

Sea Ice Engineering

for ships and offshore structures

C l a u d e D a l e y



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Version 10j

Main additions since V7

- Addition of problems with solutions in appendix
- New material in ice mechanics properties
- Detailed derivation of Popov collision equations
- New appendix on numerical modelling of dynamics and collisions using excel
- New section on AIRSS and POLARIS
- New appendix on POLARIS results
- Several corrections to notes and solutions (Thanks to HJ Jang)

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Contents

Acknowledgments	v
1 Introducing Sea Ice Engineering.....	1
1.1 Overview	1
1.2 Basics.....	1
1.3 Current Arctic Engineering Activities.....	3
1.4 Transportation	4
Chapter 1: Problems	7
2 Physical properties of ice	8
2.1 Properties of Water.....	9
2.2 Freezing	10
2.3 Crystal structure of Ice	10
2.4 Ice Impurities.....	12
2.5 Table of properties.....	13
Chapter 2: Problems	14
3 Ice Formation at Sea	15
3.1 Types of Sea Ice	15
3.2 Initial Ice Formation	17
3.3 First Year Ice	20
3.4 Temperature Profiles through First-Year Ice	25
3.5 Ideal Growth of Clear Ice	25
3.6 Ideal Growth of Ice with Snow	28
3.7 Actual Growth of Ice.....	30
3.8 Gas and Brine Pockets.....	31
Chapter 3: Problems	34
4 Sea Ice Evolution	39
4.1 Formation of First Year Ridges.....	39
4.2 Ice Melting Process	41
4.3 Second-Year Ice	42
4.4 Multi-Year Ice	43
4.5 Multi-Year Ridges.....	44
4.6 Ice Charts.....	46
4.7 Ice Cover Changes and Decline	49
4.8 Differences in Arctic and Antarctic Sea Ice.....	54
4.9 Wave and Ice Interactions in Marginal Ice Zones.....	58
4.10 Ice accretion	60
Chapter 4: Problems	63
5 Icebergs	65
5.1 Iceberg Formation	65
5.2 Antarctic Icebergs.....	66
5.3 Arctic icebergs.....	67
5.4 Iceberg structure.....	67
5.5 Iceberg size and shape.....	68
5.6 Erosion and melting.....	69
5.7 Iceberg distribution and drift trajectories	69
Chapter 5: Problems	71

6	Mechanical strength of sea ice.....	72
6.1	Uniaxial Compressive Strength of Ice.....	72
6.2	Fracture of Polycrystals.....	77
6.3	Tensile and Flexural Ice Strength.....	78
6.4	Cantilever Beam Test Calculations.....	82
6.5	Young's Modulus Data.....	83
6.6	Flexural Strength Data.....	84
6.7	Mechanics of Beams on Elastic Foundations.....	85
	Chapter 6: Problems.....	87
7	Ice Sheet Bearing Capacity.....	88
7.1	Infinite plate on an elastic foundation.....	88
7.2	Response to concentrated load.....	94
7.3	Response to circular load.....	97
7.4	Dynamic behavior.....	99
	Chapter 7: Problems.....	101
8	Ice load processes - crushing, bending, rubble formation.....	102
8.1	Developing ice load models.....	102
8.2	Vertical structures in ice.....	104
8.3	Limit Load Concept.....	106
8.4	Loads on upward sloping structures.....	110
8.5	Ice Induced Structural Vibrations.....	116
8.6	Ice Crushing Forces and Pressures – History of Developments.....	123
8.7	Pressure-Area Data.....	130
8.8	USCGC Polar Sea Data.....	135
8.9	Other Ice Pressure Data.....	140
	Chapter 8: Problems.....	143
9	Ship-ice interactions.....	147
9.1	Introduction.....	147
9.2	Vessel operations.....	148
9.3	Ship Icebreaking process.....	151
9.4	Ship Icebreaking Resistance – General Discussion.....	154
9.5	Resistance and powering – Lindqvist's model.....	155
9.6	Interactions with pack ice.....	159
9.7	Ice Impact Loads.....	165
	Chapter 9: Problems.....	175
10	Ice Model Testing.....	179
10.1	General Discussion.....	179
10.2	Icebreaking Mechanisms – Components.....	180
10.3	Requirements of Similarity.....	180
10.4	Dimensionless Numbers.....	183
10.5	Model Ice Formulations.....	186
10.6	Ice Testing Techniques.....	188
10.7	Data Analysis and Full Scale Predictions.....	193
10.8	Data Quality.....	196
10.9	Consideration of Hydrodynamic Effects.....	198
10.10	Differences between Ships and Offshore Structures.....	199
	Chapter 10: Problems.....	200
11	Ice regulations and standards.....	201
11.1	Ice class rules for ships.....	201
11.2	Ice codes for offshore structures.....	206
11.3	ISO Arctic Structures Standard.....	208
	Chapter 11: Problems.....	210

12	Safe Operations of Ice Class Ships	212
12.1	Zone/Date System	212
	Chapter 12 Problems.....	218
13	Offshore Engineering Operations in Ice	219
13.1	Ice Forecasting	220
13.2	Weather restricted and unrestricted operations	220
13.3	Environmental and Met-ocean criteria	221
13.4	Transport Operations	223
13.5	Stationary Operations	223
13.6	Environmental Impact	228
	Chapter 13: Problems	228
14	Future of Ice Class Ships	229
14.1	Introduction	229
	Chapter 14: Problems	234
15	General Review Questions.....	235
16	References.....	240
17	Useful Web Sites.....	243
	Appendix A : Sea Ice (and other marine ice) Terminology	245
	Appendix B: Detailed Derivation of Popov Mass Equations	250
	Appendix C: Ice edge Crushing Geometry Cases	256
	Appendix D: Sample POLARIS RIO Maps	261
	Appendix E: Modeling Dynamic Problems with Spreadsheets	268
	Appendix F: Solutions to Selected Problems	273

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1 Introducing Sea Ice Engineering

1.1 Overview

The subject of *Sea Ice Engineering* encompasses many aspects of ship design and operations in harsh, remote, ice-infested offshore environments. We will focus on the interaction of sea ice with marine structures, and operations in ice-covered waters. While much of the material on *ice properties* and *ice mechanics* presented in this text also applies to other ice engineering topics (such as river ice and coastal ice engineering), the applications focus here will be primarily on the interaction of ships and ice and the action of ice on floating offshore structures.

A partial list of topics of interest includes:

- Mechanical properties of *sea ice* and *glacial ice*
- Powering and performance of ships in ice
- Structural design of icebreaking ships
- Design of offshore structures in ice
- Assessment of ice loads in various scenarios
- Model scale simulation of ship-ice interaction
- Study of iceberg behavior for management and towing

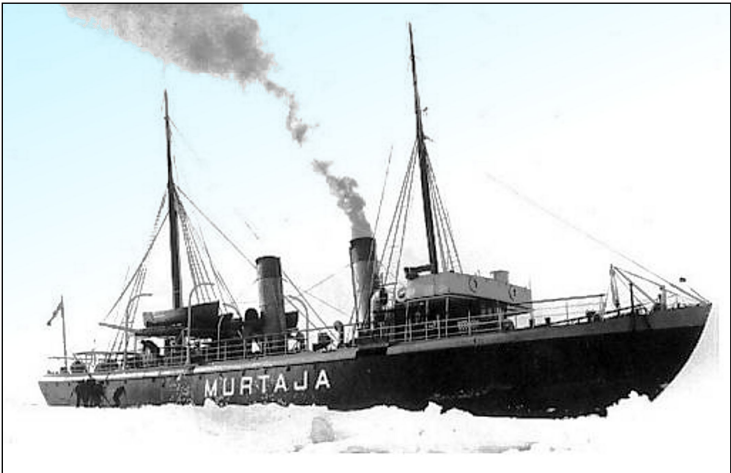
Arctic Offshore Engineering in general, is a new and exciting field of study; mainly because there is still so much left to learn. Like the *Polar Regions* themselves, the field of Arctic Engineering has only been partially explored, by a relative few. This course will aim to cover the basic ideas and methods used in *Arctic Offshore Engineering*.

1.2 Basics

Glaciology is the name for ice science. It is the scientific study of all forms and properties of ice; not just the study of *glaciers*. A lot is known about ice as a substance. We know its chemical structure, its morphology (form and structure) and its thermodynamic properties. Glaciology provides one of the fundamental supports for sea ice engineering.

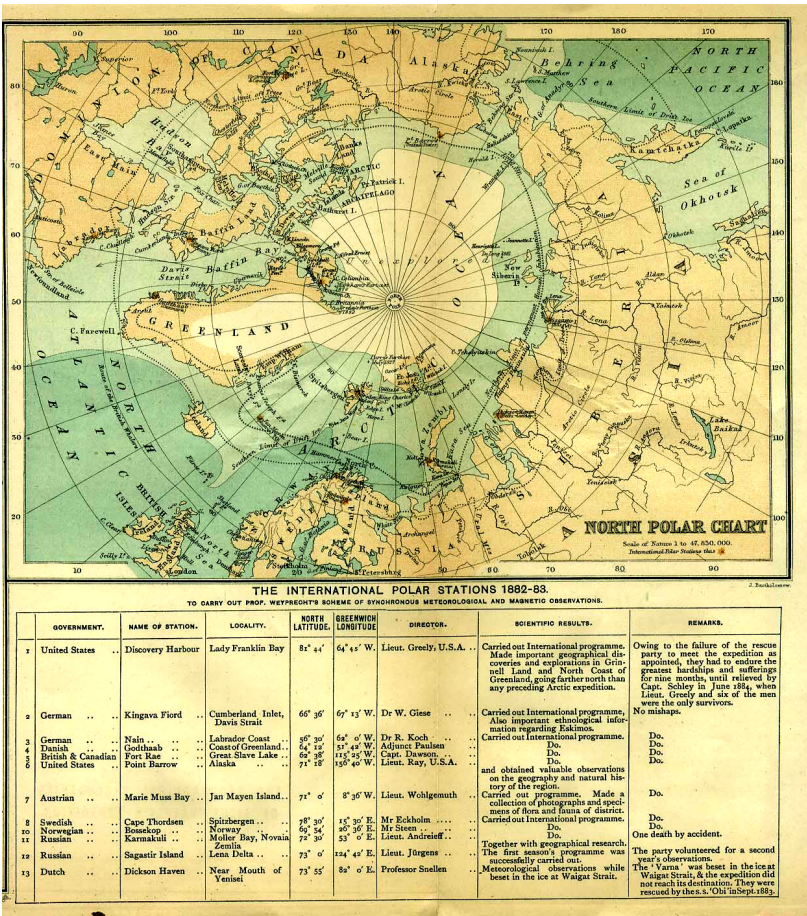
Newtonian and *continuum mechanics* provide a second fundamental support for sea ice engineering. We can borrow much from Newton as we seek to understand how ice behaves as it contacts ships and structures.

The third leg holding up much of sea ice engineering knowledge is empirical data from field and experimental observations, together with a bit of guesswork. Ice behavior is often exceedingly complex. When ice contacts a structure, the result is a cascade of *fractures* and *pulverization* (or *crushing*). Continuum mechanics models, smooth as they are, have never really explained the discontinuous mess that is broken ice. We do have models, even some good ones, but having so many different models is an indication of the immaturity of the field. For the present, ice engineers need to be aware of the empirical evidence and the various models that have been proposed to explain the observations.



uppslag.kaapeli.fi

Figure 1.1 The first Finnish icebreaker, at the time Europe’s biggest at 1600 HP, was built in 1890 in Sweden. Murtaja means “The Breaker”.



Published by the Scottish Geographical Society and edited by Hugh A. Webster and Arthur Silva White. Volume I, 1885.

Figure 1.2. Map of Arctic Research Stations from the 19th Century

1.3 Current Arctic Engineering Activities

There is a lot of interest in ice in recent times. There are three primary reasons for the renewed interest. One is the economic value of the extensive resources to be found in the arctic. The key resources, where individual projects are worth billions, are mining and petroleum. As well, transportation links and tourism are two additional resources that have significant economic value. Figure 1.3 shows many of the recent and current areas of ice engineering activity.

Another reason for interest in the arctic is environmental. The arctic is seen as both an indicator and regulator of climate change. Loss of sea ice affects the Albedo (reflectivity) of the surface, and so has a significant effect on solar heating. Ice reflects 5-6 times as much energy as water or dark soil. Melting of ice injects a large volume of fresh water, which changes the salinity (density) driven currents that are a significant influence on the climate.

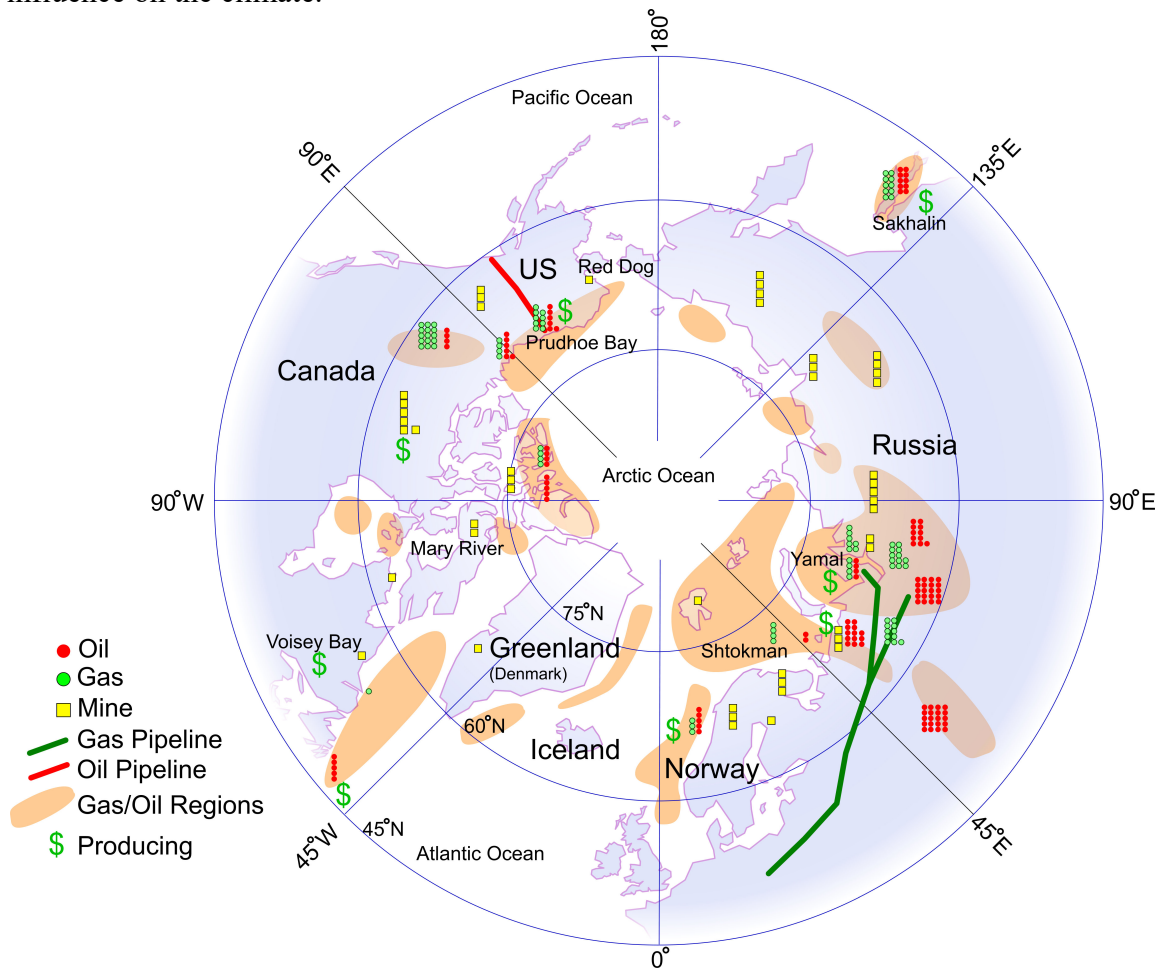


Figure 1.3 Northern Resource Activities.

The final reason is *sovereignty*. Sovereignty implies autonomous control/power over, and responsibility for, a particular thing. There are not many people in the Arctic, and not much infrastructure. It is not trivial to maintain sovereignty in remote locations. In Canada, the Canadian Rangers - a military group that are not trained specifically for combat but are present in sparsely settled areas of Canada – conduct sovereignty patrols in the Arctic. This ensures that at least there are “boots on the ground”.

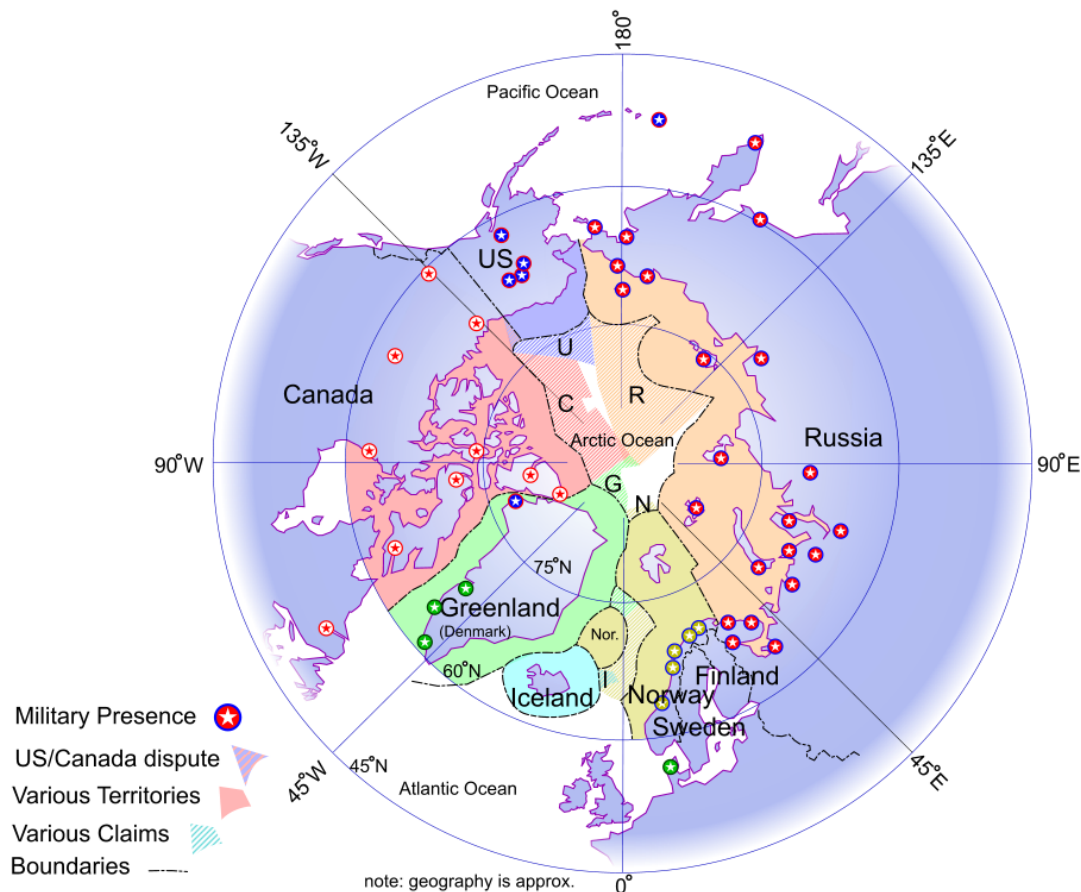


Figure 1.4 Northern Military/Sovereignty Map.

