ICE RIDGE FORMATION

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Contents

Summary

Ridges are important features of the northern seas. Ridges are elongated, ridge-like accumulations of broken ice resulting from deformation of sea ice. Ridges form when sea ice is deforming and fracturing due to forces from winds and currents. Rafting is another form of deformed ice. During rafting, one ice sheet overrides another ice sheet. Models for ridging and rafting are reviewed.

1. Introduction

Sea ice is stationary only near the coast and only in sheltered sea areas, where the level ice is held landfast by the shape of the coast and by the possible islands. In archipelagos and sheltered bays, we may find level ice with a smooth surface and of more or less constant thickness, but outside this landfast zone, sea ice moves due to forces by winds and currents. It is this *motion* of sea ice that causes ice ridges to form.

Consider a large sea area with an ice cover, and assume then that a winter storm comes with strong northerly winds. Assume further, that the sea area has such a shape, that the ice cannot flow outside the area. If the northerly winds are strong enough, they start to move the ice cover southwards creating decrease of ice in the northern part of the sea area, and increase of ice in the southern part of the sea area. The ice cover is moving, but it is also *deforming*, as we assume here that the ice cover cannot move outside the sea area. In the northern part, cracks are formed and areas of open water are created. In the southern part, where the amount of ice is increasing, the ice cover deforms through *ridging* and *rafting* processes. Ridging and rafting are thus the terms used to describe the mechanical deformation of ice cover, where the ice cover thickness is increasing. The term *mechanical* is used here to distinguish mechanical thickening of ice cover from thermodynamic (freezing) thickening of ice cover. In more general terms, without considering our bounded example sea area, a deforming sea ice cover may include areas of compaction (compression) and divergence (tension). Under compaction, the ice cover thickness is increasing through ridging and rafting. Under divergence, the average ice cover thickness is decreasing, as leads and areas of open water are formed.

Sea ice ridges are easy to find and ridge formation is a common phenomenon. Figure 1 shows a photo of ridged sea ice. Ridging is usually understood as a process which occurs when two ice sheets move towards each other, ice blocks break off from the sheets and accumulate to form a pile. Ridges are thus piles of ice rubble that crisscross the sea ice cover. Rafting, in turn, is usually defined as a process where two ice sheets override and no piling up or down occurs. The case where several roughly horizontal layers of ice sheet lay on top of each other is also often termed rafting. However, as will be described below, the division of ice cover deformation into rafting and ridging may not be that simple and clear.

Figure 1. Ridged sea ice field in the Northern Baltic.

Understanding ice ridge formation and properties is important to both Arctic engineers and geophysicists. Ridges can be large, and are thus obstacles for shipping and can cause high loads on offshore structures. In order to understand ridge properties, for example ridge geometry, size and strength, it is important to understand how the ridges form. The geometry of a ridge is the end result of the ridge formation process. A very important aspect of ridging is that it is one of the processes that define the strength of a sea ice sheet in compression. Thick Arctic ice sheets under compression may fail by crushing, but thinner ice types under compression fail by ridging. From an engineering point of view, this means that ridging is one of the physical processes that define the load from an ice sheet to an offshore structure. The ridge formation process is very similar to the process of ice sheet failure and pile-up against coastlines and offshore structures. Thus the work towards understanding ridging helps us also to understand the pile-up process and therefore also ice loads on structures. In a similar manner, ridging is an important constituent in geophysical sea ice models, where also the sea ice strength is needed. In large scale geophysical sea ice models, ridging constitutes the thickness redistribution caused by ice motion due to winds and currents. During thickness redistribution by ridging, the amount of thin ice is decreasing while the amount of thick ice (ridges) is increasing.

The goal of this presentation is to describe the physical processes active during rafting and ridging of sea ice. The emphasis will further be on the sea ice on northern seas. There are ridges also in the Antarctic waters, but this chapter concentrates on the deformation of sea ice cover of the northern seas. As always in ice mechanics, it is important to define the scale of focus. In this chapter, the emphasis is on ice sheet deformation in the scale of meters and tens of meters, that is, in the scale of ice sheet thickness and ridge thickness and width.

