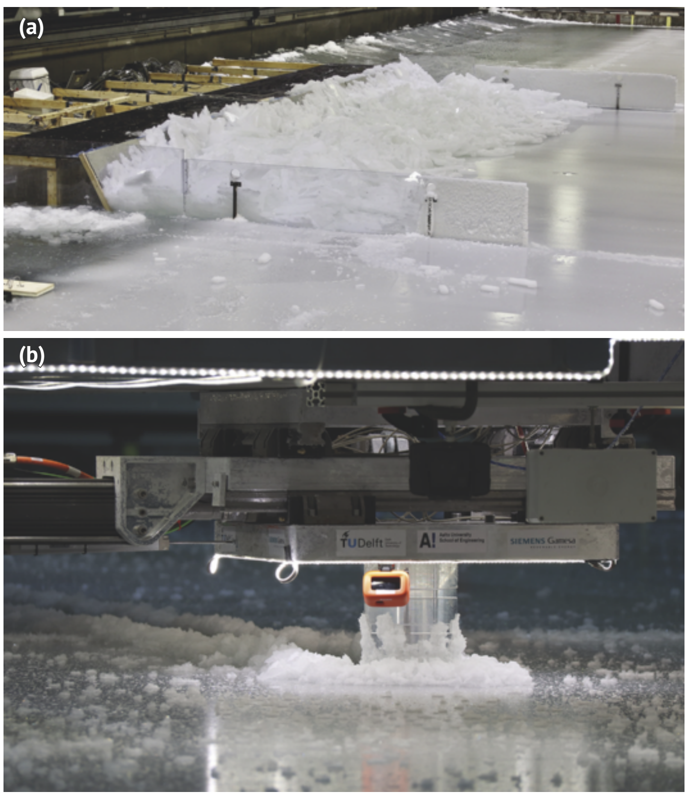

Figure 4.6 Laboratory-scale experiments performed in an ice basin: (a) ice-loading process on an inclined offshore structure (Lemström et al., 2022) and (b) ice interacting with a cylindrical structure. *Source:* Photos by Otto Puolakka.

used in a model-scale experiment reproduces the mechanical behavior and failure modes of its full-scale counterpart to sufficient extent. Once this is ensured, the central challenge is the scaling of the model-scale results to full scale: If a load of given magnitude is measured in a model-scale experiment, what is the actual ice load on a full-scale structure? In order to scale results from model to full scale, a scaling law should be chosen for the experimental design. It is intuitive that geometric scaling is used to scale the ice thickness and the size of the structure, but the ice properties, including the ice strength, must be scaled as well. How to do this for a given type of structure remains a source of scientific debate (Palmer & Dempsey, 2009).

The scaling law for a given model-scale experiment is usually chosen based on the assumptions on the most relevant features of the ice failure process in the ice-loading scenario studied (Timco, 1984). From this aspect, it is worthwhile to remember that the ice-loading processes can be divided into two categories described earlier: (i) processes where flexural failure of ice is the governing failure mode (Figure 4.2a) and (ii) processes where the crushing failure of ice and perhaps the dynamic interaction between the ice and the structure govern the loading (Figure 4.2b). Traditionally, the model-scale experiments in the first category have included those performed for ice-going ships and inclined offshore structures, whereas the second category includes problems with compliant vertical structures, such as the offshore wind turbines.

The most common approach used for scaling of an ice-loading process where flexural failure of ice is the governing failure mode is to combine Froude and Cauchy scaling laws. These scaling laws, when used together, preserve geometric, kinematic, and dynamic similitude (Timco, 1984). When such scaling is used, the Froude and Cauchy numbers, referring to the ratios between inertial and gravitational forces and inertial and elastic forces, respectively, are preserved. In practice, when one first applies Froude scaling, the application of Cauchy scaling implies weakening the model scale. This is done to adapt the elastic forces to scaled structural geometries (Palmer & Dempsey, 2009). Consequently, since the strength of the model-scale ice is scaled by the same factor than the geometry of the structure, the model-scale ice can be often characterized as slushy.