1.4 Transportation

North West passage

The Northwest Passage is a shipping route connecting the Atlantic and Pacific Oceans north of the North American mainland through the Arctic Archipelago across the north of Canada. It consists of a series of deep channels through Canada’s Arctic Islands, extending about 900 miles east to west, from north of Baffin Island to the Beaufort Sea. The first single-season transit was achieved in 1944, when Sergeant Henry A. Larsen, of the Royal Canadian Mounted Police, made it through in a small schooner. Canada regards the Passage as lying within its territorial waters, while other nations (especially the United States) regard it as an international waterway. The issue was highlighted

when Americans sailed the reinforced oil tanker Manhattan through the Northwest Passage in 1969, followed by the icebreaker Polar Sea in 1985, both without asking for Canadian consent.

In 1970, Canada enacted the Arctic Waters Pollution Prevention Act, which asserts regulatory control over pollution within a 100-mile zone and dictates standards for ships entering the arctic. The US did not recognize this assertion. A compromise was reached in 1988, with an agreement on “Arctic Cooperation,” which agrees that voyages of American vessels “will be undertaken with the consent of the Government of Canada.” However, the agreement did not alter either country’s basic legal position.

Recently, warmer global temperatures have made the Passage reliably clear of ice for a significant part of the year. However, ice conditions are still not entirely predictable. Opening the Northwest Passage to commercial vessel traffic would have worldwide significance in transportation, and trade. However, many complex economic and political issues are likely to determine when, and how much, the route would be used. The cost of strengthening ships and the consequent higher rates, for use in Arctic service could limit use of the Passage as a trade route.

As an example of the benefits, the Northwest Passage would cut the distance between London and Tokyo, for example, to less than 8,000 miles from the nearly 15,000-mile route around Africa made necessary if the Suez Canal cannot be used. The Northwest Passage would permit use of larger vessels than allowed by the Panama and Suez canals.

Northern Sea Route

The Northern Sea Route is a shipping channel from the Atlantic to the Pacific Oceans along the northern Russian coast from the Barents Sea to Alaska. The route is essentially the other side of the Arctic Ocean and, like the North West Passage, ice-free for only two months or so per year. Before the early 20th century the route was known as the North East Passage, and that name is still sometimes used.

Most shipping in the Northern Sea Route has concentrated on transporting Siberian raw materials and delivering goods from other parts of the country to coastal ports and the Siberian river routes. The use of the Arctic Ocean as a short cut between Europe and Asia or North America has previously been limited. Recent political changes in Russia have encouraged international use of the sea route. Use of the Northern Sea Route could have significant benefits for the shipping industry. For example, on a trip from Rotterdam to Japan, currently routed through the Suez Canal, the voyage time would be reduced to one third, from approximately 60 days to 20 days. In addition to the time saved, even with extra requirements for some ice transit, fuel savings would be significant.

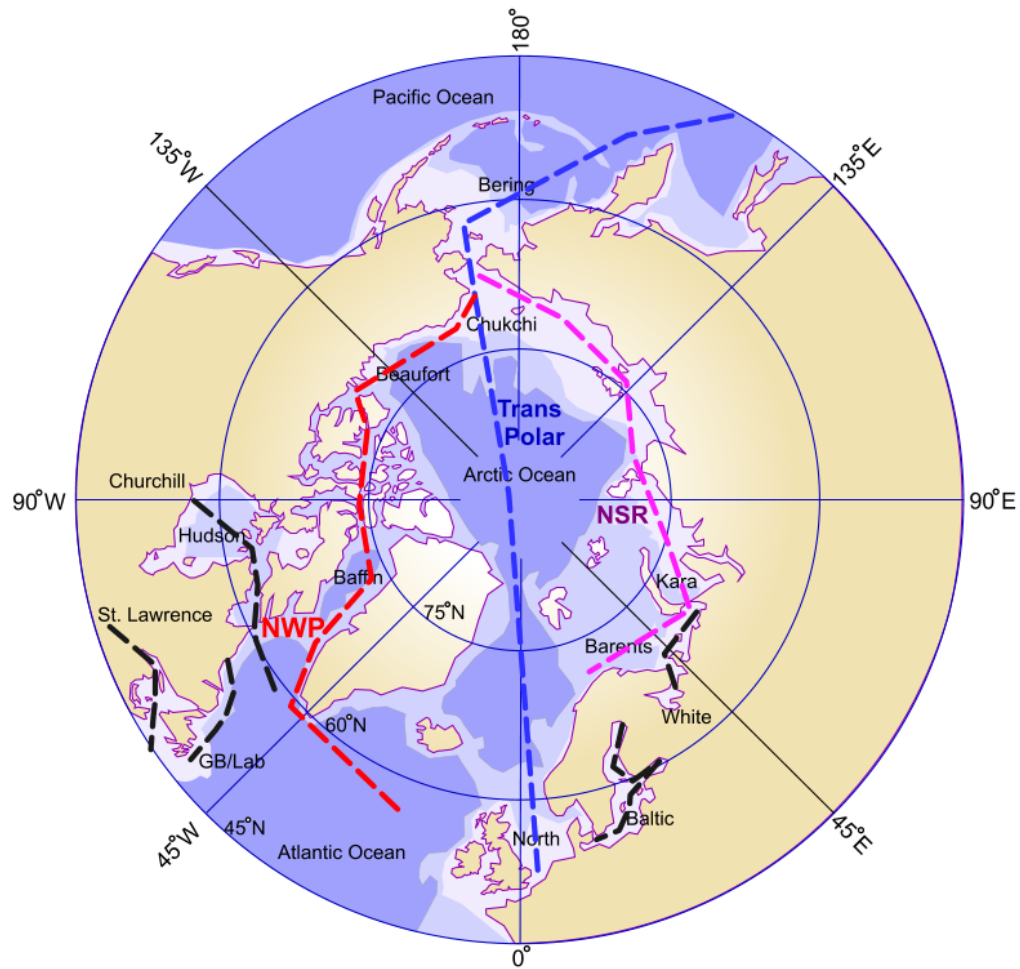


Figure 1.5 Northwest Passage (left) and Northern Sea Route (right).

Chapter 1: Problems

- 1.1 Which of the following is the best description of the term Glaciology.
- a) the study of glaciers
 - b) the study of the material properties of ice
 - c) the study of ice science
 - d) the study of the mechanics of ice
 - e) the study of glacial ice (including icebergs)
- 1.2 Which of the following countries does not have territory north of 60 latitude?
- a) Finland
 - b) United Kingdom
 - c) Iceland
 - d) Sweden
 - e) United States
- 1.3. The Russian controlled sea territory that can be used to go from Europe to Asia is called:
- a) the North East Passage
 - b) the Northern Sea Route
 - c) the Northern Channel
 - d) the Russian Coastal Channel
 - e) the North East Sea Route
- 1.4 Make a sketch of a map of the arctic ocean, naming some of its seas and neighboring lands

Ice Ih, is the phase of ice that occurs naturally on Earth and comprises 100% of the ice we need to be concerned with in Arctic Offshore Engineering. For this reason from now on in this text, the term *ice* refers to “ice Ih”.

2.1 Properties of Water

Because many of the properties of ice arise from the unique properties of water it is worthwhile to review the properties of water before considering the ice. The simplest way to think of a water molecule is shown in Figure 2.2.

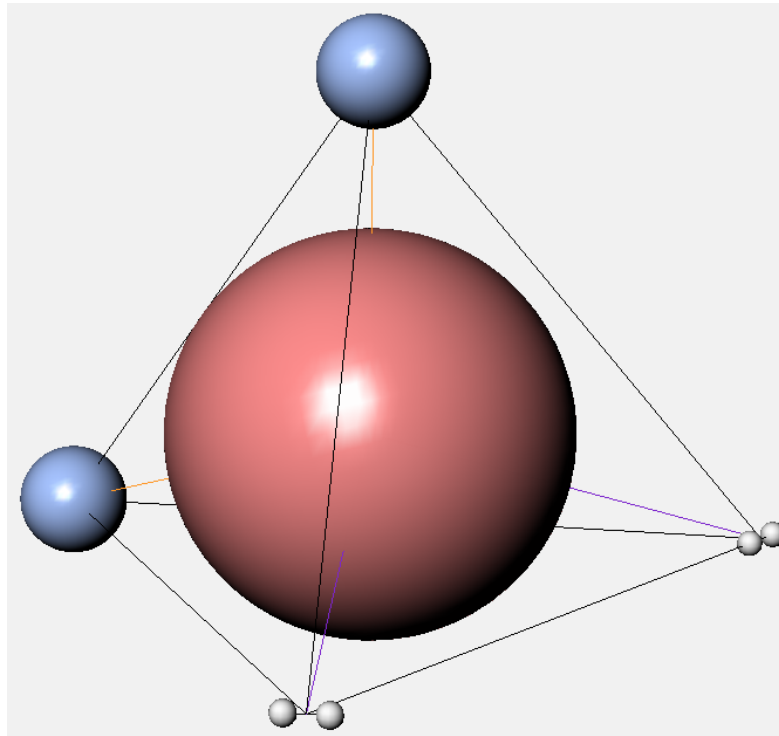


Figure 2.2 Simple Model of Water Molecule.

Figure key:

- Red Sphere: Oxygen atom
- Blue Spheres: Hydrogen atoms
- Orange Lines: covalent bonds between O and H atoms
- Pairs of White Spheres: nonbonding electron pairs
- Purple Lines: indicating position of nonbonding electron pairs
- Black lines: showing tetrahedral shape

Definition: *Covalent bond* – a type of bonding in which electrons are shared by atoms.

Water is one of the most stable (and thus difficult to decompose) of all molecules. Each hydrogen nucleus is bound to the oxygen atom by a pair of shared electrons in the *covalent bond*. However only two of the six outer-shell (i.e. valence) electrons of oxygen are used in these covalent bonds, leaving four electrons to form two non-bonding pairs. The four electron pairs surrounding the oxygen arrange themselves as far from each other as possible due to repulsion between the clouds of negative charge. This would ordinarily result in a tetrahedral geometry in which the angle between electron pairs (and therefore the H-O-H bond angle) is 109.5° ; however because the two non-bonding pairs tend to remain closer to the oxygen atom, they exert a stronger repulsive force on the two

covalent bonded pairs. This forces the two hydrogen atoms closer together resulting in a tetrahedral arrangement in which the H—O—H angle is 104.45° .

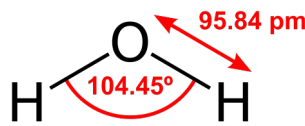


Figure 2.3 H₂O Bond angle and length.

2.2 Freezing

In lowering the temperature and moving to the solid phase of water, the hydrogen bond becomes more stable and ice develops a well-defined hexagonal crystal structure with each water molecule surrounded by four neighboring H₂O molecules. Two of these are hydrogen-bonded to the oxygen atom on the central H₂O molecule, and each of the two hydrogen atoms is hydrogen bonded to the oxygen atom of another neighboring H₂O molecule.

2.3 Crystal structure of Ice

The stable form of ice at normal temperatures and pressures is called *ice Ih*. The h stands for hexagonal. Under laboratory conditions, fifteen other atomic forms of ice can exist. These other phases of ice are present at pressures greater than 200 MPa or at temperatures below -100°C . These laboratory forms of ice do not exist naturally, even beneath the Antarctic ice cap.

Since ice forms from liquid water it retains much of the geometry of the liquid water molecule. Water, or H₂O, is an oxygen atom linked with two hydrogen atoms forming an angle of $104^\circ45'$ between the two hydrogen atoms. The H₂O molecule can be seen in Figures 2.2. In either figure we can see that the water molecule is not symmetrical in all primary planes. This asymmetrical shape is attributed to the existence of two lone-pair electron orbitals. These two lone-pair orbitals form an approximately tetrahedral molecular system with the two bonding orbitals.

The tetrahedral shape of the water molecule enables the creation of the ice Ih crystal. The solid ice Ih crystal is a repeating tetrahedral of oxygen atoms, in which each oxygen atom is bonded through a hydrogen bond to four other oxygen atoms. This arrangement for the crystal structure can be seen in Figure 2.4. In the Figure each of the oxygen atoms has two hydrogen atoms closely associated with it at a distance of $0.95\text{ \AA}$. The oxygen atoms in Figure 2.4 also have two hydrogen atoms less closely associated with them at a distance of $1.76\text{ \AA}$. The allocation of the hydrogen atoms in the Figure is one of many different ways that an oxygen atom can have two hydrogen atoms closely associated with it. The angle between the bonds is $109^\circ30'$, and the individual units of oxygen and hydrogen in ice differ only slightly from the molecular structure of water.

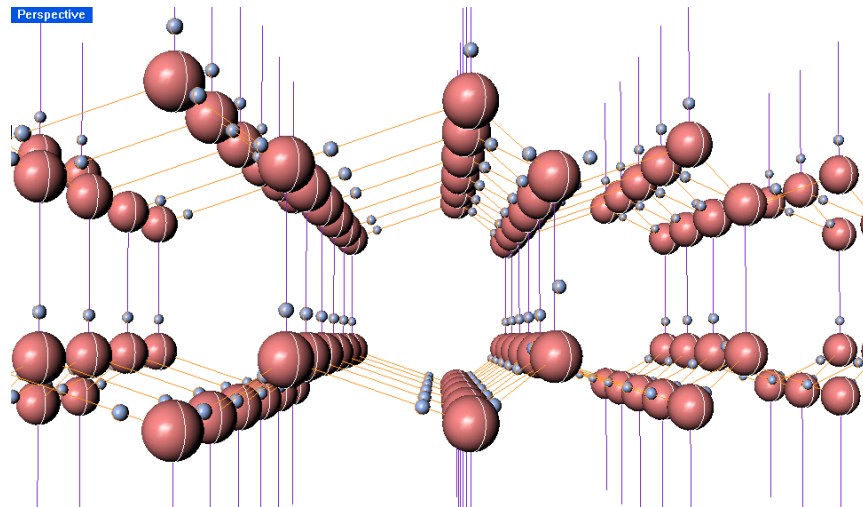


Figure 2.4 Crystal lattice of ice.

Two viewpoints of the resulting crystal lattice are shown in Figures 2.5 and 2.6. From Figure 2.5 we can see that the oxygen atoms are bonded in layers of hexagonal symmetry. In Figure 2.6 we see that the oxygen atoms are less attached between layers of the crystal lattice. Each of the oxygen atoms have three hydrogen atoms bonded to it in the layers of the crystal but only one hydrogen atom bonded to it across layers.

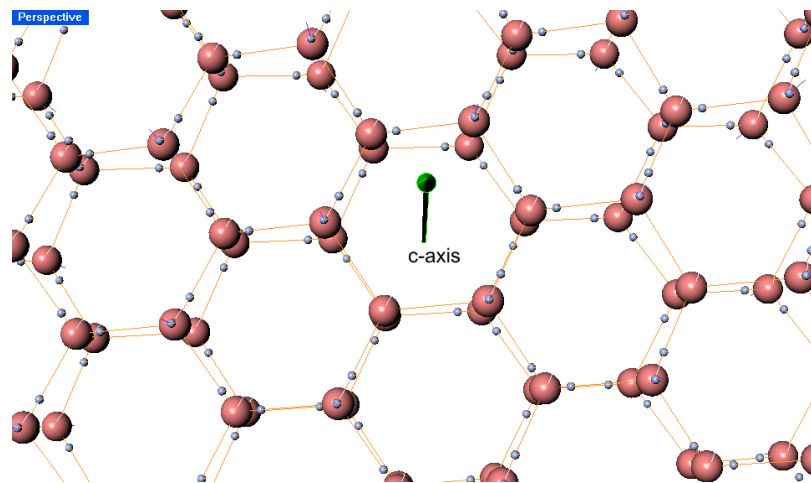


Figure 2.5 Bonding within layers of the crystal lattice.

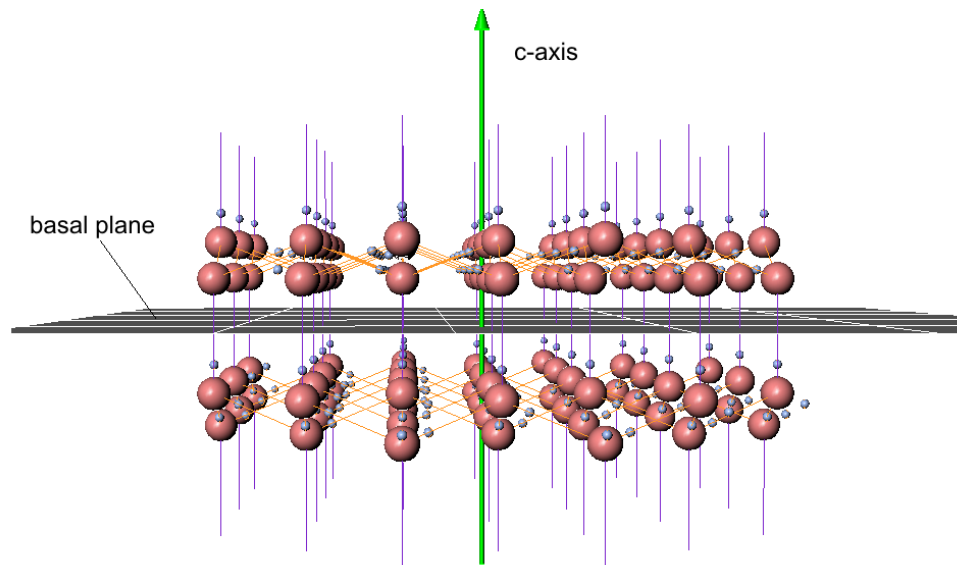


Figure 2.6 Bonding Between Layers of the Crystal Lattice.

The *basal plane* is parallel to the layer structure and is the plane along which deformation mechanisms such as *gliding* and *cleavage* take place. Perpendicular to the basal plane, depicted in Figure 2.6, is the crystal *c-axis*. The *c-axis* is important when explaining the different macroscopic forms of sea ice and glacial ice. In Figure 2.5 the view is looking along the *c-axis* and in Figure 2.6 the view is looking perpendicular to the *c-axis*.

Definition: *c-axis* – the principal axis of a hexagonal crystal perpendicular to the close-packed plane.

The close-packed plane is the densest plane and the basal plane is parallel with it.

2.4 Ice Impurities

No matter what the composition of the water that ice forms from, the resulting crystals are usually of high purity. The high purity of the ice crystals is a result from the fact that very few chemical substances have the proper dimensions and valence for replacement in the crystal ice lattice. Substitute substances that may possibly fit into the lattice structure are some fluoride-based compounds, some ammonia-based compounds and some hydrohalogen acids. Most impurities are rejected as the ice crystal lattice is formed. Usually the impurities within an ice crystal structure don't make up more than 0.02 mole percent of the crystal.

