ICE RIDGE CHARACTERISTICS AND ENGINEERING CONCERNS REGARDING ICE RIDGES

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Keywords: ice ridges, ice ridge action, geometry, morphology, first-year and old ice, thermal processes, physical and mechanical properties, full-scale, numerical models, scale-model tests.

Contents

Summary

Ice ridges are vital ice features and have important implications for engineering activities in icy waters. The forces at play when an ice ridge hits a ship, a moored or fixed structure, often give the design quasi-static environmental action, and a realistic estimation of these forces is important to make safe and sound solutions. Before any design can be chosen, the ice ridges in an area need to be characterized in a sufficiently accurate manner, and the first important distinction is that between first-year- and old ridges. Old ridges are believed to be completely consolidated and considerably stronger so they are assumed to give higher forces. The ridge geometry is important input and the most important parameter is the keel depth. Keel depths up to 50m have been measured in the central Arctic, but a 100 year ridge in the Fram Strait has been estimated to 37 to 41m. For first-year ridges the thickness of the consolidated layer is essential and a good conservative estimate is 2-2.5 times the level ice thickness. The mechanical properties of the solid parts of ice ridges (the consolidated layer and old ridges) are assumed to be close to those of level ice (though no measurements have been done deep down in old ridges). One may use simple analytical models, advanced discretized numerical models or scale-model experiments to estimate the ridge action on structures. All three methods have weaknesses and a designer should not rely on only one of these.

1. Introduction

There are three subtypes of floating ice: icebergs, undeformed ice and deformed ice. Ice ridges belong to the latter category. When floating ice is compressed (or sheared and compressed) it can deform and form ridges. The part above the water surface is called the sail, and the submerged part of a ridge is called the keel. Ice ridges can be substantially thicker than the surrounding level ice (undeformed ice) and cover up to at least 70% of the surface area. It is common and useful to distinguish between first-year (melt during the first summer) and old ridges (have survived one or more summers). Old ridges are often believed to be more or less completely consolidated, whereas the keels in first-year ridges have an upper consolidated layer and unconsolidated layer of rubble beneath. Figure 1 shows a young ridge in the Barents Sea in May 2005, where the blocks in the sail are clearly visible as there is no snow covering the ridge.

Figure 1. A young first-year ice ridge in the Barents Sea 2005

Ice ridges are a major concern both to engineering and in a larger geophysical context. Next to icebergs, ice ridges are the ice features that have most impact on the quasi-static design ice load for surface penetrating and sea bed structures. They also represent the highest resistance for ships in transit. In many major waters such as the Caspian Sea, the Bohai Sea, the Sea of Okhotsk, the Baltic, and the south-eastern part of the Barents Sea (the Pechora sea), there are no icebergs, so that ice ridges determine the quasi-static design ice load. In deeper waters, where iceberg may be present, floating solutions are commonly used (e.g. the Stockman gas deposit in the Eastern Barents Sea). A floating structure can disconnect and interrupt an operation to avoid iceberg impact; hence ice ridges may also become vital under such conditions.

In a geophysical perspective, ice ridges affect the ocean-ice-air heat transport and they contribute significantly to the total ice volume. Ridges consume mechanical energy during formation. A ridging event leaves open water where new ice can grow, and initially new ice is also formed in the ridge keel. Later the main effect is melting as first-year ridge keels melt faster than un-deformed ice and old ice. Finally we may add that in an Arctic basin with an increasing ratio of first-year to old ice it is important to understand how ice ridges affect the ice thickness distribution both statistically and thermo-mechanically.

2. Ice Ridge Characteristics

2.1. Ridges, Rafted Ice and Rubble Fields, First-year and Old Ridges

A distinction must be made between three different forms of deformed ice: ridges, rubble fields and rafted ice. A *ridge* is an accumulation of broken ice pieces that has a linear or sinuous linear appearance. A *rubble field* is a large accumulation of broken ice which covers a large area (Figure 2). It has a rough surface, with numerous ice blocks frozen together resulting in a feature thicker than the surrounding ice cover. Rafted ice is formed when one ice floe smoothly rides up over another floe. It may appear to be level ice, but its thickness starts as the sum of the thickness of the two ice covers (and generally it thickens with time during the winter months). In the following we will not distinguish between ice ridges and rubble fields and simply address both as ice ridges. Rafted ice will not be discussed further.