2. Rafting

Rafting is overriding of one sea ice sheet by another. For rafting to occur, there must be a crack dividing a sea ice cover into two sheets, and a compressive force driving these two sheets towards each other. There are two main variants in rafting: simple rafting and finger rafting. Simple rafting is basically a two dimensional process, where one ice sheet overlaps another ice sheet, and the ice thickness doubles, as shown in Figure 2. Figure 2 illustrates also finger rafting, a form of rafting where the two ice sheets form overlapping fingers. Finger rafting is clearly a three dimensional process and includes, in addition to one ice sheet sliding over another, also fracture of the sheets to form the fingers. Even though these simple definitions define rafting as a process where the ice thickness doubles, a rafting process often results into three or more horizontally stacked layers of ice.

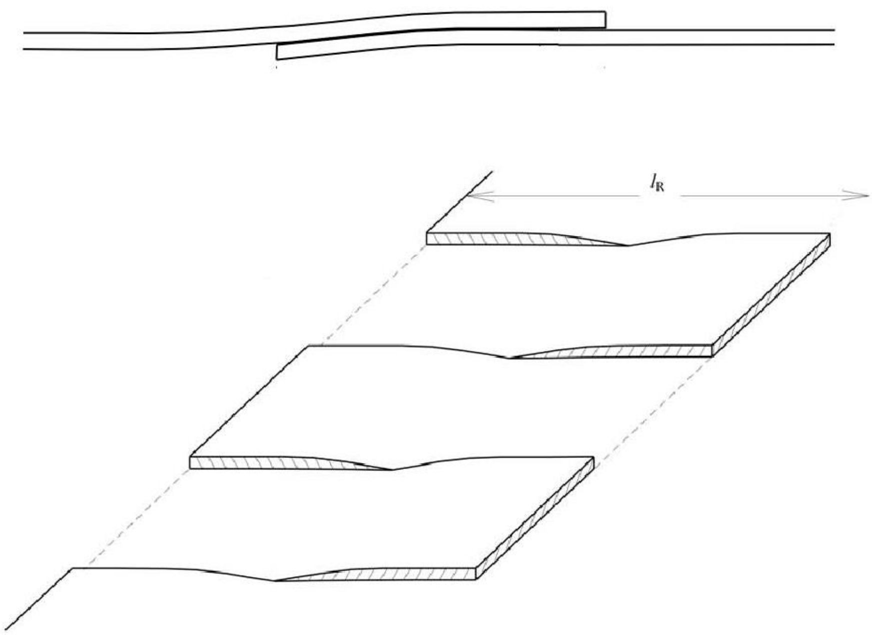

Figure 2. Simple rafting of two ice sheets (top), and finger rafting (bottom). l_R denotes the length of rafted fingers.

Rafting begins when one ice sheet overrides the other, and progresses as long as there is enough driving force to maintain the motion, or until either one of the ice sheets fail through buckling or bending. This rafting force F_r is primarily a result of the frictional contact at the interface between the two sheets. The frictional force depends on the weight and buoyancy of the ice sheets, and on the coefficient of sliding friction μ between the sheets. If the coefficient of friction is known, it is trivial to calculate the rafting force, and to observe that the rafting force increases linearly in proportion to the relative displacement L of the sheets. Through laboratory experiments it has been observed that the rafting force has also a constant component F_0 that is due to the curvature of the ice sheets and to the tearing of the ice sheets between the fingers in finger rafting. The rafting force for unit width can be calculated from

$$F_\mathrm{r} = F_0 + \mu(\rho_\mathrm{w} - \rho_\mathrm{i})ghL \qquad (1)$$

where ρ_w is density of water, ρ_i is density of ice, h is thickness of ice, and g is acceleration of gravity. In Eq. (1) it is assumed that both ice sheets have the same constant thickness h. From this equation it can be observed, that if the friction coefficient μ is small, long rafts can develop before the rafting force is high enough to break one of the ice sheets by buckling or bending. And indeed, rafting lengths of hundreds of meters have been observed for smooth and thin ice. But if the friction between the two sheets is high, due to wet snow for example, or if the sheets are thick, the rafting length L may not get large before either one of the sheets fail. It is important to note further, that rafting length depends also on the available driving force, which is caused by winds and currents. The rafting at one location of an ice sheet stops when there is no force to continue the overriding process, and after that the ice sheet may start rafting at another location.

Field observations suggest that thin ice sheets raft more often than thick ice sheets. This has led to a simple idea, that thin ice sheets deform through rafting and thick ice sheets deform through ridging. While this may work as a rule of thumb, it is not good enough as a general model, as there are several observations that ice sheets thicker than one meter can also raft (Weeks, 2010). The challenge remains to determine under what conditions rafting occurs.