The fact that impurities are generally rejected as ice crystals form is very important when considering sea ice. Even though the sea ice is formed from saltwater, the solid ice contains little salt. Most of the salt content in sea ice is saltwater (brine) pockets or salt crystals that are trapped between pure ice crystals. Thus, sea ice crystals are essentially the same as freshwater ice crystals. However, on a larger scale the thing that needs to be

accounted for mechanically is the presence of fluid pockets, called brine pockets or brine channels, trapped in the sea ice. These pockets exist between the ice crystals as voids and thus influence the overall strength properties of the material.

2.5 Table of properties

Listed below are some of the physical properties (physical constants) of ice. Some of these will be used later to calculate ice growth. Sea ice contains brine in channels, so that the density of solid ice is lower than pure ice, even though the density of the ice/brine system is higher than pure ice.

Table 2.1: Physical Properties of Fresh Water Ice Ih at 0°C

Density	917 kg /m ³
Melting point	0°C
Specific heat (heat capacity)	2.01 kJ / kg /°C
Latent heat of fusion (or melt)	334 kJ / kg
Thermal conductivity	2.2 W / m / °C
Linear expansion coefficient	55·10 ⁻⁶ / °C
Vapor pressure	610.7 Pa
Refractive index	1.31
Acoustic velocity	
Longitudinal wave	1928 m/s
Transverse wave	1951 m/s

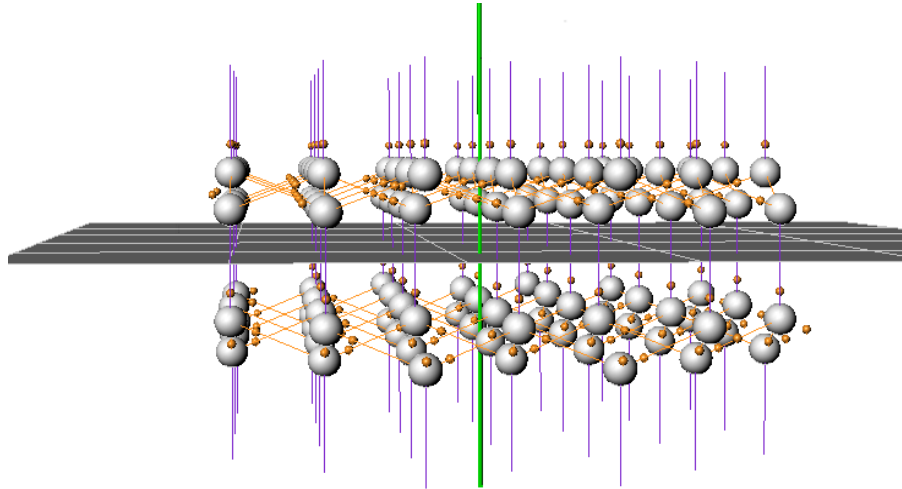
Table 2.2: Physical Properties of First Year Sea Ice (for 35 ‰ water, ice at -5°C)

Density (of the solid phase)	~ 900 kg /m ³ (varies with salinity)
Melting point	-1.8 °C (varies with water salinity)
Specific heat (heat capacity)	~ 8 kJ / kg /°C
Latent heat of fusion (or melt)	~ 280 kJ / kg
Thermal conductivity	~ 2.1 W / m / °C

Note: These values for sea ice are approximate. The exact values depend on the salinity of the sea water and ice, and the temperature. For the data above 35 ‰ water and ice at -5°C is assumed.

Chapter 2: Problems

2.1 Describe and label the sketch shown below.



2.2 Describe ice at the atomic scale, including a sketch.

3 Ice Formation at Sea

There are many types of sea ice, each having its own load characteristics. In order to properly design structures loaded by ice, it is important to be able to classify and understand how each type of ice forms.

Ice ‘remembers’ its past history. Ice forces depend on mechanical properties, which depend on physical properties and structure, which in turn depend on the ice formation and growth process.

3.1 Types of Sea Ice

Listed below are the names and descriptions of increasingly thick forms of sea ice. These are the basic ice types and do not include the great many types of artificial or natural deformed ice. Figure 3.1 shows the progression of ice development. This figure does not include various forms of glacial ice (e.g. icebergs shown in Figure 3.2) or surface ice (e.g. from icing spray on vessels). These are forms of ice will be covered later.

New Ice Types

- **Frazil Ice:** Fine spicules (needles) or plates of ice suspended in water.
- **Grease Ice:** A later stage of freezing than frazil ice where the crystals have coagulated to form a soupy layer on the surface. Grease ice reflects little light, giving the water a matte appearance.
- **Slush:** Snow which is saturated and mixed with water on land or ice surfaces or as a viscous floating mass in water after a heavy snowfall.
- **Shuga:** An accumulation of spongy white ice lumps having a diameter of a few centimeters across; they are formed from grease ice or slush and sometimes from *anchor ice* rising to the surface.

Nilas

- **Dark Nilas:** Nilas up to 5 cm in thickness and which is very dark in color.
- **Light Nilas:** Nilas which is more than 5 cm thick and lighter in color than dark nilas.
- **Ice Rind:** A brittle, shiny crust of ice formed on a quiet surface by direct freezing or from grease ice, usually in water of low salinity. It has a thickness of about 5 cm. Easily broken by wind or swell, commonly breaking into rectangular pieces.

Young Ice

- **Grey Ice:** Young ice 10-15 cm thick, less elastic than nilas and breaks on swell. It usually rafts under pressure.
- **Grey-White Ice:** Young ice 15-30 cm thick. Under pressure it is more likely to ridge than to raft.

First-year Ice

- **Thin First-year Ice/White Ice - First Stage:** 30-50 cm thick.
- **Thin First-year Ice/White Ice - Second Stage:** 50-70 cm thick.
- **Medium First-year Ice:** 70-120 cm thick.
- **Thick First-year Ice:** Greater than 120 cm thick.

Old Ice

- **Second-year Ice:** Old ice which has survived only one summer's melt. Thicker than first-year ice, it stands higher out of the water. In contrast to multi-year ice, summer melting produces a regular pattern of numerous small puddles. Bare patches and puddles are usually greenish-blue.
- **Multi-year Ice:** Old ice which has survived at least two summers' melt. Hummocks are smoother than on second-year ice and the ice is almost salt-free. Where bare, this ice is usually blue in color. The melt pattern consists of large interconnecting, irregular puddles and a well-developed drainage system.

Development of Sea Ice

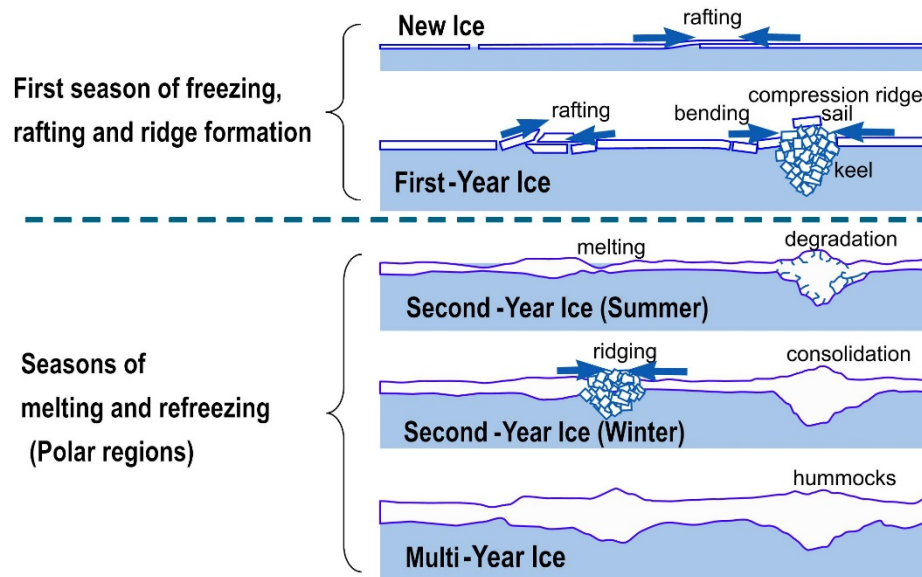


Figure 3.1 Stages in the development of sea ice (after Sanderson).



Figure 3.2 Sea ice and icebergs.

3.2 Initial Ice Formation

Seawater that has a salinity of 35 parts per thousand (ppt or ‰) by weight has a freezing point of -1.8°C . Water with a salinity of 30 ‰ has a freezing point of -1.63°C . The salinity of the Arctic Ocean surface water is generally in the range of 30 – 34 ‰ during the winter. The salinity of the Arctic Ocean surface water is generally in the range of 25 – 30 ‰ in the summer. This is because of run-off from rivers and melting of sea ice.

The freezing process is different in freshwater lakes than it is in seawater. Fresh water has a maximum density at 4°C . Sea water, on the other hand becomes progressively denser as it approaches its freezing point. This is the case for all water that has salinity higher than 24.7‰ . In fresh water, a stable layer of cold (near 0°C), less dense, water forms on the surface when the air temperature drops to 0°C or below. This cold water layer does not mix with the denser (and warmer at 4°C) deeper water. Once the surface water is at 0°C , and the air temperature drops below 0°C the surface layer quickly freezes and forms an ice cover. The ice cover floats on the water and continues to grow if the air stays cold. Deeper lake water stays near $+4^{\circ}\text{C}$ all winter. The ice cover insulates the lake. There is a heat flux, but this heat comes from the heat of fusion, which turns more of the surface water to ice. The heat loss tends not to cool the deeper water. There is a great benefit to this density minimum phenomenon. Both as the lake cools in the fall, and

warms in the spring, the whole lake ‘turn’s over’, which brings oxygen to the deeper waters of the lake and is good for fish living through the winter under the ice.

Seawater undergoes a very different process when the temperature drops. As the surface of the seawater is cooled, there is an intricate mixing process. As top layers in the sea are cooled they become denser than the layers below and sink until they reach equilibrium with the lower layers. The temperature and density of the lower layers are not constant with depth, and these factors too influence the upper cooled layers final equilibrium depth. Warmer and/or less saline water from below replaces the cooled upper layer. Generally the deeper lower layers have a high salinity of (say 35‰) and are denser than the surface layers. For sea ice to form, a layer of water in the upper 10–20 m of the sea must all be cooled to the freezing point. This surface layer is within itself completely mixed, but does not mix much with the saltier layers below.

Once the top 10–20 meters of water is cold and the surrounding air temperature remains at or below -1.8°C , small ice crystals up to a few centimeters across begin to form and float to the surface of the upper layer. Figure 3.3 illustrates the process. The slurry of small crystals is called *frazil*. The c-axes of these crystals are usually vertical (the platelets grow along the basal plane). At first a thin layer of slush is formed as the small platelets are loosely linked together. This thin layer of slush gives the sea water a leaden tint and a smooth mat appearance. This is also called *grease ice* (see Figure 3.4). The frazil tends to calm the surface, much like oil on water will damp small waves. If conditions permit, ice crystals will come together to form an *ice rind* of solid ice. This initial solid ice will be up to 5 cm thick. If this thin layer is subjected to a wave disturbance it will quickly break up to form uneven rounded discs (see Figure 3.5). The rounded discs, called pancake ice, are usually between 3 cm and 30 cm thick.

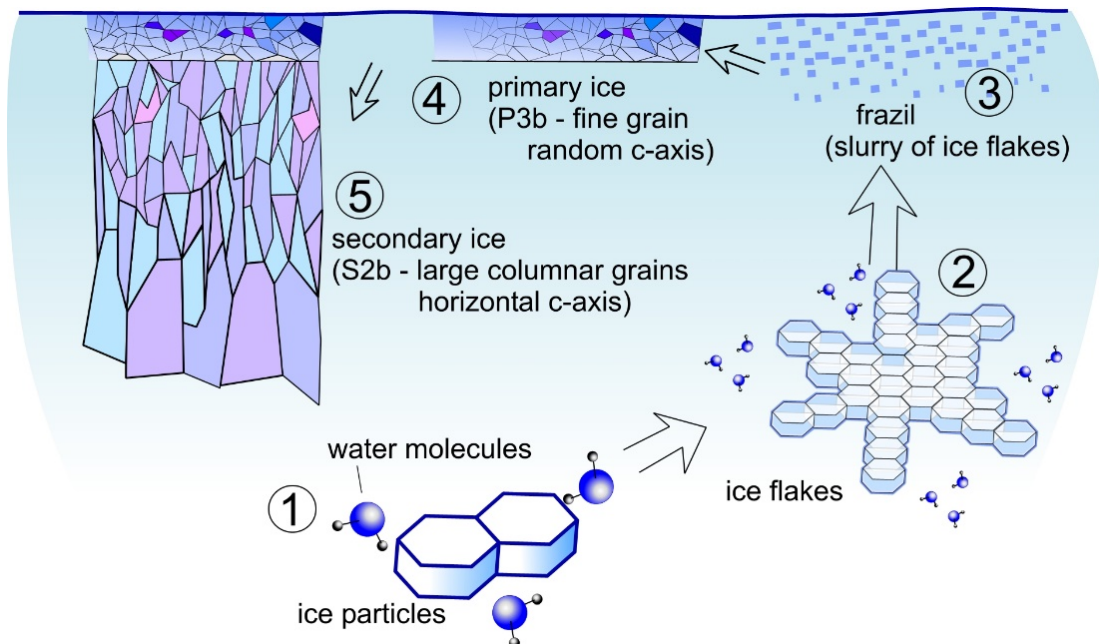


Figure 3.3 Ice formation at sea.



Figure 3.4 Frazil Ice.



Figure 3.5 Pancake Ice.

The next stage of the ice development is the formation of young ice (see Figure 3.6). Young ice is the coalescence of pancake ice or the remains of rind ice frozen into a solid and stable layer that is 5 – 30 cm thick. In this stage of development the ice appears greenish-blue and can be moist on the surface. Since young ice develops from pancake ice you can usually see rings in the ice, which are the edges of the individual pancakes. The young layer is composed of ice crystals that are approximately 1 mm in diameter. These crystals are frozen together in a random fashion and the layer itself is called granular ice.



Figure 3.6 Young Ice.

Since salt from the water is expelled while the water is freezing, the crystals are of pure ice. Brine along with air and gas becomes a part of the layer since pockets of fluid and gas can become trapped in the layer. If one were to melt sea ice the salinity of the resulting liquid would be about 5 – 10 ppt.

3.3 First Year Ice

Once a solid layer of ice is formed, the freezing process changes. As long as the ice sheet remains intact, ice growth will continue from the lower surface downwards. This downward growth process begins quickly and slows as the increasing ice thickness insulates the water. As the process continues, the new ice crystals are increasingly large and can lead to large crystals of about 1–10 cm and larger. These crystals, known as *underwater ice*, or ‘secondary’ ice, appear as large plates that hang down from the upper solid surface in the early stages (see Figure 3.7). The crystals are elongated in the vertical direction and have a substructure consisting of platelets approximately 1 mm thick (Figure 3.8), with a horizontal c-axis. The predominance of the horizontal c-axis is due to preferential growth rates for crystals oriented in this direction: the direction of the heat flux is vertical, and crystals grow with their maximum thermal conductivity aligned with the heat flux.

As the fresh ice crystals form, salt is expelled at the ice-water interface of growing platelets, and cold briny streamers fall from the surface, to be replaced by warmer and fresher water from beneath. The ultimate salinity of sea ice is due to salt trapped between platelet boundaries as they coalesce to form a coherent solid. Ice formed in this way, with predominantly horizontal c-axes, is known as *columnar ice*. A horizontal section through columnar sea ice is shown in Figure 3.8 through cross-polarized filters. The brine pockets between ice platelets can be seen. Figure 3.9 shows how the orientations of the c-axis in an ice sample are plotted.

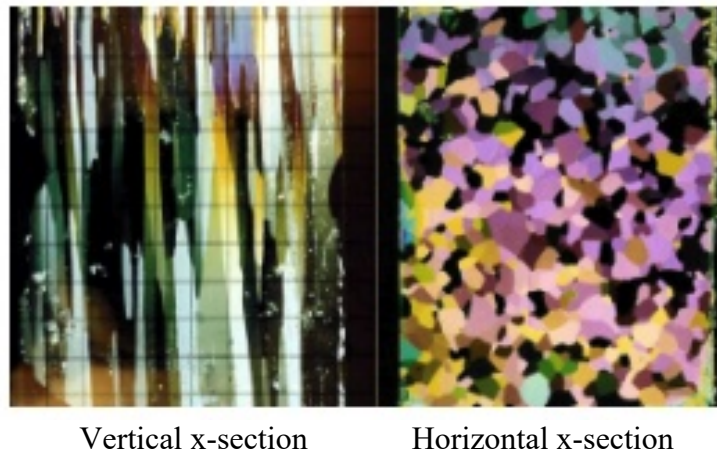


Figure 3.7 Columnar Sea Ice.

If the young ice drifts freely around or grows in an environment where sea currents are highly variable, the columnar crystals grow without any preferred direction on the horizontal plane. This is *transversely isotropic* – that is, its properties are the same in all horizontal directions.

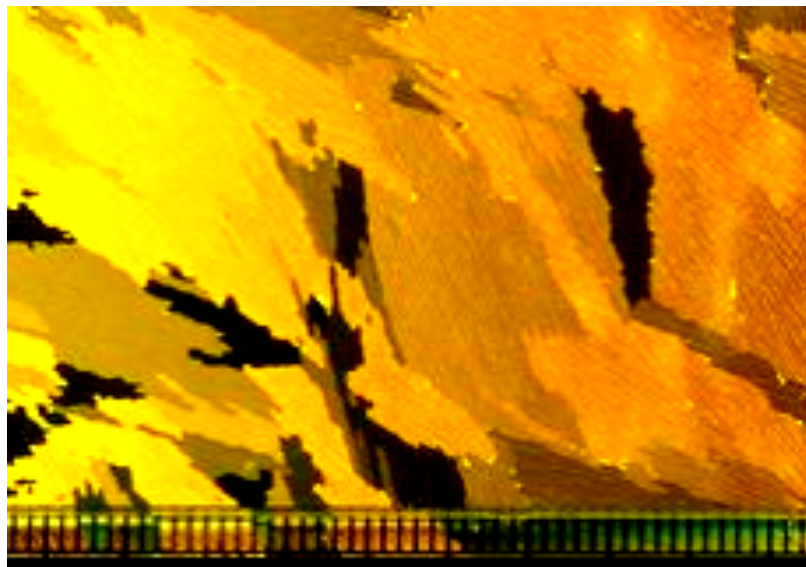


Figure 3.8 Close-up of grains of columnar sea ice.

However, in land-fast ice conditions, where ice is stable relative to the seabed and where uniform directional currents occur, preferred orientations of columnar crystals develop. The occurrence of this has been documented by Cherepanov and Weeks and Gow, who mapped long-range correlations of c-axes direction in first year ice in the Kara Sea and offshore Alaska. In Figure 3.10 the correlation of c-axis orientation for sea ice in the Kara Sea is displayed. Measurement sites are indicated by circles and c-axis orientation by lines through the circles. The c-axis orientation is correlated with prevailing sea currents which are indicated by arrows. The dashed line marks the fast-ice boundary.