Figure 2. A large rubble field in the Canadian Beaufort Sea. Note the people in the photo crossing this rubble field. Picture taken by Anne Barker and appears with the courtesy of the National Research Centre of Canada.

An important distinction is that between first-year and old ridges. The World Meteorological Organization defines first-year ice as having survived only one winter, and second-year ice as having survived only one summer. This makes ridges (and level ice) less than one year old in the autumn both first-year and second-year ridges. The Canadian ice community simply defines that any ice existing after 1 October is old ice. Following this view, it makes sense to use the summer as a yardstick for defining ridge age; the basic transformation from first- to second-year ridge takes place in the summer so that when the winter starts all ice is already second- or multi-year.

The distinction between ridges and level ice is relatively easy for first-year ice as the level ice is relatively homogeneous horizontally. But this distinction is less obvious in old ice, both from a theoretical and a practical point of view. The summer melting is not homogeneous horizontally and creates substantially higher spatial ice thickness variations in old ice compared to first-year ice (excluding any mechanical deformation).

2.2. Geometry, Occurrence and Morphology

The key geometrical parameters of ridges are the keel depth, sail height, keel width, keel shape and possibly block thickness. There are different sources for ridge geometry and for the sake of simplicity we may distinguish between continuous and discrete methods. Discrete methods, that is, survey on individual ridges by for example drilling, only amounts to 300 – 400 ridges the last 40 years. A main advantage of discrete methods is that both the top and bottom profile can be mapped; continuous measurements can be done of either top or bottom profile. Bottom profiles can be measured by an Upward Looking Sonar (ULS) either mounted on a submarine or fixed to the seabed. Submarine data give directly spatial series, whereas a bottom-fixed ULS may yield a time series that can be converted into a spatial series only if the ice drift velocity can be estimated or measured. Surface profiles have been measured using laser scanning from ships. The continuous methods enable the measurement of a high number of ridges and allow for a quantification of statistical properties of a ridge population. Within such a ridge population is difficult to distinguish between first-year and old ridges.

The keel depth is the main ice ridge characteristics. Keel depths of 37m have been measured in the Canadian Arctic, and the 100 year ice keel thickness in the Fram Strait has been evaluated to be about 40m. In the central Arctic basin a 50m deep ice ridge was measured. It is not clear which physical conditions limit the size of a ridge, but aspects such as the duration of the driving force, the available amount of ice and the ice properties (thickness, strength, temperature) are important. It is also important how fast the lower part of the keel melts, so that the ridge keel permeability and the vertical profiles of temperature and salinity in the ocean could also be important for the probability of a certain keel depth.

The sail is in itself of little importance, but as the keel depth to sail height ratio seems to be around 4 - 5 for first-year ridges and 3 - 4 for old ridges a mapping of sail height gives valuable information. Some work has been done on the characterization of the blocks in the sail. The average inclination angle to the horizontal plane has been measured to approximately 35 - 40°. The average thickness can, as a first approximation, be considered as the level ice thickness at the time of formation. The available data suggest that it is about 0.5 - 0.6m in the central Arctic and in the Beaufort Sea, 0.4 in the Barents Sea and the Sea of Okhotsk and about 0.15 - 0.2 in the Baltic.

The porosity of the consolidated layer in first-year ridges, and old ridges is believed to be close to that of level ice. But the rubble in first-year ridges has noticeable higher porosities. The normal porosity definition is the ratio of the non-sea ice volume to the total volume. This *macro-porosity* has been measured between 25% and 40% mostly around 30%. One may also include the porosity of the sea ice in the rubble and define a total porosity. Typical values here are 40% to 45%.

Ice ridge frequency is determined by the local met-ocean conditions. It can vary substantially and in some offshore regions such as the Beaufort Sea ridges can cover up to 70% of the ice covered area.