A classical rafting model by Parmerter (1975) considers two ice sheets with equal thickness, and analyses the initiation of rafting. He calculated the bending stress within the submerging ice sheet to determine whether breaking would occur. In this model it is thus assumed, that rafting turns into ridging when a fracture initiates in an ice sheet. The model by Parmerter suggests that the likelihood of rafting decreases with increasing modulus of elasticity and ice thickness. By using reasonable values for elastic properties and strength of ice, Parmerter obtained an estimate of 17 cm for the maximum thickness of ice that can raft. Ice sheets thicker than that would then deform through ridging. Parmerter suggests further that the occasional rafting of thick ice sheets can be explained through the variability of ice properties, especially the strength of ice. Tuhkuri and Lensu (1998, 2002) have described scale model tests on rafting designed to verify the analytical model by Parmerter. It was found out, that even if ridging should have resulted based on the material properties of the model ice, only rafting was observed. The experiments included cases where the ice sheet thickness was about 5 times the Parmerter's crossover thickness between ridging and rafting, and still only rafting took place. It turned out, that the way to initiate ice sheet ridging and not only rafting, was to introduce ice sheet with non-homogenous thickness. This would increase the friction between the ice sheets, but also create weak areas for fracture initiation. It thus appears, that thin ice sheets raft more often than thick ice sheets, not because of the thickness, but because of other properties of the thin ice sheet. This will be discussed in more detail below.

3. Ridging

3.1 Introduction

Sea ice ridges are the elongated piles of ice rubble that crisscross the ice pack in a similar way as mountain ridges in a mountainous area. Ridges can be isolated, straight, and separated from other ridges by smooth level ice; or ridges can have a curved shape and can form a field of ridges, where it is hard to tell where one ridge ends and another starts. Such ridge fields are often called *hummock fields* or *rubble fields*. Although it should be recognized that the ridge building process is not well known, ridges are still often categorized according to the assumed principal formation mechanism. *Pressure ridges* are accumulations of ice blocks and may form when two ice sheets are compressed together, and *shear ridges* may form when the two ice sheets move parallel to each other. One type of pressure ridge, characteristic of the central Arctic pack, forms when a sheet of relatively thin ice is pushed against a thick floe. Another type of pressure ridge forms from two ice sheets of roughly similar thickness. Such ridges are common in the marginal seas, like the Baltic Sea. Ridges can float, or they can get grounded, if they form in a shallow area. Large grounded ridges are called *stamukha*.

Figure 3 shows a simplified cross sectional profile of a ridge. Usually, three parts can be identified in a ridge. Ridge *keel* is the large underwater part and ridge *sail* is the part that is visible and above water. Both keel and sail have often a triangular shape. The third main part of a ridge is the *consolidated layer* at the waterline of a ridge. While the keel and sail are composed of discrete ice blocks either frozen together or loose, the consolidated layer is more or less solid block of ice.

In a simplified presentation, like in Figure 3, it is natural to define a ridge with parameters like maximum keel depth, maximum sail height, slope angles of the keel and sail, width of the ridge, thickness of the consolidated layer, cross sectional area of the ridge, and porosities in different parts of the ridge. This kind of parameters can be measured from ridges in the field by drilling and leveling, and a large data base from different sea areas have been collected during the last decades, even though measuring ridge dimensions is physically hard work in the cold. A review of the measured ridge dimensions has been compiled by Timco and Burden (1997).

Measuring of ridges is a very important part of the research on sea ice and its dynamics. However, knowing what ridges look like does not necessarily tell us why ridges look the way they do. And thus another important part of the research on sea ice dynamics is the work towards understanding the ridging process. If we understand ridging, we can model the ridging process, and then, for example, explain the observed relationships between maximum ridge keel depth and level ice thickness. As will be reviewed below, there are different ridging models and ridging has been studied in laboratory conditions, but unfortunately, there are very few direct observations on the ridge formation process in the field. This is a major challenge in understanding ridging, we know the end result of different ridging events, but our knowledge on the formation process itself is much more limited.