The mechanism for this to occur is not yet fully understood. The degree of alignment of c-axes generally improves with depth through the ice cover, and a typical land-fast first-year ice cover consists of about 50 cm of more or less randomly oriented columnar ice, followed finally by preferentially oriented columnar ice. The lower columnar crystals frequently have a c-axes aligned to better than $\pm 5^\circ$.

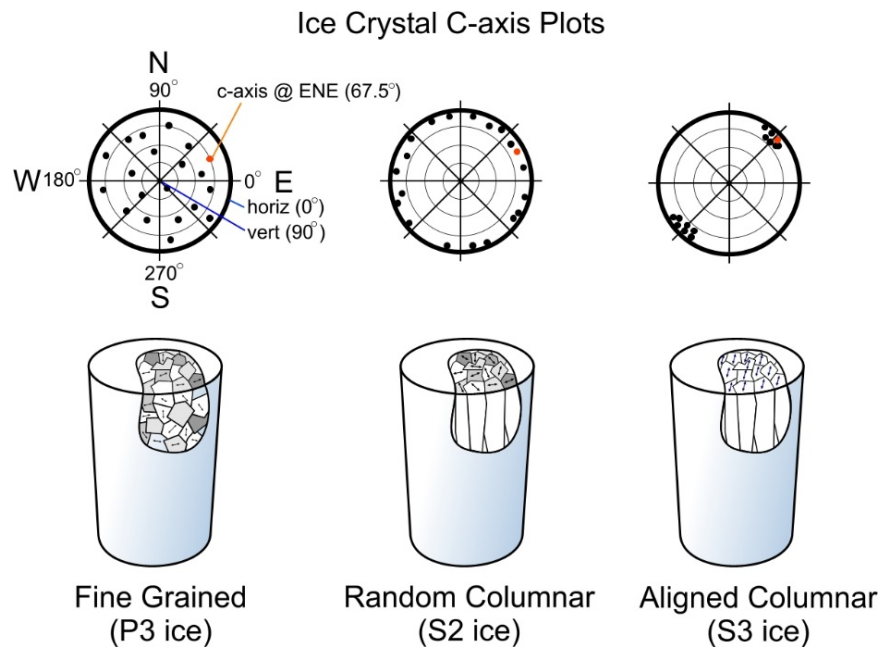


Figure 3.9 C-Axis Plots.

Further offshore, where growing ice is less stable with respect to sea currents, there is generally less preferred orientation of columnar crystals. Indeed, in more dynamic environments, mechanical action and ice rafting processes lead to an altogether more confused picture of first year ice structure. This can be seen in Figure 3.11.

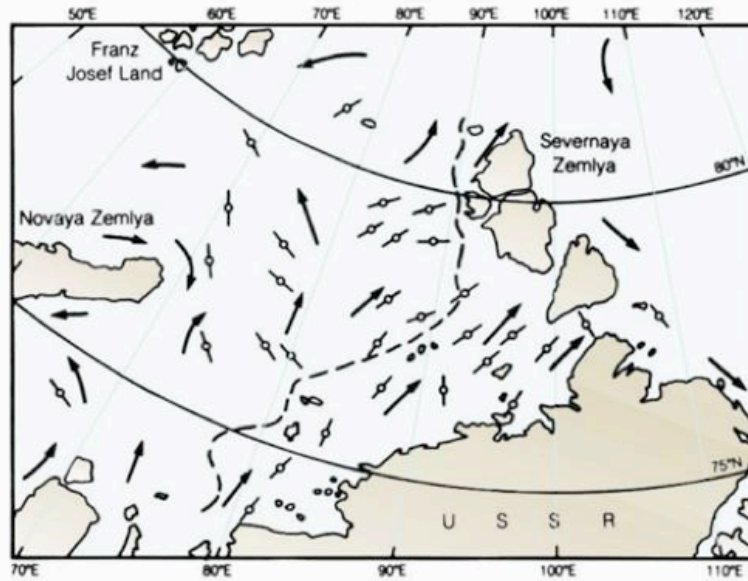


Figure 3.10 Correlation of c-axes orientation for sea ice in the Kara Sea (Sanderson).

From Figure 3.11 (a) we see that stable land-fast ice growing in the presence of sea currents, developing lower layers of oriented columnar ice crystals. In Figure 3.11 (b) demonstrates how ice formed further offshore in a more dynamic environment, showing evidence of ridging and rafting. We can see, in Figure 3.11 (c), *infiltration ice*, formed when the amount of snow cover is sufficient to depress the ice surface below the sea level. The type shown in Figure 3.11 (c) is very common in the Antarctic.

Inclusions of frazil ice and fragments of columnar ice, which have not grown in situ, may occur at any depth, and become incorporated during the freezing process, creating a complex composite material. In addition, flooding of surface snow cover may occur, leading to large amounts of *infiltration ice* being formed. *Infiltration ice* closely resembles frazil ice, being composed of small ice crystals seeded by snowflakes, and is especially prevalent in the Antarctic Ocean, where snow cover on sea ice is often sufficiently deep (about 25% of the ice thickness) to depress the surface below sea level. Recent studies have indicated that as much as 50% of the ice of the Weddell Sea may be of this type.

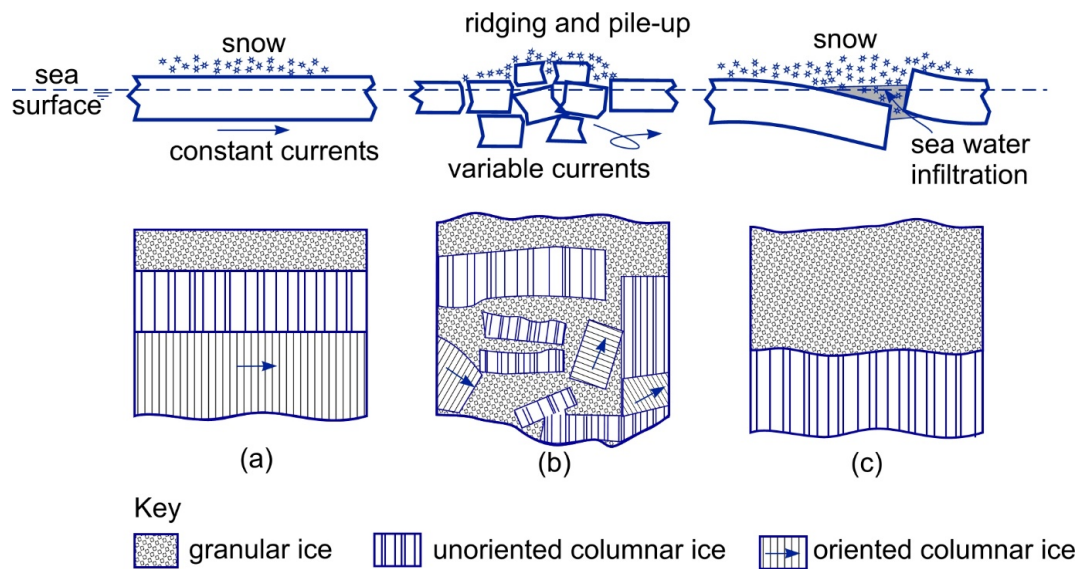


Figure 3.11 First - year ice internal structure (Sanderson).

Much of the early work on first-year ice structure was performed in near-shore landfast ice in the Beaufort Sea, which is not necessarily representative of conditions further out to sea, or in the rather different growth conditions of the Antarctic. In fact, as we have seen, first-year ice may take a variety of forms, depending mainly on the degree of mechanical action it has been subjected to.

Ice is quite flat and uniform for miles near the coast. This uniform structure is usually broken by occasional long cracks (see Figure 3.12).



Figure 3.12 Land Fast Ice split by long-range cracks.

3.4 Temperature Profiles through First-Year Ice

The temperature profile through sea ice in winter is usually roughly linear. The upper surface of the ice normally remains within about $\pm 1.0^\circ\text{C}$ of the mean daily air temperature. The underside remains regularly at -1.9°C , as it is in contact with the seawater. This leads to characteristic profiles as shown in Figure 3.13 (dashed line). As air temperatures increase (e.g. as summer approaches), thermal changes spread through the ice cover, leading to general warming and temperature profiles shown in Figure 3.13 (dotted line).

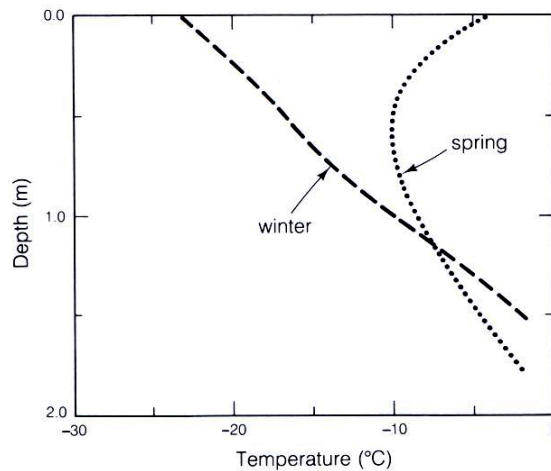


Figure 3.13 Temperature Profiles through Ice.

3.5 Ideal Growth of Clear Ice

Ice growth is a thermal process in which a phase change occurs. In an ideal situation, the air is uniformly cold, the water is uniformly at the freezing temperature and the heat is transmitted upward by conduction. As heat is extracted, the ice grows on the bottom of the ice sheet. The rate of ideal ice growth depends on the rate of heat conduction and the heat budget needed to freeze ice. Figure 3.14 illustrates the assumed temperature profile.

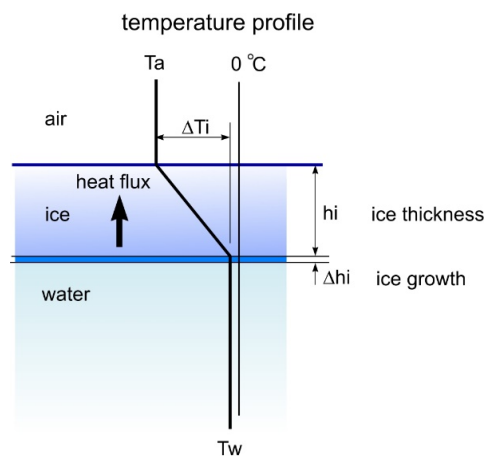


Figure 3.14 Ideal Ice Growth Model.

The growth model will all assume one unit of surface area (1 m²). The rate of heat flow (heat flux) per square meter of ice is given by;

$$Q = \frac{k_i \Delta T_i}{h_i} \quad (3.1)$$

Where Q is heat flux in W/m², k_i is thermal conductivity in W / m / °C, h_i is the ice thickness in m and ΔT_i is the temperature difference across the ice sheet. Q represents the energy that flows up through the ice. Where does this energy come from?

The source of the energy is the energy released as the ice solidifies (called the latent heat of fusion L , with units of J/kg). The rate of ice growth can be found by equating the heat flux with the heat needed to freeze a layer of ice Δh_i thick, onto the bottom of the sheet;

$$\frac{\Delta h_i}{\Delta t} = \frac{Q}{L \rho_i} = \frac{k_i \Delta T_i}{h_i L \rho_i} \quad (3.2)$$

Note: Total Energy/m² = $Q \Delta t = \Delta h_i L \rho_i$

Where Δt is a short interval of time, and ρ_i is density of the ice.

As an example of the basic growth model, consider a sheet of sea ice 4 cm thick. The air temperature is -11.8 C. How thick will the ice be, after one hour (3600s)? The calculation will use the properties from Table 2, (Section 2.5) converted to consistent units (m, kg, s, J, W).

$$\Delta h_i = \frac{k_i \Delta T_i}{h_i L \rho_i} \Delta t = \frac{2.1 \cdot 10}{.04 \cdot 280000 \cdot 900} 3600 = .0075 \quad (3.3)$$

Therefore, the ice thickness will increase from 4 to 4.75 cm.

As the ice thickness increases, the rate of growth decreases. Another problem with growth is that it depends on temperature, which tends to vary. A general model of ice growth, in the form of a differential equation, can be expressed as follows;

$$\int_{h_{start}}^{h_{final}} h_i dh_i = \frac{k_i}{L \rho_i} \int_0^t \Delta T_i dt \quad (3.4)$$

The time integral of the freezing temperature (deg C) is called the Freezing-Degree Time. With time in units of seconds, it is called FDS (Freezing-Degree Seconds), or FDM for minutes or FDD with time in units of days. FDD is the most common unit for field engineering purposes. For model ice making FDM would normally be used. Thus, in consistent units eqn. (3.4) gives:

$$\frac{h_{final}^2}{2} - \frac{h_{start}^2}{2} = \frac{k_i}{L \rho_i} FDS \quad (3.5)$$

Which gives is the standard growth equation:

$$h_{final} = \sqrt{\frac{2 \cdot k_i}{L \rho_i} FDS + h_{start}^2} \quad (3.6)$$

Converted to a simple formula in terms of freezing degree-days, the ideal growth model for sea ice becomes (zero initial thickness):

$$h_i = 0.037 \sqrt{FDD} \quad (3.7)$$

Using the values in Table 2, the results shown in Figure 3.15 were calculated. This shows the influence of time and temperature separately. When time and temperature are combined into an FDD value, the result is Figure 3.16.

As an example, in Resolute, Nunavut in Canada's north, in a typical month of January, there are 1000 Freezing Degree Days (average daily temperature is -32.4°C). At these temperatures, under ideal conditions, open water would grow to a meter of ice in about 20 days. It would take only about 2 days for a foot of ice to grow.

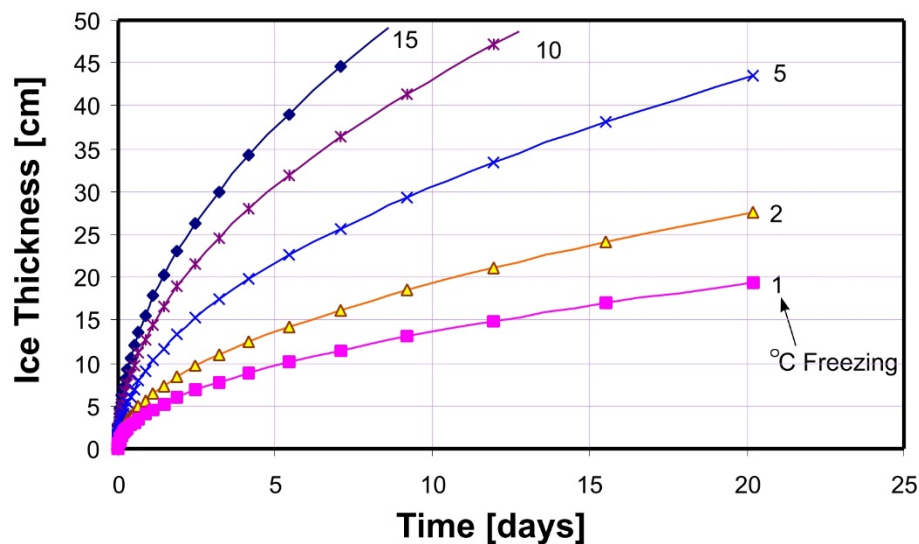


Figure 3.15 Ideal Sea Ice Growth Rate.

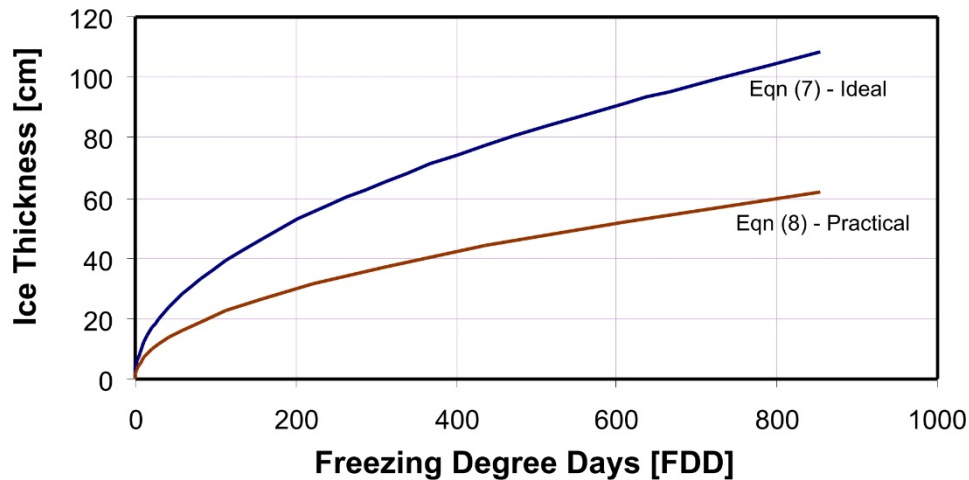


Figure 3.16 Ideal and Realistic Sea Ice Growth in FDD.

However, equation (3.7) likely overestimates ice growth, because it ignores several factors including heat input from sun and water, and it ignores the insulating effect of snow and the air boundary layer. A more practical estimate would be found with the following equation (Cammaert and Muggeridge, 1988);

$$h_i = 0.025\sqrt{FDD} \quad (3.8)$$

3.6 Ideal Growth of Ice with Snow

When there is snow on the ice surface, the heat flux and ice growth is reduced. Figure 3.17 illustrates the growth model. The snow insulates the surface and lowers the heat flux through the ice.

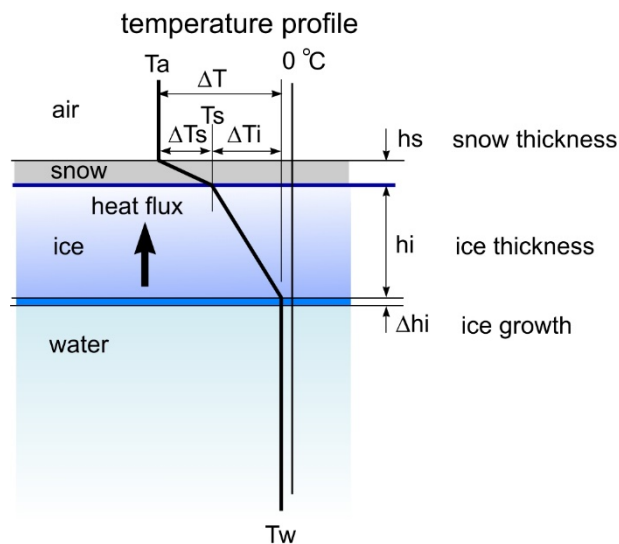


Figure 3.17 Ideal growth of ice with snow.