When crushing and dynamic ice–structure interaction govern the ice-loading process, different approaches for scaling must be used. Related to this, in his experiments with freshwater ice, Sodhi (1992) noted that the relative velocity between the structure and the ice should not be scaled. Indeed, when delayed-elastic or viscous behavior of ice is important, as in the case of dynamic ice–structure interaction, it would appear to be relevant to focus on scaling the properties that control this behavior. Even with the development of model-scale ice being an active area of ice engineering research, controlling such properties of model-scale ice is currently not possible; thus, the approach taken recently has been to not apply any scaling of ice properties. While this may seem contradictory, accepting the fact that we do not know how to scale dynamic ice–structure interaction opens new avenues for testing. Hammer et al. (2024) performed a series of tests aimed at replicating full-scale observations of ice-induced vibrations, by assuming the interaction process is mainly defined by the mean ice load and that even the geometrical scaling requirements could be relaxed.

4.5 Simulations of ice failure processes

Numerical tools for ice-loading processes are challenging to implement due to the complexity of the processes modelled. For example, to model a bending-failure-dominated scenario, where a moving ice sheet fails against an inclined structure, one must consider the deformation and multi-fracture of intact ice, large displacements of ice blocks, and ice rubble pile formation, which requires

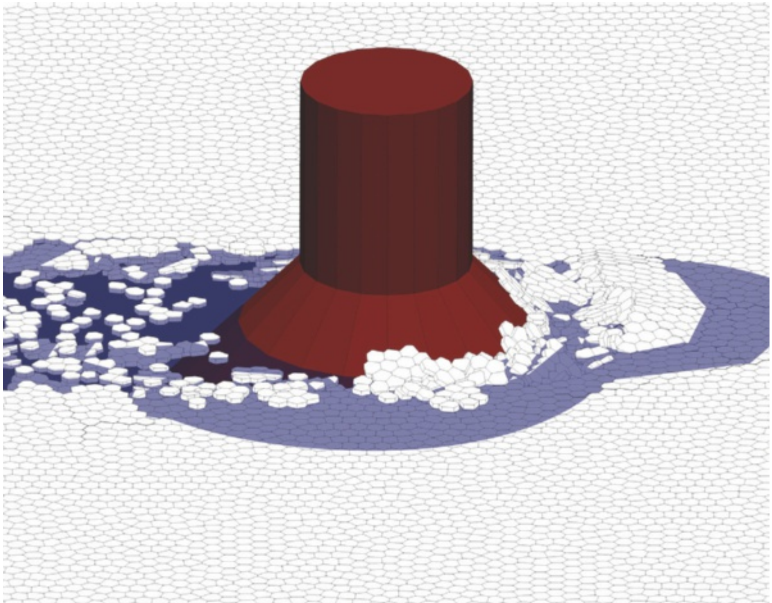

Figure 4.7 Ice engineering simulation: a three-dimensional discrete element simulation of intact ice sheet loading a wind turbine foundation furnished with an ice cone at the waterline (Polojärvi, 2022 / Elsevier / CC BY 4.0).

modeling the interactions between the blocks and between the blocks and the structure. It has become popular to model the problems in this category by using discrete element method (DEM; Cundall & Strack, 1979; Figure 4.7). The complexity does not only show up in the modeling requirements but also makes using the simulation results challenging. However, the modeling-based scientific insight on sea ice behavior progresses only through careful analysis on simulation results.

DEM (Cundall & Strack, 1979) is a numerical modeling technique that has been used in ice engineering since the mid-1980s (Tuhkuri & Polojärvi, 2018). DEM is a method originally intended for modeling granular materials, that is, materials consisting of numerous interacting rigid particles of various shapes. In the case of ice engineering, individual discrete elements usually describe either ice blocks or ice floes. Central part of DEM simulations is the calculation of contact forces between the pairs of interacting particles. This is done by using simplified contact force models, which in the case of ice engineering applications often yield an elastic–viscous–plastic response and include a frictional component (Hopkins, 1992). Often the discrete elements are joined together with various types of finite elements to form intact ice sheets (Figure 4.7). Example applications of DEM on ice mechanics include studies on ice ridge formation (Hopkins, 1994, 1998) and ice-loading processes (Paavilainen et al., 2009; Paavilainen & Tuhkuri, 2013), and DEM has also been applied on numerical experiments on ice rubble behavior (Polojärvi & Tuhkuri, 2009, 2013). The bottleneck of DEM simulations is the computational burden related to resolving the contact forces. This may still limit the use of DEM in modeling long ice failure processes.