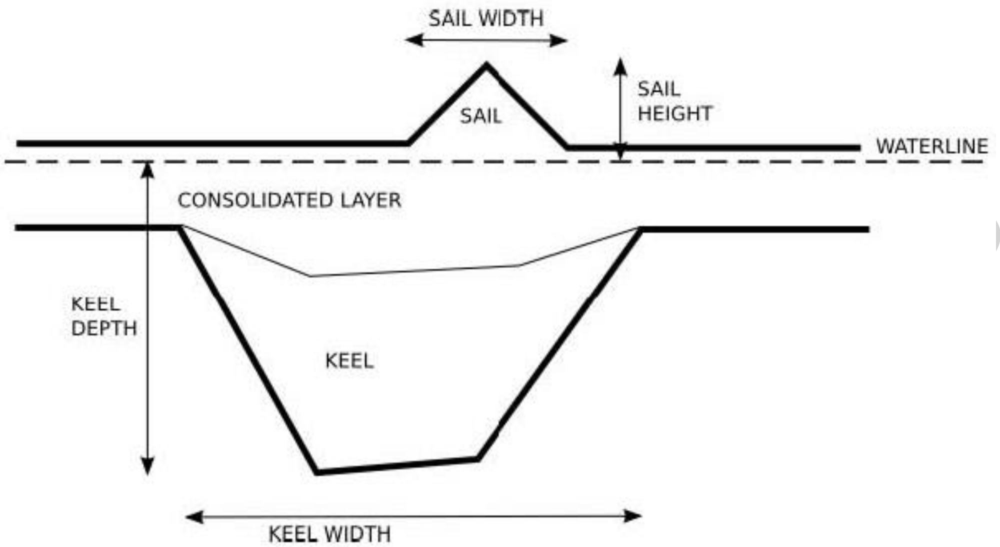

Figure 3. Simplified presentation of a cross section of an ice ridge. (After Timco and Burden, 1997.)

Several models for the ridging process have been proposed. The different models are based on different assumptions and try to answer to different questions. Ridging has been modeled as a process where kinetic energy transforms into potential energy, as a process where ice sheets break into discrete fragments and pile-up, and as a process where the ridge is modeled as a continuum. Also laboratory scale experiments on ridging have been conducted in order to study the ridging process. These different approaches and their results are reviewed below.

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Bibliography

Azarnejad, A., Brown, T.G., (2001). Ice rubble behaviour in punch tests. *ASCE Journal of Cold Regions Engineering* 15 (3), 135–153. [Model scale measurement of ridge properties.]

Bruneau, S., G. Crocker, R. McKenna, K. Croasdale, M. Metge, R. Ritch, J. Weaver, J. (1998). Development of techniques for measuring in situ ice rubble shear strength. 14th Int. Symposium on Ice, IAHR, vol. 2, pp. 1001–1007. Potsdam, New York, USA. [Full scale measurement of ridge properties.]

Evgin, E., R.M.W. Frederking and C. Zhan. (1992). Distinct element modelling of ice ridge formation. 11th OMAE Symp., Calgary, Canada, Vol. IV, pp. 255-260. [An early paper on discrete simulation of ridge formation.]

Heinonen, J., Määttänen, M., (2001). Full-scale testing of ridge keel mechanical proper ties in loleif project. 16th Int. Conf. on Port and Ocean Engineering under Arctic Conditions, POAC'01, vol. 3, pp. 1435–1444. Ottawa, Ontario, Canada. [Full scale measurement of ridge properties.]

Hopkins, M.A., W.D. Hibler III and G.M. Flato. (1991) On the numerical simulation of the sea ice ridging process. J. Geophys. Res., 96, 4809-4820. [An early paper on discrete simulation of ridge formation.]

Hopkins, M. A. (1994). On the ridging of intact lead ice, *J. Geophys. Res*. 99, 16,351–16,360. [A pioneering paper on discrete modeling of ice sheet deformation and fracture.]

Hopkins, M. A. (1998). Four stages of pressure ridging, *J. Geophys. Res.*, 103, 21,883–21,891. [Discrete modeling of ridge formation from lead ice between two thick floes.]

Hopkins, M. A., J. Tuhkuri, and M. Lensu (1999). Rafting and ridging of thin ice sheets, *J. Geophys. Res*., 104, 13,605–13,613. [Discrete modeling of ridge formation from two ice sheets with similar thicknesses.]

Hopkins, M.A. and J. Tuhkuri J (1999). Compression of floating ice fields. *J. Geophys. Res.*, 104 (C7): 15,815-15,825. [Laboratory experiments and disrete modeling of rubble formation from circular disks.]

Kankaanpää, P. (1997). Distribution, morphology and structure of sea ice pressure ridges in the Baltic Sea. *Fennia*, 175, 239-240. [Observations on Baltic Sea ridges.]