To solve the growth problem, we assume that a steady state has been reached and that the heat flux through the ice is equal to the heat flux through the snow. This is expressed as:

$$Q = Q_i = \frac{k_i \cdot \Delta T_i}{h_i} = Q_s = \frac{k_s \cdot \Delta T_s}{h_s} \quad (3.9)$$

Where Q is heat flux in W/m², k_s is thermal conductivity of snow in W / m / °C, h_s is the snow thickness in m and ΔT_s is the temperature difference across the snow layer. The total temperature difference is:

$$\Delta T = \Delta T_i + \Delta T_s \quad (3.10)$$

Combining (3.9) and (3.10) above gives an expression for the freezing temperature of the ice in terms of the overall temperature difference:

$$\Delta T_i = \frac{h_i \cdot k_s}{h_i \cdot k_s + k_i \cdot h_s} \Delta T \quad (3.11)$$

Using (3.11) and (3.2), an equation for the ice growth under snow is:

$$\Delta h_i = \left(\frac{k_i \cdot k_s}{h_i \cdot k_s + k_i \cdot h_s} \right) \frac{\Delta T}{L \cdot \rho_i} \Delta t \quad (3.12)$$

Equation (3.12) can be expressed in integral form and solved in closed form (the solution of a quadratic is involved). However, that solution requires a constant snow depth, which is not reasonable for very thin ice. When snow falls on open water, it seeds new ice, instead of insulating the surface. Consequently, it is more appropriate to solve equation (3.12) numerically, with snow being added after the ice is formed. The thermal conductivity of snow is highly variable. A value of .25 W / m / °C was used for this calculation. Figure 3.18 shows the effect of adding snow to the freezing calculation. Clearly, even a thin snow cover greatly reduces the ice growth. A foot of dry light snow will practically stop ice growth.

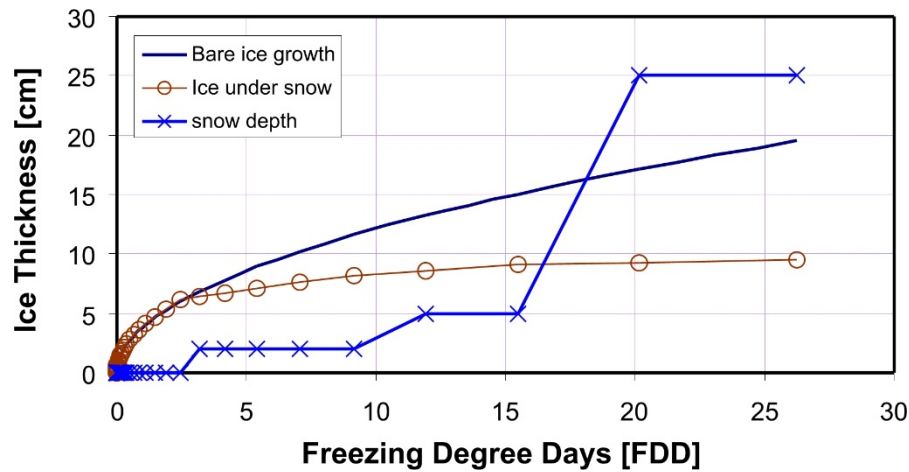


Figure 3.18 Growth of ice with and without snow.

3.7 Actual Growth of Ice

The above calculations, even with snow, assume a very ideal thermal regime. In real conditions, there are many more factors. There are both water and air boundary layers, which tend to reduce the heat flux. The sun will add energy during the daytime. Transient effects tend to affect the temperature profile in the ice. Figure 3.19 illustrates some of these factors. It is for these reasons that ice thickness can only be approximately estimated from weather data, and equation (3.8) should be seen only as an estimate.

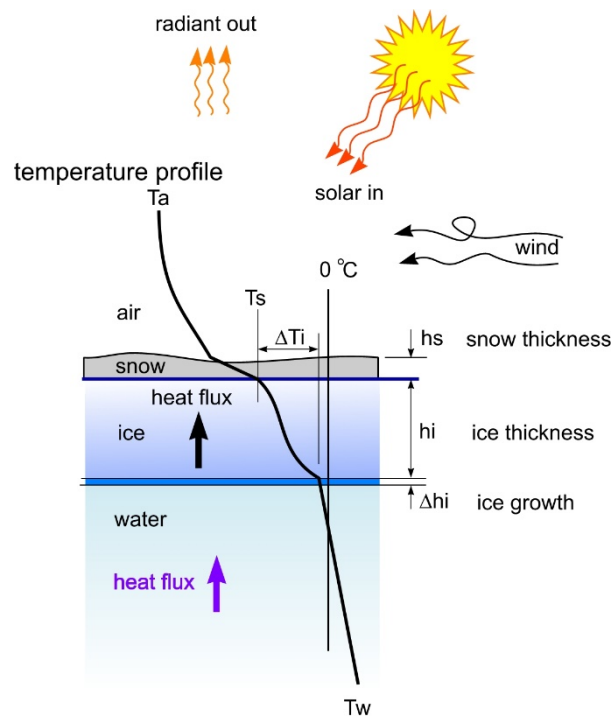


Figure 3.19 Non-Ideal ice growth.

3.8 Gas and Brine Pockets

As seawater freezes, the salt that is rejected during ice crystal formation is partly trapped in brine pockets. Most of the salt stays in the surrounding seawater. Of the trapped salt, very little makes its way into the solid ice crystals. Air pockets, or gas, also exist in sea ice. This is due to bubbles being trapped when the water freezes. Air bubble formation may occur for several different reasons:

1. Agitation of the surface from wave action.
2. Emergence of dissolved gases in the seawater.
3. Plant and animal life could also give off gases that become trapped below the growing ice

Usually the gas concentrations vary from 0.5-5% by volume. The trapped gas is typically close to pure air. Zubov (1945) showed that samples from the Barents Sea had a composition of about 82% N₂, 17% O₂, 0.4% CO₂. This is lower in O₂ and higher in CO₂ than normal air. Lower layers of ice have lower gas density of about 0.5% while higher layers have a density that can vary from 1-5%.

Gas and brine pockets, in sea ice, cause density variations compared to pure bubble-free freshwater ice. Uncontaminated bubble-free freshwater ice has a density of 0.917Mg/m³. More often than not the density contributions of brine and trapped gases cancel each other out. The characteristic density of sea ice varies from 0.915-0.920Mg/m³.

The pace of freezing controls the amount of saltwater trapped in sea ice as it forms. In the upper granular layer the salt content may be relatively high, varying from 8-12ppt. Freezing rates tend to be slower lower down and brine is more efficiently excluded from the ice as it forms. The salt content lower down in the ice cover generally varies from 5-8ppt. The connection between freezing rate and salt content is displayed in Figure 3.20.

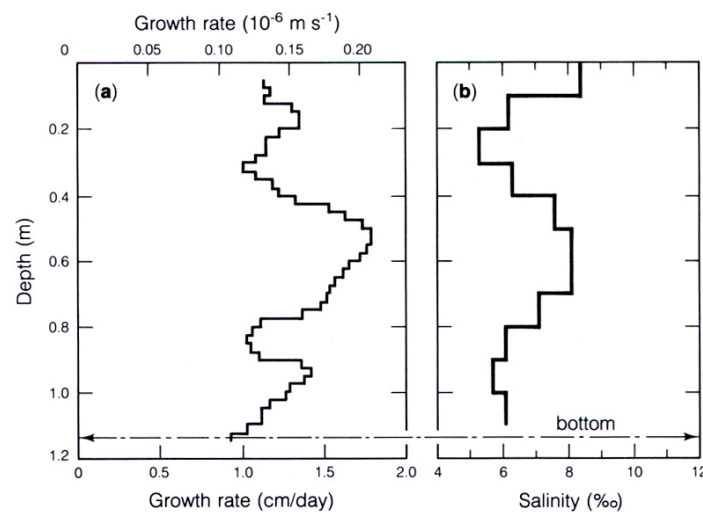


Figure 3.20 Salinity content compared with growth rate.

Figure 3.20 (left figure) shows the growth rate of first year ice compared to salinity profile (right figure). Brine is trapped in fine pockets of solution amid platelets of uncontaminated ice. This can be seen in Figure 3.8. The liquid brine exists in a complex balance with the surrounding ice. The concentration of the brine is 35 ‰ at -1.9°C. As the temperature decreases pure ice freezes out of the solution onto the walls of the brine pocket leaving behind a more concentrated solution of brine. This continues until the brine is in equilibrium at the new lower temperature. This progression is thermodynamically reversible.

Seawater has a mix of different types of salt. As the temperature falls various salts start to precipitate out (i.e. they become dry crystalline salt, rather than brine liquid). The first precipitation happens at -8.2°C, when Na₂SO₄, 10H₂O salts come out of the solution. Next, NaCl, H₂O precipitates out at -22.9°C. The remaining trace salts precipitate out at -36.8°C. NaCl is the predominant salt (85% by weight) sea ice. Thus, below -22.9°C sea ice is solid and the salt in brine pockets is almost all crystalline. This helps explain why road salt does not melt ice on roads when the temperature is very cold.

The total volume of the brine cavities can be calculated using empirical equations that are a function of temperature and salinity. These equations assume that the ice is gas free. An equation, suitable for the temperature range -0.5°C to -22.9°C is:

$$v_b = .001 \cdot S \left(.53 - \frac{49.2}{T} \right) \quad (3.13)$$

where T is temperature (°C), S is salinity of the ice (‰ (or ppt), measured after a sample is melted) and v_b is the brine volume ratio. To check the equation, note that ice with a salinity of 6 ‰ at a temperature of -10°C will have a brine volume ratio of .0327 (i.e. 3.27%).

Over time, brine cavities tend to slowly travel towards the warm direction in the ice. Usually during winter, the temperature tends to be higher, lower down in the ice column. The brine cavities move downwards by a thermodynamic process shown in Figure 3.21. Figure 3.21(a) depicts the brine cavities moving downward, as in winter, and Figure 3.21(b) depicts the brine cavities moving upward, as in spring/summer. The pocket may combine to create long conduits of thickness 0.1 – 1.0 cm. Brine convection currents assist in this development. A pictorial representation of brine conduits is shown in Figure 3.22. The brine volume becomes important when determining ice strength as will be seen later.

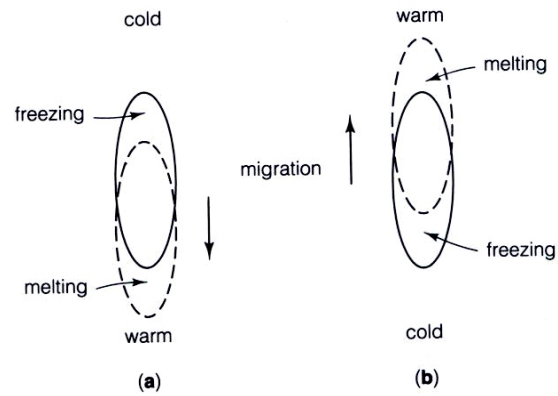


Figure 3.21 Brine Cavity Migration along temperature gradient.

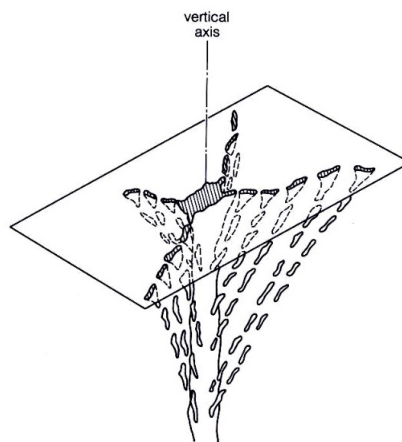


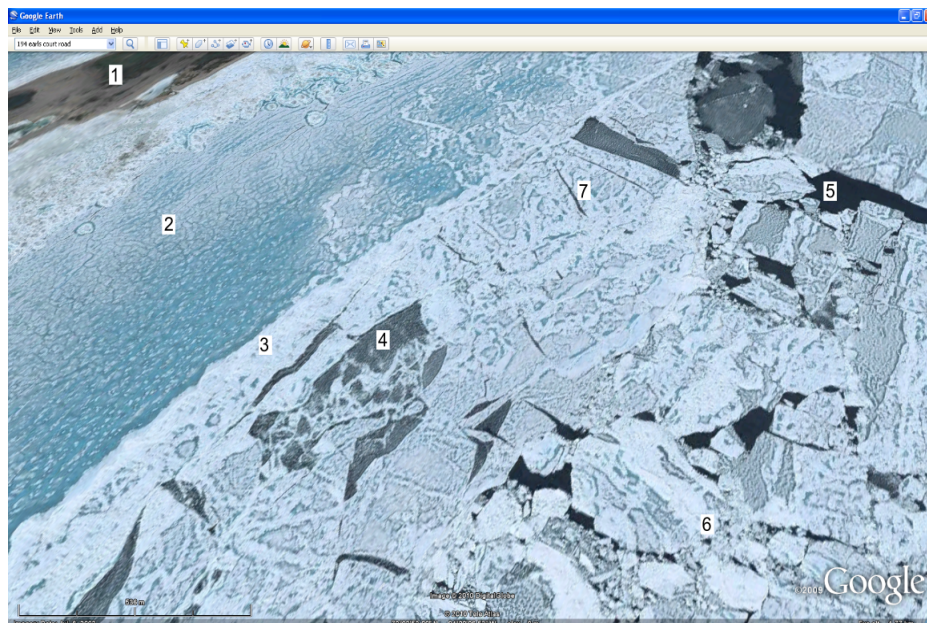
Figure 3.22 Brine Channels in First Year Ice.

Chapter 3: Problems

3.1 The photograph below was taken near the North Pole in 2004. Describe the ice feature in the photo. Estimate both the height (in air) and depth (in water) of the feature (use the people for rough scale). Sketch a possible cross section of the ice below the people.



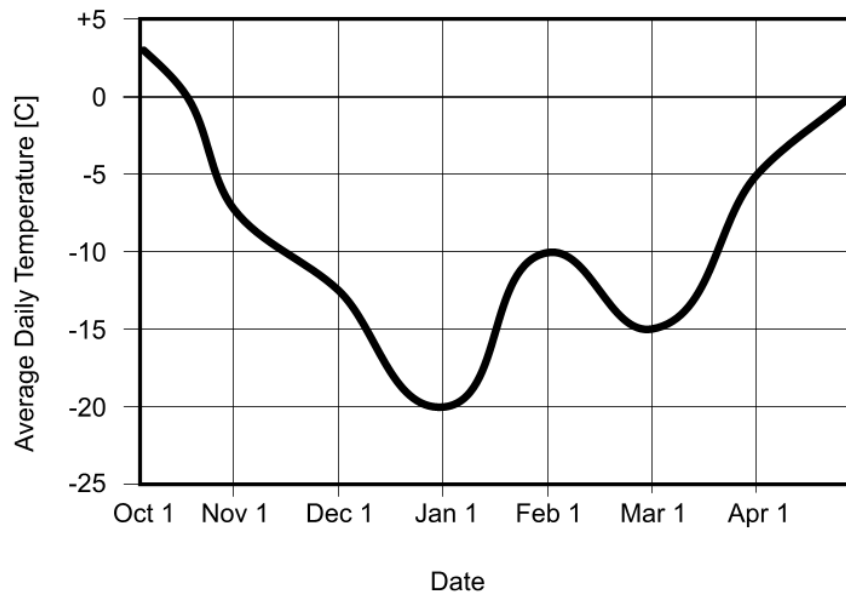
3.2 Natural ice Examine this image closely. It's an image of ice taken by Satellite. Describe the various features you see, with reference to the type, condition or other aspect of the ice. Seven numbers are on the image. You can use the numbers to help organize your description. (ie Tell me what you see, and what it means!)



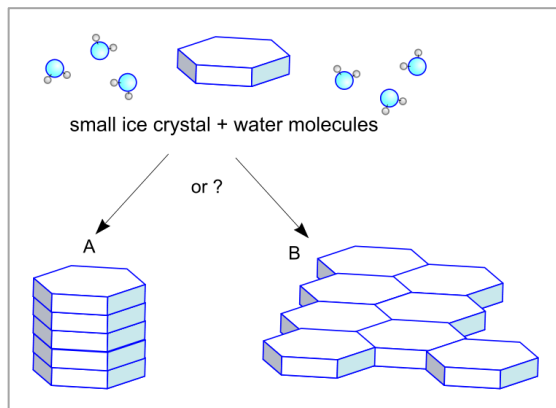
3.3 The air temperature is minus 20°C at night with a light wind blowing. The ice on a lake is 10cm thick. There is a 3cm snow cover. The snow has a thermal conductivity of $0.2 \text{ W/m}^{\circ}\text{C}$. How much will the ice grow in one hour?

3.4 Ice Growth

- Using the temperature plot below, find the estimated maximum ice thickness for the sheltered ocean bay where this record was taken? Show your calculations and explain your assumptions.
- Estimate which day the ice reached 10 inches thickness.



3.5 There is a very small single ice crystal in water in freezing conditions shown at the top of the sketch below. From this point which option A or B is most likely to represent further ice growth? Also - indicate the direction of the C axis.

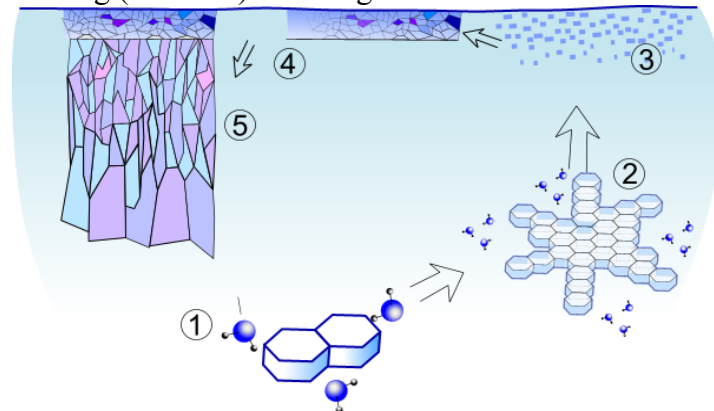


3.6 Describe the picture shown below.

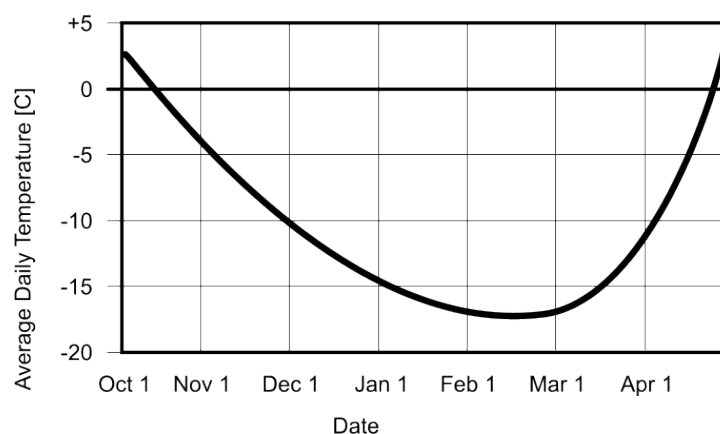


3.7 The ice in the pond is 6 cm thick. At an average temperature of -20°C , how long do you have to wait for the ice to be at least 8 cm so you can go ice fishing?

3.8 Explain what is occurring (#s 1 to 5) in the figure below:

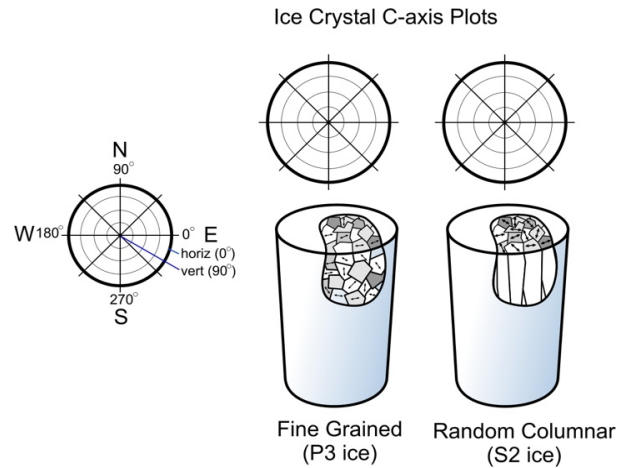


3.9 Using the temperature plot below, find the estimated maximum ice thickness for the sheltered ocean bay where this record was taken? Show your calculations and explain your assumptions.