Modeling of dynamic ice loading applied on a compliant vertical structure is also very challenging, as in this case the ice properties related to the delayed- and visco-elastic response, and the structural dynamics are all coupled and governing the loading process. Currently, there are no material models that would yield the known dependency between the ice load and the ice velocity, and that would lead to the three ice-induced vibration regimes described earlier (Figure 4.4). This restricts the use of physics-based models for dynamic ice-loading processes. This disadvantage is not related to deriving a proper material model for ice but rather due to the need for more detailed research on physical phenomena related to time- and rate-dependent behavior of ice. Despite this, phenomenological models for simulation of dynamic ice–structure interaction for application in design of structures exist (Hendrikse & Nord, 2019).

4.6 Future aspects

The profound effects of climate change are already showing at the cold sea areas (Graham et al., 2019; Rantanen et al., 2022). These changes have influenced ice engineering research. One effect is due to the drive for green energy and the related need for improved insight on offshore wind turbines and offshore wind farms in ice. Goals related to sustainable shipping may also change the engineering research related to the ships in ice, since the ice-going capabilities of the new low-emission ship types are expected to be lower than those of the current ships. Interest has also started to turn toward operations of ships not meant to enter ice-covered sea areas at all but are expected to do so related to military purposes or even tourism.

One important driver for the future ice engineering research is also the need for more detailed scientific understanding of the mechanical behavior of sea ice in the warming climate. Overall understanding on the future of ice-covered seas has been traditionally sought for by performing geophysical-scale ice dynamics simulations. The geophysical-scale models are not built to describe the ice failure processes discussed in this chapter in detail. These models cannot reliably resolve ice behavior in scales below 10 km, which may have a negative effect on their predictive power (Feltham, 2008). The ice failure processes studied by ice engineers, however, have a role in driving the overall behavior of ice (Leppäranta, 2011); thus, modeling approaches connecting engineering- and geophysical-scale research are currently seen as an important future venue for research on sea ice dynamics (Blockley et al., 2020; Hunke et al., 2020). Two already recognized ways that bridge the gap between the two scales would be (i) to extend the detailed engineering-scale DEM simulations toward the geophysical-scale modeling or (ii) to use the engineering-scale DEM to produce numerical data for large-scale model development. While the general idea of using DEM for large-scale ice dynamics simulations dates back to early 2000s (Hopkins et al., 2004; Hopkins & Thorndike, 2006), the computing power currently available allows simulations with an unforeseen combination of high resolution and unprecedented scales.

Besides modeling, the experimental work in the scales typical for ice engineering produce insight that is useful for predicting the future of cold marine environments. Since the general trend is that the sea ice will be warmer in the future, it makes sense to perform more engineering research to understand the mechanical response of warm ice. Such work has been performed already related to fracture of ice and response of ice on cyclic loading (Gharamti et al., 2021a; Wei et al., 2022). It can also be expected that the importance of ice–wave interaction increases in the future. Experimental work on ice–wave problems can be carried out in engineering scale by using the model-scale basins, which have been traditionally used in ice engineering applications related to offshore structures.

Overall, the ice engineering research has potential in producing data of high importance for large-scale studies and on understanding the effects of climate change on sea ice. The strength of ice engineering is that it always aims to connect the measurable properties of ice to the detailed observations on the mechanical response and failure of ice. Only through this type of detailed understanding on how the properties and response of ice are connected, one can start to reliably predict how the sea ice will behave in the future.

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