Kovacs, A. and D.S. Sodhi (1980). Shore ice pile-up and ride-up: Field observations, models, theoretical analyses. *Cold Regions Science and Technology*, 2, 209-288. [Observations on ice cover pile-up on shore. Also modeling considerations.]

Leppäranta, M., Hakala, R., 1992. The structure and strength of first-year ice ridges in the Baltic Sea. *Cold Regions Science and Technology*, 20 (3), 295–311. [Full scale and lab scale measurement of ridge properties.]

Parmerter, R. R. (1975). A model of simple rafting in sea ice, *J. Geophys. Res*., 80, 1948–1952. [One of the first papers on rafting.]

Parmerter, R. R., and M. D. Coon (1972). Model of pressure ridge formation in sea ice, *J. Geophys. Res*., 77, 6565–6575. [A classical paper on a ridging model.]

Polojärvi, A. and J. Tuhkuri (2012). Velocity effects in laboratory scale punch through experiments. *Cold Regions Science and Technology*, 70, 81-93. [Laboratory scale ridge strength experiments with consideration of velocity effects in this kind of experiments.]

Sayed, M. and R.M.W. Frederking (1986). On modelling of ice ridge formation. Proc. of IAHR Ice Symposium, Iowa City, Iowa, Vol. 1, pp. 603-614. [Modeling ridge formation with a soil mechanics analogy.]

Sayed, M. and R.M.W. Frederking (1988). Model of ice rubble pileup. *Journal of Engineering Mechanics, 114*, 149-160. [Modeling ridge formation with a soil mechanics analogy.]

Timco, G.W. and R.P. Burden (1997). An analysis of the shapes of sea ice ridges. . *Cold Regions Science and Technology*, 25, 65-77. [Review of measured ridge dimensions.]

Tuhkuri, J. and M. Lensu (2002). Laboratory tests on ridging and rafting of ice sheets. *J. Geophys. Res.*, 107 (C9). [Description of the first succesfull ridging process in a laboratory.]

Tuhkuri, J. and M. Lensu (1998). Ice tank tests on ridging of non-uniform ice sheets. Report M-236, Helsinki University of Technology, Ship Laboratory, Espoo, Finland. 130 pp. [Laboratory report on ridging experiments in laboratory.]

Tuhkuri, J. (2001). Deformation and failure of ice cover under compression. In: Dempsey, J.P and Shen, H.H. (Eds.), IUTAM Symposium on Scaling Laws in Ice Mechanics and Ice Dynamics, Kluwer, Solid Mechanics and its Applications, Vol 94, pp. 91-102. [Overview of laboratory scale experimental work on ridging and rafting. Also relevant field observations.]

Tuhkuri, J. and M. Lensu (2001). Energy balance of laboratory scale ridging and rafting processes. Proceedings of the 16th Int. Conference on Port and Ocean Engineering under Arctic Conditions, POAC '01, Vol 3, Ottawa, Canadian Hydraulics Centre, pp. 1473-1482. [Analysis of energy balance during laboratory scale ridging and rafting processes.]

Tuhkuri, J., M. Lensu and S. Saarinen (1999). Laboratory and field studies on mechanics of ice ridge formations. Proceedings of the 15th Int. Conference on Port and Ocean Engineering under Arctic Conditions, POAC '99, Vol 3, Espoo, Helsinki University of Technology. pp. 1118-1129. [Includes field data on rafting as a part of ridging process.]

Weeks, W.F. (2010). *On Sea Ice*. University of Alaska Press, 664 p. [An excellent textbook on sea ice.]

Zubov, N.N. 1945. *Arctic ice*. English translation by U.S. Navy Oceanographic Office and the American Meterological Society in 1979. 491 p. [A famous, early book on sea ice.]

Biographical Sketch

Jukka Tuhkuri has been working on different aspects of ice mechanics for almost 30 years. He has received his doctoral degree from the Helsinki University of Technology (now Aalto University) in Finland, has been working as a visiting scientist at the National Research Council in Ottawa, Canada, and at the US Army Cold Regions Research and Engineering Laboratory (CRREL). His current main research interest is discrete modeling and simulation of sea ice deformation and fracture, including ice loads on structures, ridge formation and strength. Since 2001 he has been a professor of solid mechanics and since 2011 the head of the Department of Applied Mechanics at the Aalto University. Professor Tuhkuri is currently an associate editor of the journal *Cold Regions Science and Technology*.