3.10 Sea ice has a salinity of 4 ppt, and is at -8°C . What is the brine volume ratio? What is the uniaxial crushing strength likely to be?

3.11 Fill in the C-axis plots with plausible examples of grain orientations for the P3 and S2 ice samples:



3.12 Sea Ice is 5cm thick. Its -25C. How long until the ice will be 10cm thick?

3.13 Describe what you see in the picture:



3.14

- a) After about four inches of ice has formed on a pond, there is a heavy snowfall which sinks the 4 inches of ice and floods the lower layer of snow, which then freezes. When you take a core sample, a week later, and examine the crystal structure – what do you expect to see?
- b) What happens to the salt in seawater when the sea freezes?
- c) Compare the terms “multiyear ice” with “ancient glacial ice”
- d) What will happen to worlds oceans if the whole of the Ross ice shelf in the Antarctic breaks off and floats up into the Pacific?
- e) What is the main difference between sea ice and lake ice?

3.15 Ice Growth

- a) Ice starts to form in a pond behind your house on December 12th. The daily average temperatures for the rest of December was -4C, and then -8 for January. That data was on a weather site at Environment Canada. There has been very little snow, which has blown off the pond, and the days in Dec and Jan have been mostly cloudy. You plan to go out on the pond on Feb 1. What do you expect the thickness to be?
- b) How would your estimate have changed if there had been a lot of sunny days or a lot of snow?

3.16 Use the following data to estimate the ice thickness on Feb 8 at 5pm;

Date	Feb 6	Feb 7	Feb 7	Feb 8	Feb 8	Feb 8
Time	1pm	1am	1pm	1am	1pm	5pm
Air temp	-6 C	-12 C	-8 C	-10 C	-15 C	
Ice thk.	1cm					?

4 Sea Ice Evolution

4.1 Formation of First Year Ridges

When first-year ice is subjected to dynamic action many distinct forms of ice are created this can be seen in Figure 4.1.

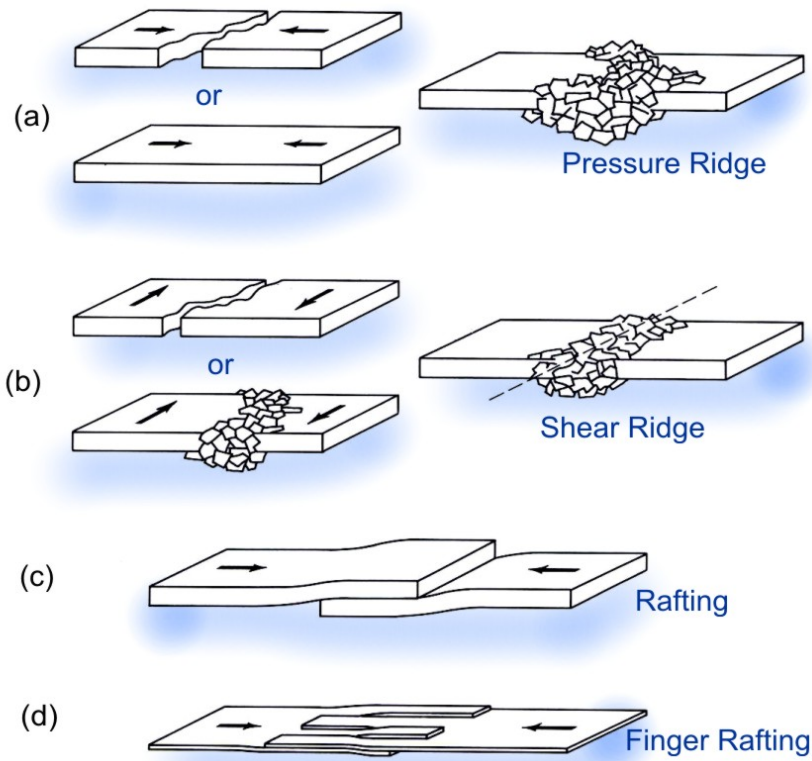


Figure 4.1 Deformation of First-year ice

Figure 4.1 (a) depicts the formation of a *compression ridge*. A compression ridge is formed when two sheets of ice are forced towards one another. The forcing together of two sheets of ice can occur at the interface of two sheets or it can happen suddenly in level ice due to large compressive stress. The ridge formed from compression is very irregular. Figure 4.1 (b) depicts a *shear ridge*. The shear ridge in first-year ice is produced by sideways movement. The shear ridge is normally very straight. The straightness is due to the fact that the shear procedure removes any out-of-straight features, much as a file or sandpaper will remove ‘high’ points. These shear ridges can be many kilometers long and have steep walls consisting of thinly pulverized ice. In Figure 4.1 (c) *rafting* is depicted. Rafting is formed as thin ice plates (usually *grey ice*) slide over and under one another. With rafting there is little *rubble* formation. Figure 4.1 (d) depicts *finger rafting*, which occurs in very thin ice. Note: Rafting usually occurs in ice less than 15 cm thick, but can occur in ice up to 1 m thick.

We can see a summary of the formation process of *first-year ice* and its subsequent development into *multi-year ice* in Figure 4.2.

Development of Sea Ice

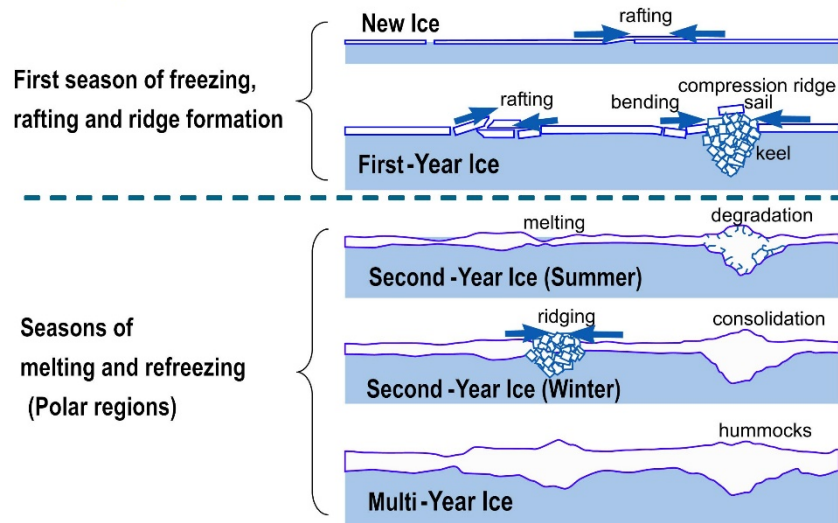


Figure 4.2 Progression of First-year ice into Multi-year Ice

Figure 4.2 (topmost) depicts young ice that is about 30 cm thick in early winter. As the season progresses, this grows to *first-year ice* that is approximately 1.5 m thick. Simultaneously, ice dynamics cause *ridging* and *rafting*. This *first-year ice process* is depicted in Figure 4.2 (second from top). Some first-year ice will survive the Spring and Summer melt (see Figure 4.2 (third down)). The linear shape of the melt pools that form on ice during the summer is depicted in Figure 4.3. In Figure 4.2 (second from bottom) we have *second-year ice* – ice that has survived though the summer. During its second winter, the *second-year ice* undergoes refreezing and further ice dynamics. Depicted in Figure 4.2 (bottom) is *multi-year ice* approximately 4-6 m thick and around 5-10 years old. The multi-year ice contains old smoothed *ridges*, *hummocks* and *bummocks*. A more detailed description of ice types beyond first year will be described later.

Hummocks – small hills of broken ice forced upwards by pressure. They appear jagged when “fresh” (i.e. newly formed) and smooth(er) when “weathered”. Care must be exercised around hummocks because they usually have a lower salinity and may be much stronger than the surrounding ice cover.

Bummocks – the submerged volume of ice under a *hummock*.



Figure 4.3 Melt Pool Shapes

4.2 Ice Melting Process

As the summer season approaches, first-year ice begins to deteriorate (melt). The temperature of the seawater rises and begins to melt the bottom surface of the ice. The air temperature rises and (as) solar radiation increases causing the upper layer of snow and/or ice to begin to melt. *Melt pools* begin to form on the surface of the ice cover. These melt pools are usually blue or blue-green in colour, and can take on a straight-line form (as in Figure 4.3). As the ice surface melts, the entire melting process speeds up. This is partly because water has a lower *albedo* than ice and snow. *Albedo* is a measure of the reflectivity of a surface. Ice/snow has a high albedo; meaning it reflects much of the solar radiation it is subject to. Water has a lower albedo; implying that it absorbs more energy from the sun than ice or snow. The melting process also accelerates as inclusions such as dirt and brine pockets in the ice cover are exposed. Particulate inclusions (e.g. dirt) have a low albedo, and absorb the sun's energy regularly. In combination with the albedo effects are the effects of the brine pockets. As more brine is released the salinity of a melt pool increases. This too speeds up the overall melting process. Together these two processes (along with other weathering factors like winds and currents) cause the ice cover melt ever faster.

There are, however, processes that may slow the melting process and tend to purify the ice. Melt pools may run off the side of the ice floe, thereby increasing the overall albedo of the floe and removing the impurities. Also, as melt-pools warm above zero the top layer of water becomes denser. An effect of this is efficient convection currents, which promote melting of the ice surface at the bottom of the melt pool. As seen Figure 4.5 the inverted convection currents allow the warmer water to sink. This can cause the melt-pool to melt completely through the ice cover. These *melt holes* drain off the melt water as well as the inclusions. Together, the melt pools and melt holes form a drainage network (see Figure 4.4). One of the visible features of old ice is a well-established drainage network.



Figure 4.4 Melt pool and drainage channels

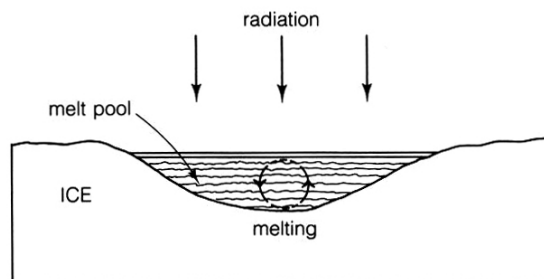


Figure 4.5 Process of melting in a melt pool

With progressive melting, floes separate from the ice cover. Sea currents and wind cause these floes to drift. Usually most of the first-year ice melts completely during the summer season. This is not the case at high latitudes. At high latitudes some of the first-year ice survives and remains at the onset of the next winter. This is known as second-year ice.

4.3 Second-Year Ice

Second-year ice has less brine, since most of the brine has drained out during the summer. Salinities in the summer vary from 1-4ppt. Surface salinity may be low at around 1ppt. This ice is porous and granular since re-crystallization occurs during consecutive freeze-thaw sequences.

During the second winter, second-year ice experiences re-freezing and environmental forces that cause it to deform. This can be seen in Figure 4.2 (second from bottom). Due to this process, second-year ice can have a range of thickness of 2 to 3 meters. Second-

year ice is hard to study specifically since it is hard to tell the difference between second-year ice and multi-year ice. Figure 4.6 shows multiyear ice flows with melt pools.



Figure 4.6 Multi-year ice floes

4.4 Multi-Year Ice

Ice which survives more than two summer seasons is known as *multi-year ice*. Second-year ice is often included in this definition since it is hard to distinguish the two. Generally, the ice in the polar pack varies in age from 5 to 10 years old.

When second-year ice undergoes continuing environmental forces and melt-thaw processes it becomes multi-year ice. This process is described visually in Figure 4.2. Compressive stress causes new ridges to form in multi-year ice. The old ridges become smooth from melting processes. A collection of melt pools forms in valleys and can flow out or refreeze during the following winter season. There also may be a flooding and freezing of surface snowdrifts. If the ice is sufficiently thin and the winter season adequately cold, additional freezing may occur at the bottom surface of the ice.

The Arctic polar pack's interior is almost completely multi-year ice. This interior section does have widespread structures of fractures and open water leads. If one is considering near-shore characteristics, multi-year ice is generally in the shape of distinct floes approximately 1 km in diameter. A multi-year ice floe is depicted in Figure 4.6.

The thickness of multi-year ice floes in the polar pack varies from 2 to 6 meters. When cores of this ice are examined, there appears to be a distinct annual layer structure. This annual layer structure is much like the rings of trees. This tree ring similarity is especially predominant if the ice has grown in very stable conditions. The thickness of these annual layers is usually in the range of 30-50 cm. If a floe is undeformed, then it generally has about 10 annual layers. When referring to multi-year floes it is hard to speak of a typical floe since they are highly irregular and uneven in quality. No stable

annual layering may be found if the floe has been through extreme deformation conditions. It may also have a range of thicknesses.

The surface *sails* of multi-year ice *ridges* can be 5 meters or more higher than sea level. The *keels* of these ridges may be 20 meters below sea level.

Sail – the above water portion of an ice ridge.

Keel – the submerged portion of an ice ridge.

These heights for sails and keels may occur when the floe they are attached to is only 1-2 meters thick. Large regions of regular and very thick landfast multi-year ice are known to exist in some regions. One of these regions is the Queen Elizabeth Islands. This ice has an estimated thickness of 15 meters to 30 meters. The surface of this extremely thick ice is asymmetrical only on account of drainage and melting processes.

The salt content of multi-year ice is usually in the range of 0.5 – 4 ppt. The salt content level is a result of persistent discharge of salt during the formation process of the multi-year ice.

4.5 Multi-Year Ridges

Multi-year ridges have been studied extensively because they are extremely dangerous to marine infrastructure. Cross sections of old ice floes from the Beaufort Sea are shown in Figure 4.7. The vertical scale is increased by a factor of 2 and the snow cover has been left out for clarity.

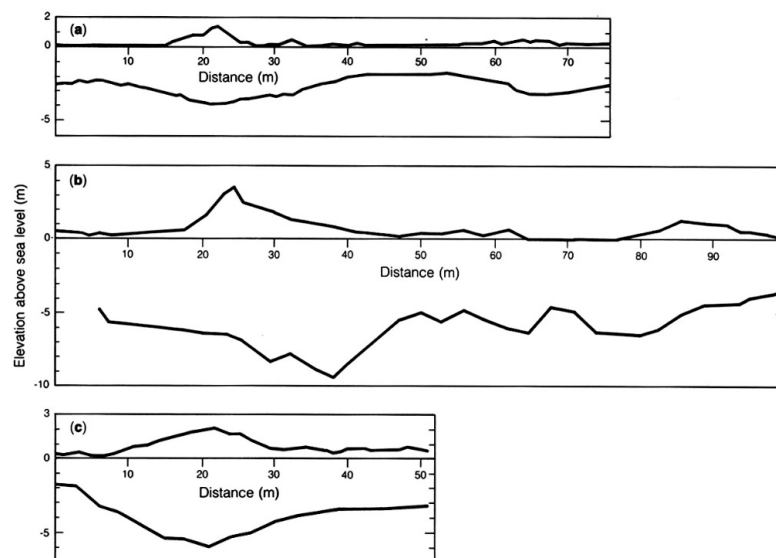


Figure 4.7 Cross Sections from Multi-year ridges

The outlines shown in Figure 4.7 include a ridge of thickness greater than 10-12 meters bordering multi-year ice of mean thickness of about 6 meters. The flat extent of the keel is usually greater than that of the sail. From Figure 4.7 you can see that slim areas of just 2 to 3 meters thickness are regularly experienced on the same ice floe. Figure 4.8 shows

a major multi-year ice ridge offshore northwest Greenland. Figure 4.9 shows satellite radar imagery of various types of ice cover in a region.



Figure 4.8 Multi-Year Ice Ridge

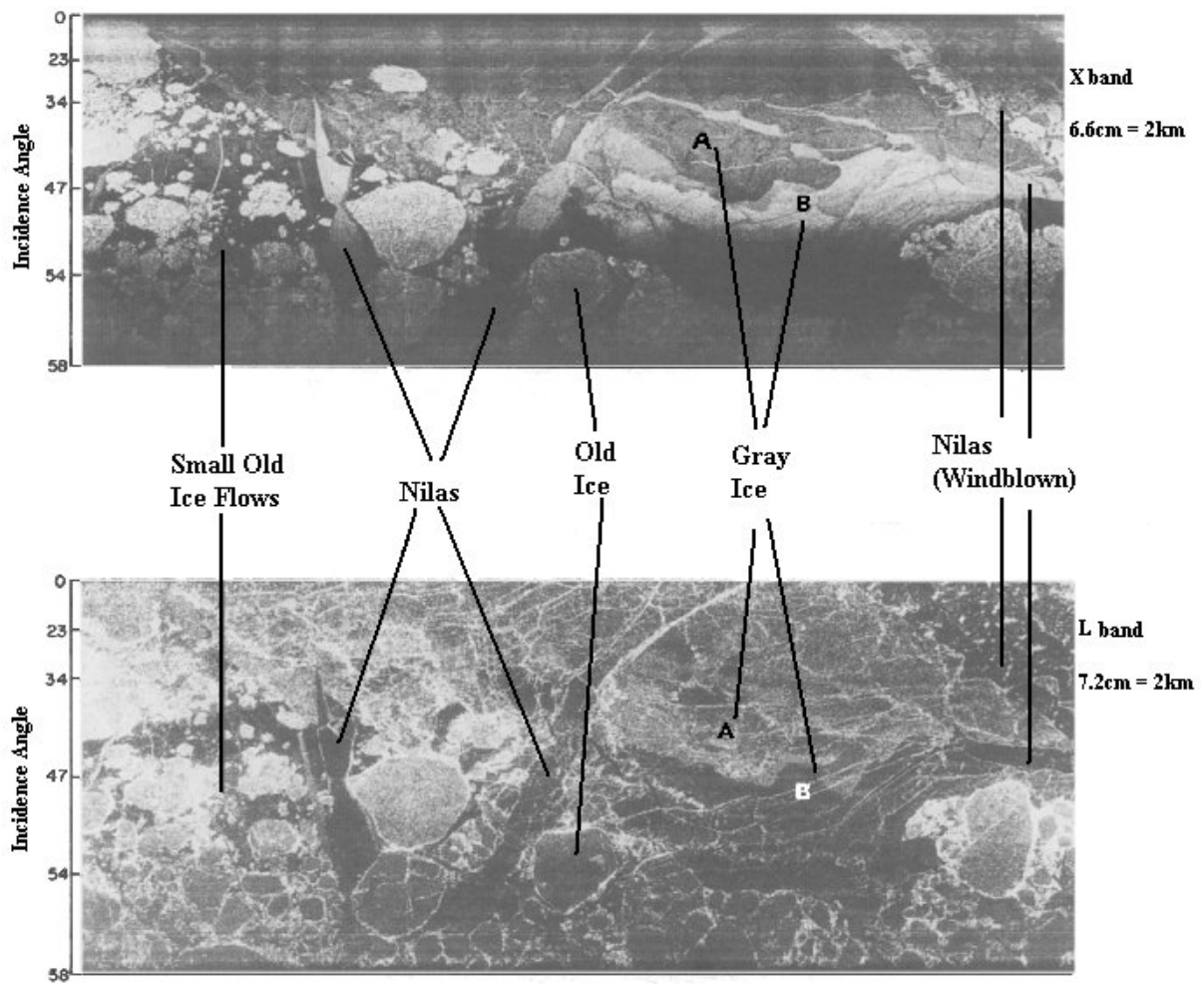


Figure 4.9 Remote Sensing of an Ice Cover

4.6 Ice Charts

Ice charts show maps of current and historical ice conditions. A number of countries have ice specialists who constantly monitor ice conditions and produce charts. Marine operations and weather forecasting are just two areas where ice charting is of crucial importance. In 1999, The International Ice Charting Working Group (IICWG) was formed to facilitate cooperation among the world's ice centers on all matters concerning sea ice and icebergs. The current members of the IICWG include;

- [Canadian Ice Service](#)
- [Danish Meteorological Institute](#)
- [Finnish Ice Service](#)
- [Federal Maritime and Hydrographic Agency of Germany](#)
- [Icelandic Meteorological Office](#)
- Hydrographical Department, [Maritime Safety Agency, Japan](#)
- [Norwegian Meteorological Institute](#)
- [Russian Federation Arctic and Antarctic Research Institute](#)
- [Swedish Meteorological and Hydrological Institute](#)
- [United States National Ice Center](#)
- [U.S. Coast Guard](#) [International Ice Patrol](#)

Ice conditions are available on the internet from all these agencies, though in a variety of formats. Canada and some others use a WMO (World Meteorological Organization) standard called the 'Egg Code' (see Figure 4.10).