2.3. Thermal Processes and Physical Properties

2.3.1. Lifespan of an Ice Ridge

An ice ridge can be defined in terms of its geometrical, physical and / or mechanical properties. All these properties continuously change through the lifespan of the ridge, and five different stages or phases can be identified; a) Initial phase, in which there are internal temperature differences in the rubble, b) Main phase (first-year ridges) in which the consolidated layer can be defined, c) Decay phase where the ridge is heated from both above and below, d) Second-year ridge, between first and second summer and e) Multi-year ridge.

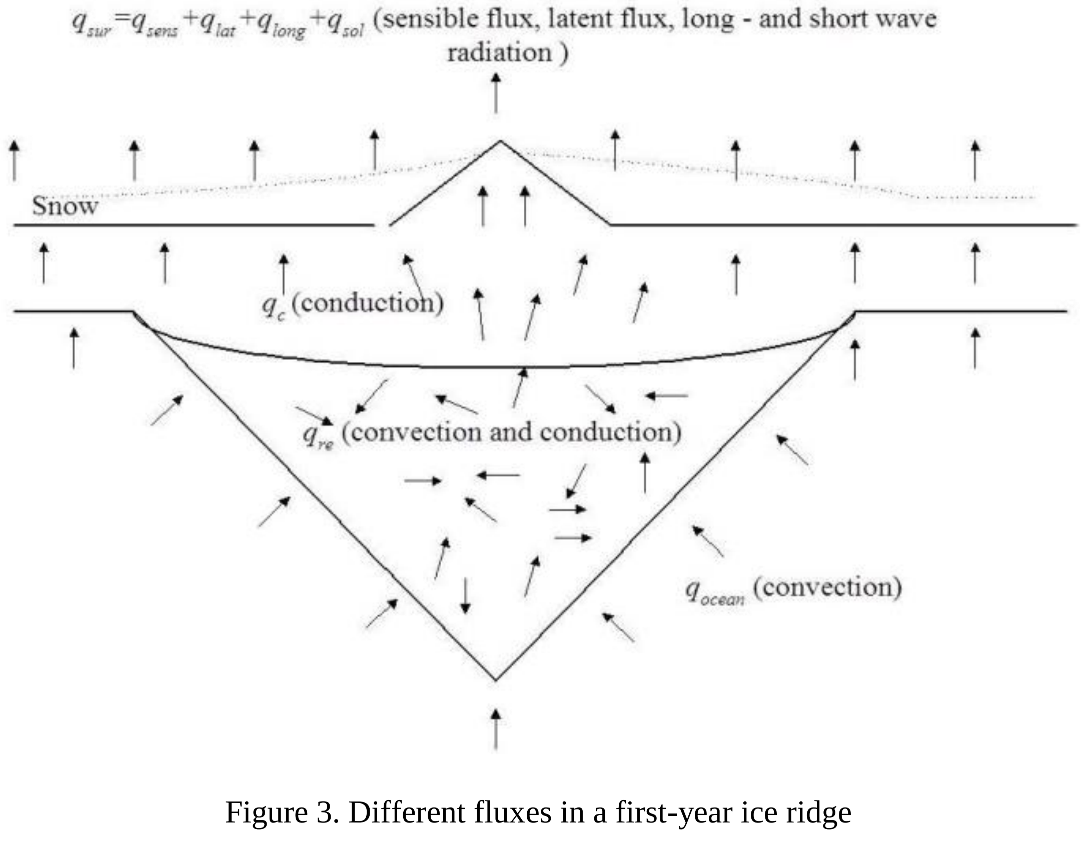

Figure 3. Different fluxes in a first-year ice ridge

The initial phase starts during ridge formation and is characterized by the formation of freeze-bonds. Three different heat fluxes are important: a) the surface flux (q_{sur}), into the cold surrounding air, b) the oceanic flux (q_{ocean}), from the ocean beneath and c) the internal fluxes (q_{re}), in between the cold pieces of ice and the warm water pockets inside the keel (Figure 3). The surface flux freezes the water pockets from the top and downwards and creates a cold front that defines the consolidated layer. The initial cold content of the ice is partly spent in making freeze bonds and partly consumed by the oceanic flux. The fraction that goes into making freeze bonds depends on the initial ice temperatures, the block thicknesses, the ridge size and the oceanic conditions. When all the ice and water below the cold front is isothermal that is at the freezing point of the surrounding water the initial phase ends.