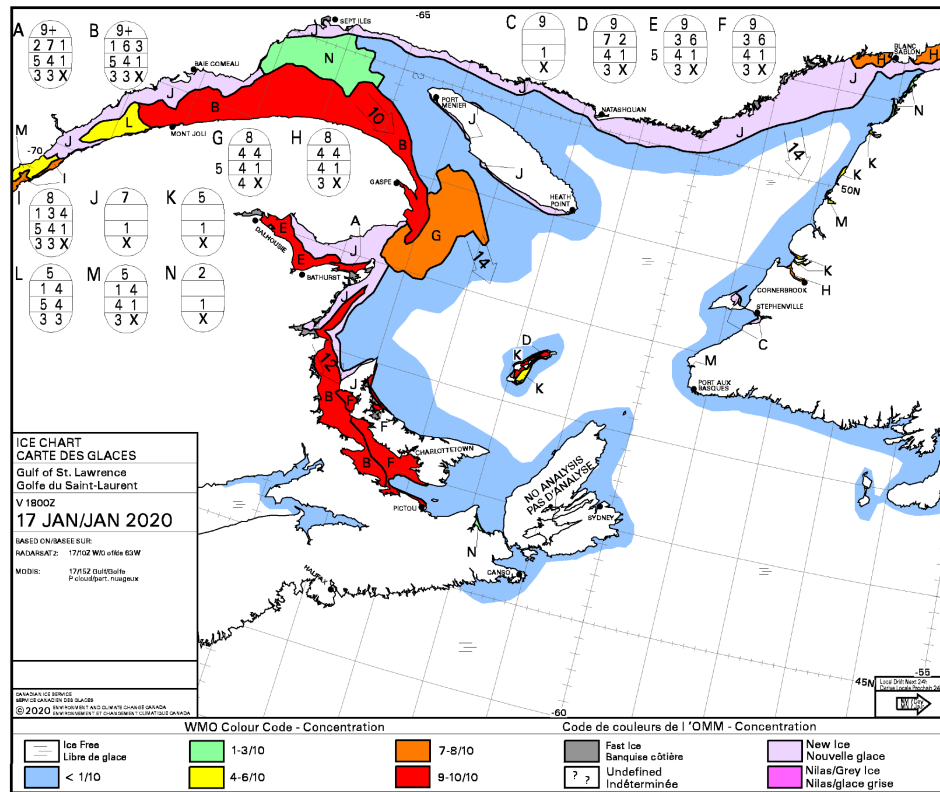


Figure 4.10 Ice Chart for Gulf of St. Lawrence showing Egg Codes

Egg Code

Ice charts are like weather maps. They represent a summary of a large amount of information, at a scale to be of use for the user of the chart. In Canada, ice charts use egg codes. The Canadian Ice Service (part of Environment and Climate change Canada) collects ice data from multiple sources (ships, aircraft, satellites) and produces a variety of information products. Sea ice comes in many forms and sizes. The egg code (see Figure 4.11) is a way of summarizing a potentially complex mix of ice conditions in a standard way. The egg contains 4 lines of information with three columns. The top number is the overall concentration of sea ice in 1/10ths. A 7 represents 7/10ths or 70% ice, which would mean 30% of the sea surface area would be open water. The concentration is a key descriptor. The lower rows describe the ice in up to 3 main groups, with a code for the concentration, stage (=thickness) and form (=floe size) for each of the sub-groups. If the ice is only of 1 or 2 types, then the egg code would contain 1 or 2 columns of sub-groups. The presence of a trace (<1/10th) can also be noted to the left of the egg.

A more detailed description of the egg code and other notations on ice charts can be found in the Ice Service publication MANICE (Manual of Standard Procedures for Observing and Reporting Ice Conditions) <https://www.canada.ca/en/environment-climate-change/services/weather-manuals-documentation/manice-manual-of-ice.html> MANICE also contains information on icebergs, and river and lake ice. The ice service also maintains an archive of ice charts going back to the 1960s.

Norwegian and Russian examples of recent ice charts are shown in Figure 4.12 and Figure 4.13.

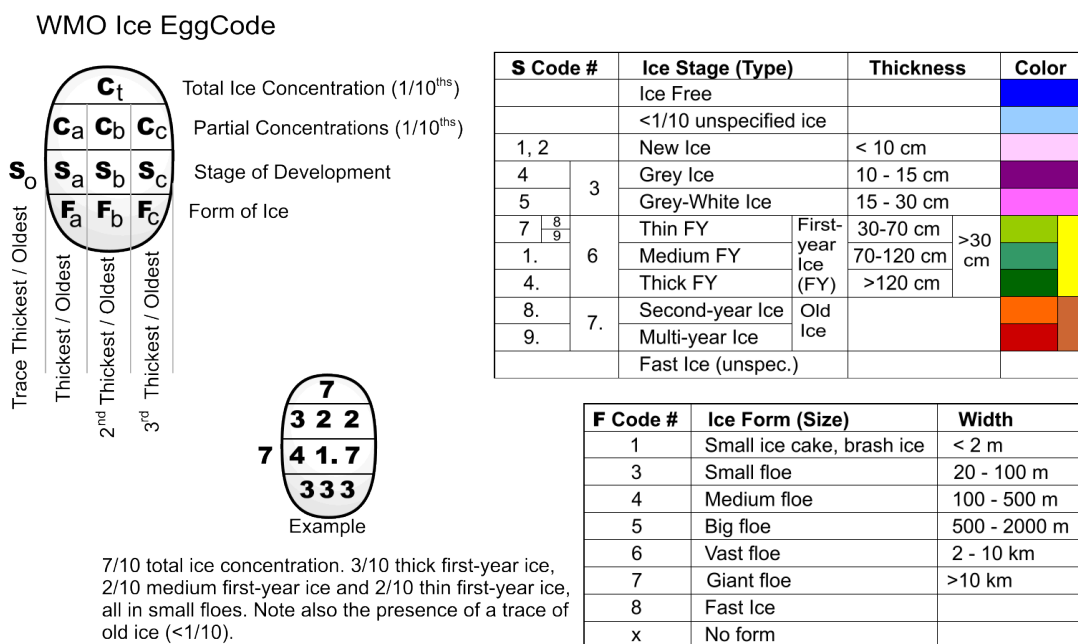


Figure 4.11 WMO Egg Code Components.

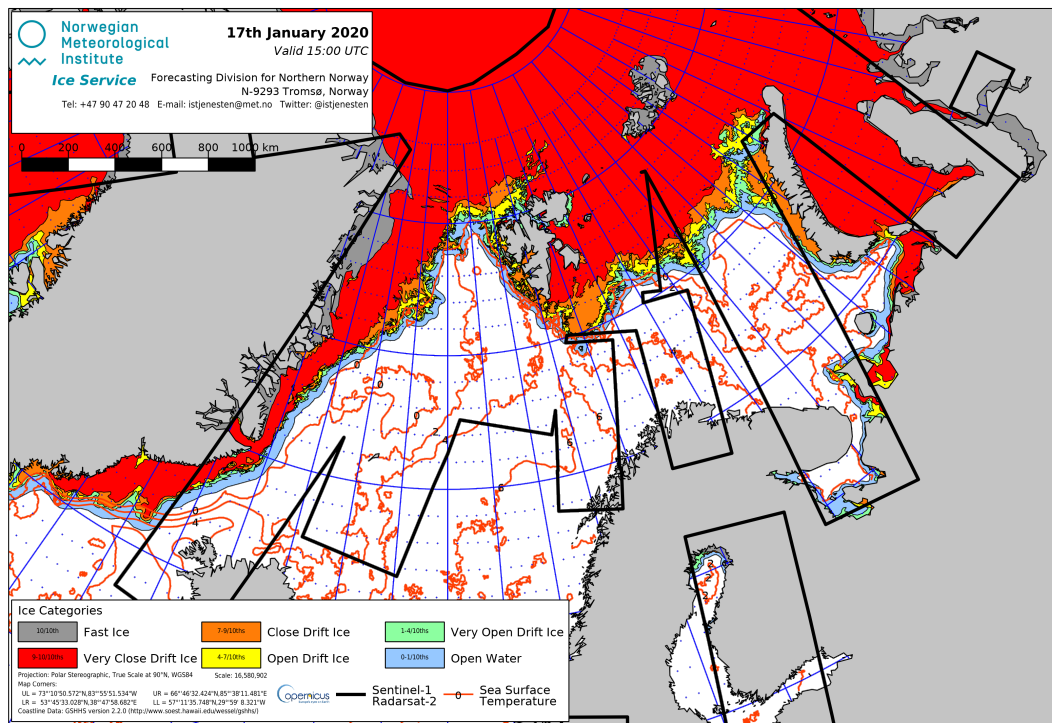


Figure 4.12 Norwegian Ice Charts.

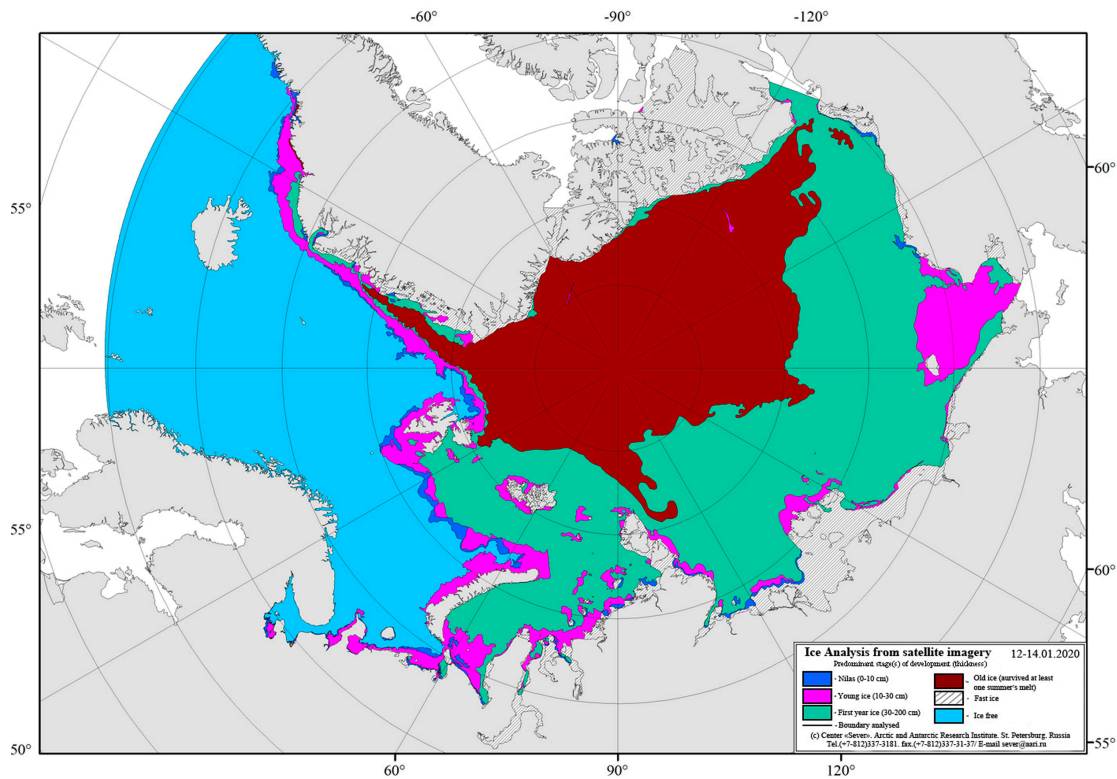


Figure 4.13 Recent Russian Ice Chart.

4.7 Ice Cover Changes and Decline

We are currently experiencing quite rapid changes in climate. The ice in the polar regions is experiencing notable changes. The figures below show recent maps of ice coverage compared to 30yr averages. Recent ice coverages in the Arctic and Antarctic are near the lowest in recent times. Projections suggest a much greater decline in ice extent in the coming years. (<https://nsidc.org/>)