The main phase in the life of a first-year ice ridge is characterized by the growth of the consolidated layer. The thickness of this layer is important and can be calculated by discretized numerical models, simpler semi-analytical or simply through comparison with surrounding level ice (Eq. (1)).

$$h_{\mathrm{c}}^2(\mathrm{t}) = h_{\mathrm{c}}^2(\mathrm{t}_0) + \frac{h_{\mathrm{i}}^2(\mathrm{t}) - h_{\mathrm{i}}^2(\mathrm{t}_0)}{\eta} \tag{1}$$

where h_{c} and h_{i} are the thicknesses of the consolidated layer and the level ice, t and t_0 are the current and initial time and η the macro porosity.

The ratio R between h_{c} and h_{i} (Eq. (2)) is a useful concept as level ice thicknesses are better known and easier to estimate. A good rule of thumb is that R is between 1.5 and 2. If we include rafting it can be thicker, but rarely more than three times level ice thickness. Five layers of rafted ice have been observed in the consolidated layer of first-year ridges, but only for relatively thin level ice (≈ 0.2m).

$$R = \frac{h_{\mathrm{c}}}{h_{\mathrm{i}}} \tag{2}$$

The rubble beneath the consolidated layer is thermally insulated by the freezing front on top of it, and feels only the water below. Since the conditions are isothermal there is no longer any cold reserve available and the rubble decays continuously. The rubble transforms from individual ice blocks with freeze bonds to an ice skeleton with a hierarchy of pores, from a few centimeters and up to meter(s).

In the decay phase the ridge is heated both from the top and from the bottom. The ridge now either melts completely, or it transforms into a second-year ridge during the summer. Several processes take place. On the surface the warm air and the sun radiation melts the snow and the surface ice and creates relatively fresh melt-water. Its freezing point is above the temperature in the rubble so it will freeze as it drizzles down in the keel. This freezing process release heat and increases the temperatures in the rubble. In this way the decay phase includes both melting and freezing. Freezing can take place as long as there is cold capacity (ice temperature less than the freezing point of the melt water) in the keel. However, another mechanism can contribute to further consolidation. If the pore water salinity is changed cyclically, either by periodic surface melting or by tidally driven river runoff the ridge could actually expel heat into the surrounding water and contribute to further freezing (consolidation). This mechanism is only shown in laboratory investigations and in simulations. Finally the ridge keel could collapse and in this way decrease the porosity and increase the degree of consolidation. By the end of the melt season the ridge has become a second-year ridge.

The most striking difference between a first and second year ridges is that the latter is almost completely consolidated. The physical process giving this consolidation is not properly understood, but some mechanisms are sketched above.

After the second summer the ridge becomes a multi-year ridge. It may be difficult to separate the two, but if remains of the original blocks can be identified in the sail it is an indication of a second-year ridge. A multi-year ice ridges has a smoother surface than second-year ridges, after two summers no traces of the original blocks in the sail remain. Another difference is that a multi-year ridge has had more summers to drain salt so one could expect a somewhat lower salinity.

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Biographical Sketch

Knut Vilhelm Høyland received both his Master thesis and PhD thesis from the Norwegian University of Science and Technology (NTNU), respectively in 1993 and 2000. In 2001 he moved to Svalbard to work as associate Professor in Arctic Technology at the University Centre in Svalbard (UNIS). In 2006 he moved back to Trondheim and became a Post-doc at NTNU, in 2009 he became a Professor in the same group at NTNU. From 2007 to 2012 he was also Adjunct Professor at UNIS. He is a member of the international committees of the Port and Ocean Engineering under Arctic Conditions (POAC) and the Ice Symposiums under the International Association for Hydro-Environment Engineering and Research (IAHR). His main interest is physic-mechanical and statistical properties of sea ice in an engineering context. He has worked on consolidation and properties of first-year ridges, scale-model ridges, level ice growth, thickness and properties in Svalbard area and material modeling of first-year ice ridges.