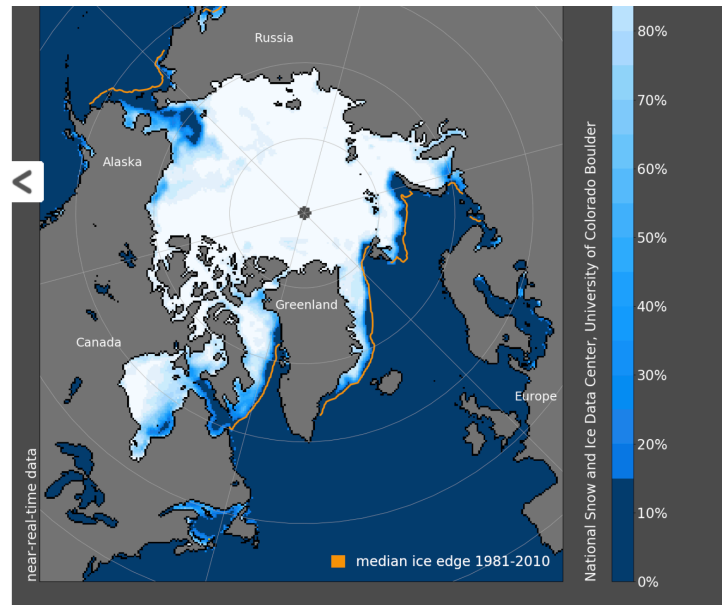


Figure 4.14 Arctic Sea Ice – Dec 16 2019

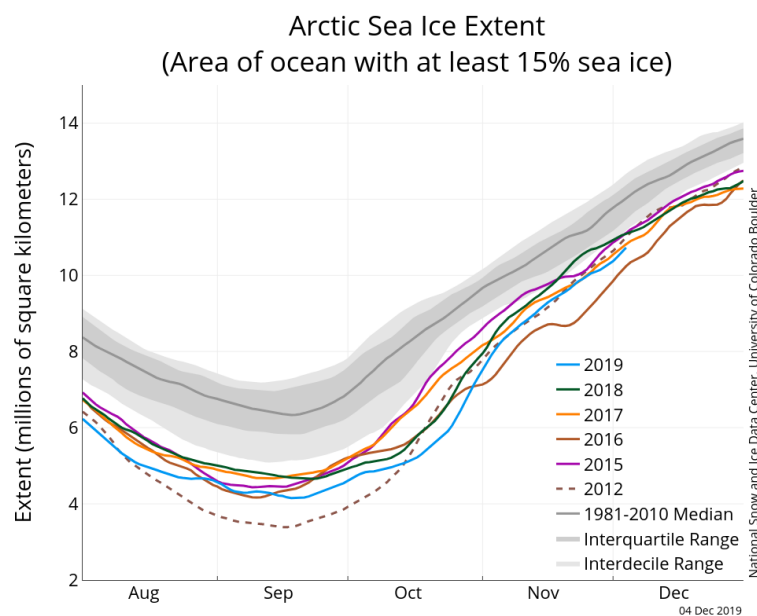


Figure 4.15 Arctic Sea Ice Extent – up to Dec 16 2019

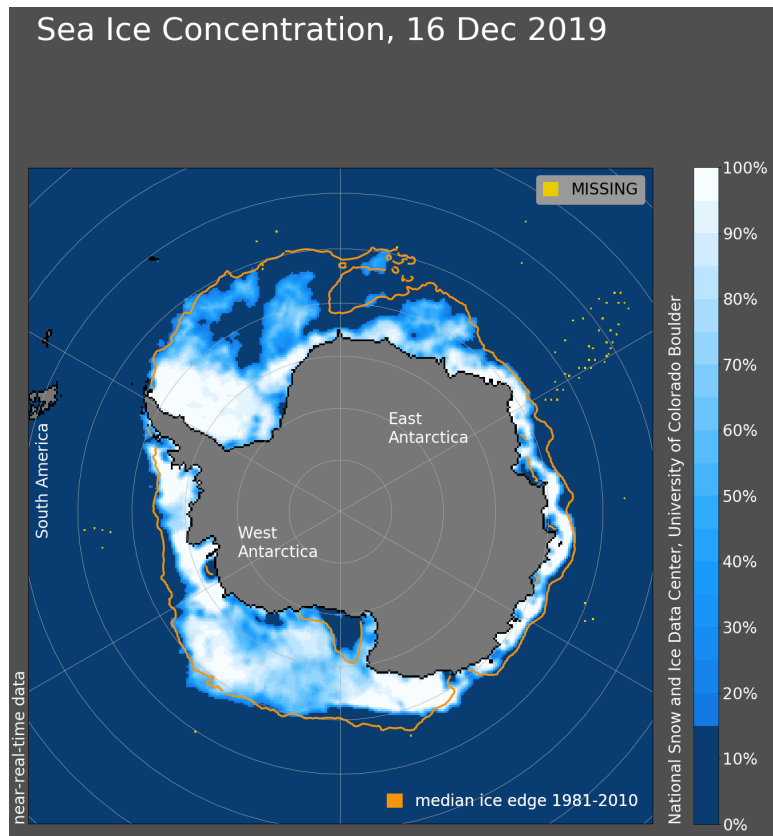


Figure 4.16 Antarctic Sea Ice – Dec 16 2019

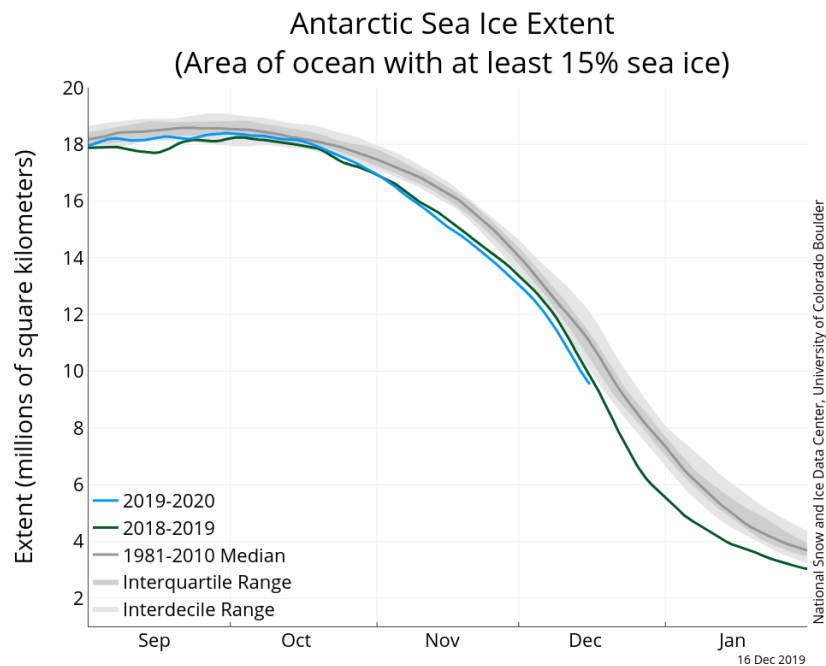


Figure 4.17 Antarctic Sea Ice Extent – up to Nov 21 2018

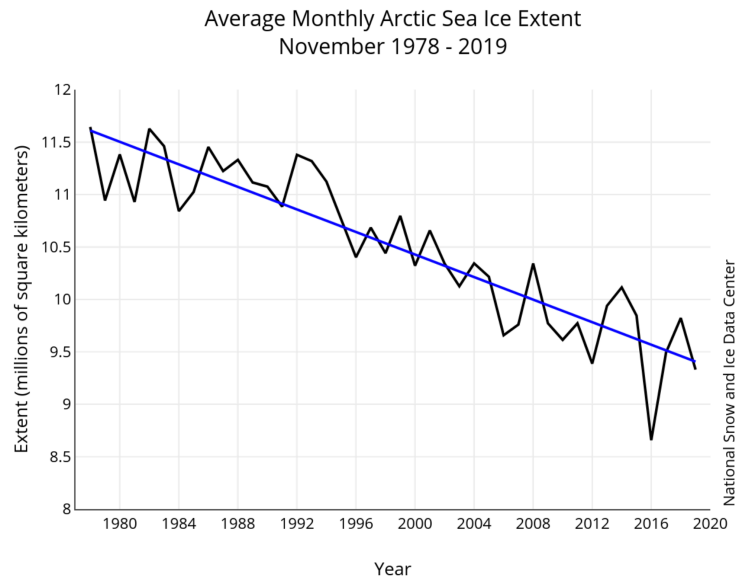


Figure 4.18 Arctic Sea Ice Extent – November Trend

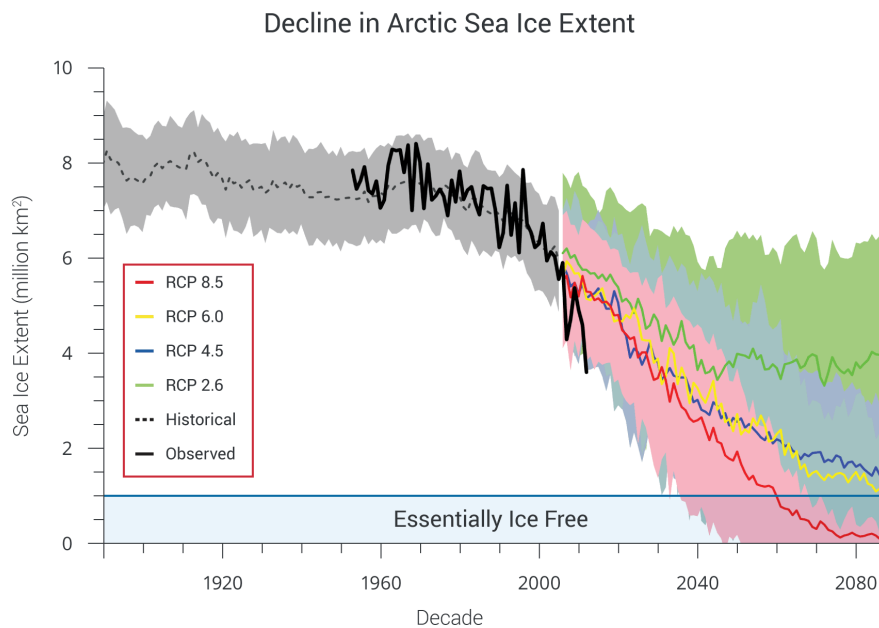


Figure 4.19 Arctic Sea Ice Extent – Projections

One of the consequences of the general decline in arctic ice is the even greater loss of old ice. As summer ice cover shrinks, there is greater chance for old ice to melt and less chance of new (old) ice being formed. The loss of old ice will significantly affect the design condition for ships and offshore structures.

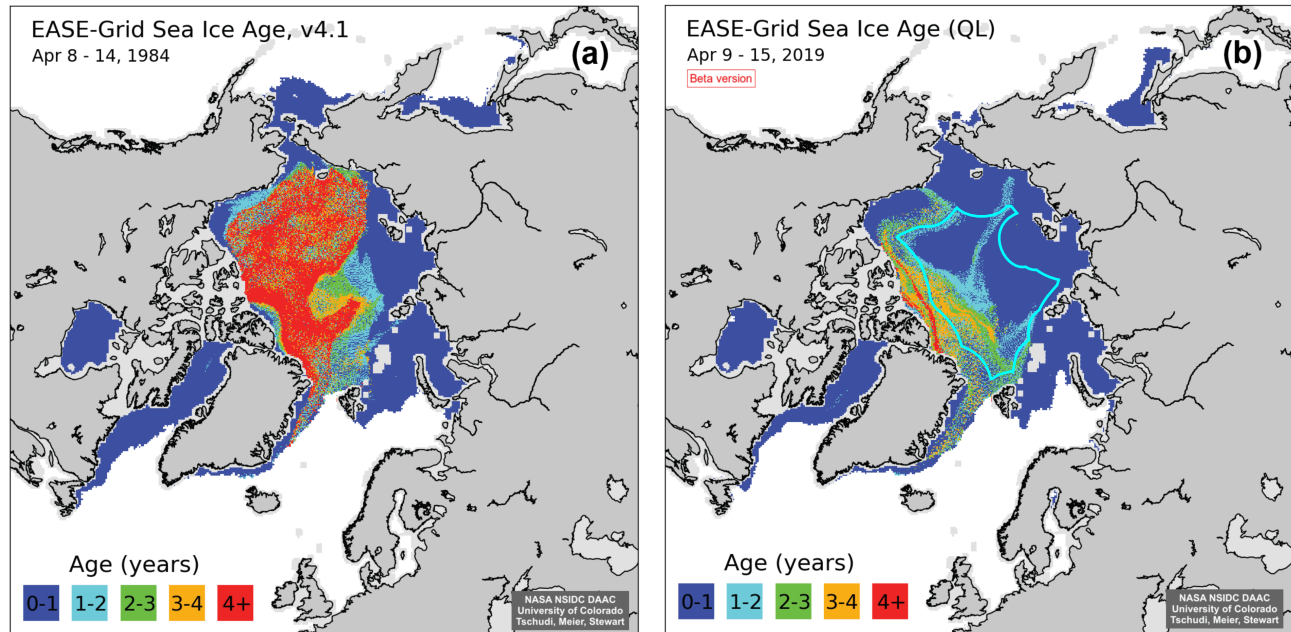


Figure 4.20 Age of Arctic Sea Ice – April 1984 vs 2019

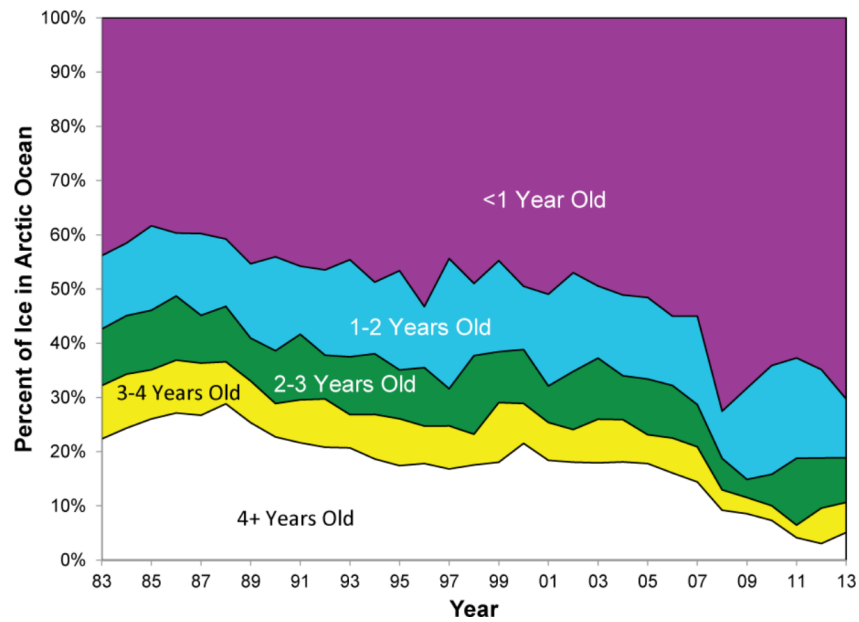


Figure 4.21 % Old Ice in Arctic – 1983-2013

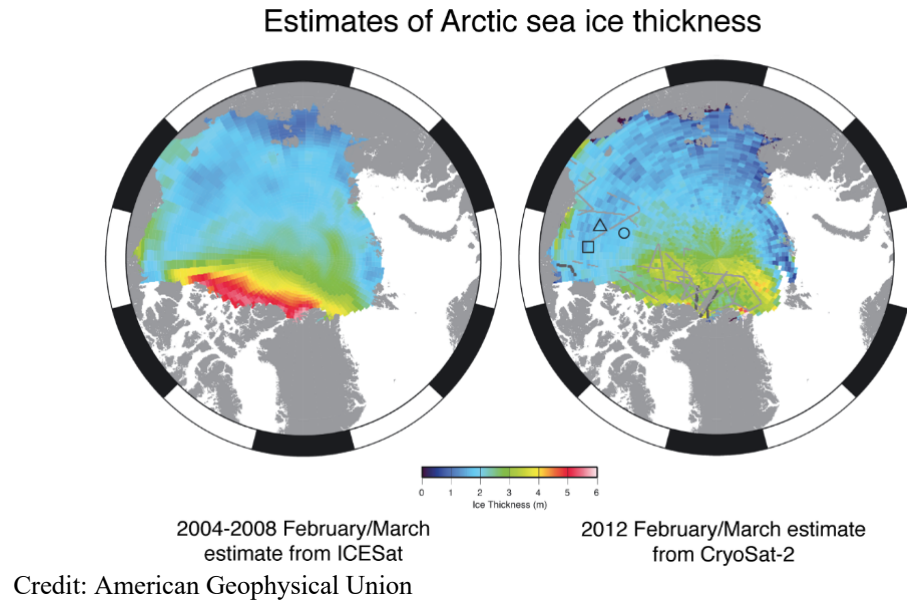


Figure 4.22 Decline in Ice Thickness in Arctic – 2004-2012

The issue of climate change should not be thought of only in terms of recent changes. While there is little doubt that climate change is strongly affected by humans, the climate has always been changing. The figure below shows one example. Over the last million years, the earth's mean temperature has varied greatly, often with much colder temperatures, much drier conditions, much lower sea levels and much of Canada and northern Europe covered in ice. Our 'recent' times were an inter-glacial warm time, which absent 'climate change' would have likely ended recently or soon. Climate change appears to be bringing us into a dangerous time of sea level rise and much greater weather anomalies. Without anthropogenic 'climate change', we may have been in for something equally bad.

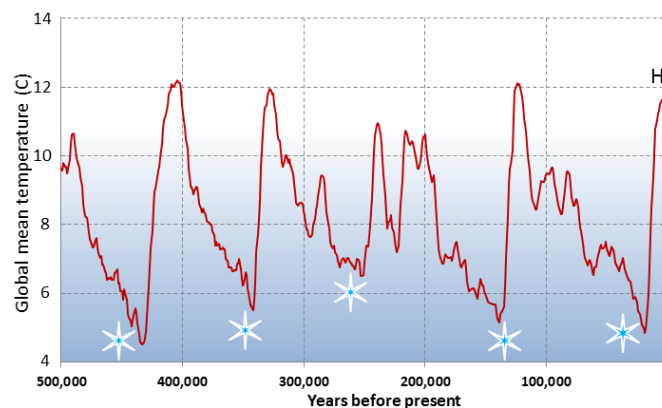


Figure 4.23 Earth's temperature over 5 glacial periods

4.8 Differences in Arctic and Antarctic Sea Ice

Although the Arctic and Antarctic are superficially similar, they are quite different in terms of ice characteristics. Sea ice differs between the Arctic and Antarctic, due mainly to the different geography. The Arctic is an ocean, almost completely surrounded by land and with many islands located within it (Figure 4.24 (top)). Sea ice that forms in the Arctic is not as mobile as sea ice in the Antarctic. Although sea ice does move around within the Arctic basin, it tends to stay in the colder Arctic waters. Because of the many land features in the basin, ice floes are forced – by relative movements – to pile up into ridges. These moving floes make Arctic ice thicker on average due to the piling up action. The presence of thicker ice and its longer life cycle leads to ice that stays frozen longer during the summer melt. So some Arctic sea ice remains through the summer and continues to grow the following autumn.

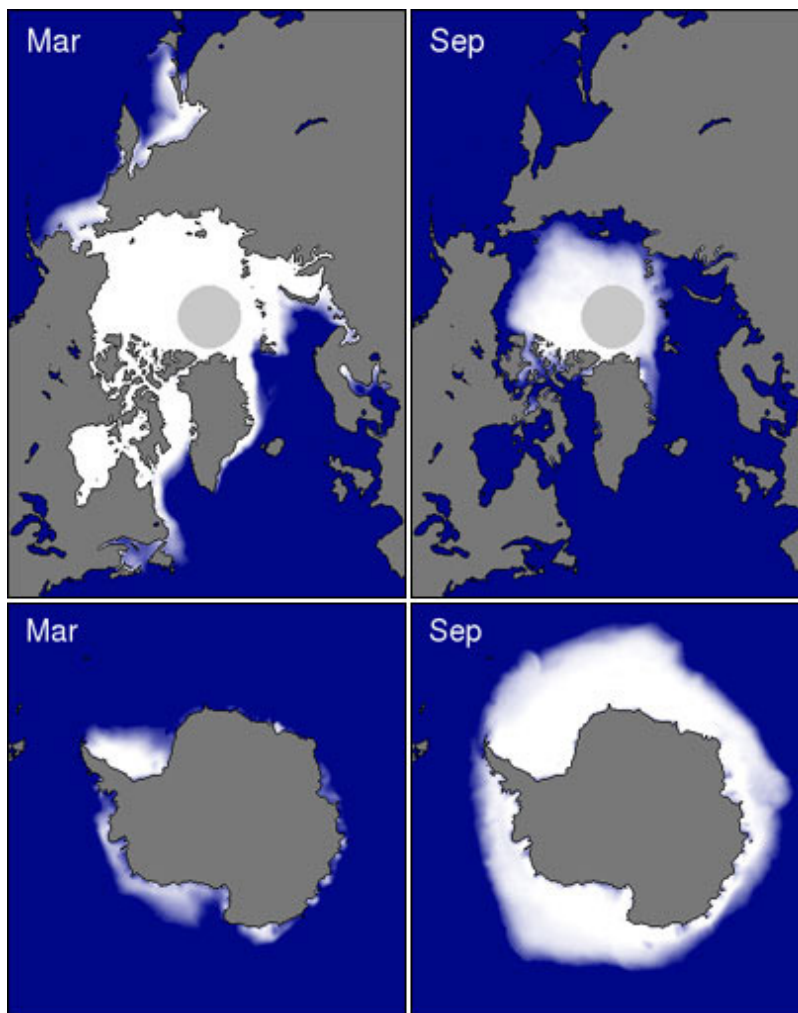


Figure 4.24 Minimum and maximum sea ice cover for the Arctic and Antarctic (Image from the National Snow and Ice Data Center, University of Colorado, Boulder, Colorado).

The Antarctic is essentially the geographic opposite of the Arctic, Antarctica is a land mass surrounded by an ocean that is effectively unbounded and contains very few land features that prevent ice movement (Figure 4.24 (bottom)). This allows the sea ice to move freely, leading to higher drift speeds. Despite these higher speeds, Antarctic sea ice forms ridges much less often than sea ice in the Arctic because of the lack of restraint. Also, because there is no land boundary to the north, the sea ice is free to float northward into warmer waters where it melts. Consequently, almost all of the sea ice that forms during an Antarctic winter melts during the following summer.

Thickness

Because sea ice does not stay in the Antarctic as long as it does in the Arctic, it does not have the opportunity to grow as thick as sea ice in the Arctic. While thickness varies significantly within both regions, Antarctic ice is typically thinner than that found in the Arctic.

In addition, water from the Pacific Ocean and several rivers in Russia and Canada introduce fresher, less dense water into the Arctic Ocean. As a result, the Arctic Ocean has a layer of cold, fresh water at the surface with warmer, saltier water below. This colder fresher layer typically allows more ice growth in the Arctic.

Patterns of Ice Extent

Figure 4.24 shows the pattern of Antarctic maximum sea ice is roughly symmetric around the pole, forming a circle around Antarctica. In contrast, Arctic ice coverage is asymmetric, with much more ice in some areas than others. Sea ice off the eastern coast of Canada extends south to the island of Newfoundland at 50° North latitude, and ice off the eastern coast of Russia extends south to Bohai Bay, China, at about 38° North latitude. On the other hand, in Western Europe, the northern coast of Norway at 70° North latitude generally remains ice-free. This asymmetry of ice formation is driven by patterns of ocean currents and winds.

The Arctic region above the Atlantic Ocean is open to warmer waters from the south, because of the way ocean currents (mainly the Gulf Stream – North Atlantic Drift) flow. These warmer waters flow into the Arctic and prevent sea ice from forming in the Eastern North Atlantic. The waters off the eastern coasts of Canada (western north Atlantic) and Russia are also affected by cold air moving off the land from the west. The eastern Canadian coast is also fed by southward-flowing cold-water currents (The Labrador Current) that make it easier for sea ice to grow.

In the Antarctic, the currents and winds tend to flow without interruption around the continent in a west-to-east direction, acting like a barricade to warmer air and water from the north.

Antarctic sea ice does not reach the South Pole, extending only to about 75° South latitude (in the Ross and Weddell Seas), because of the presence of the Antarctic continent. However, Arctic sea ice can extend all the way to the North Pole. At the North Pole, the sea ice receives less solar energy at the surface because the sun's rays strike at a more oblique angle, compared to lower latitudes.

Both Arctic and Antarctic sea ice extent are characterized by large variations from year to year. The monthly average extent can vary by as much as 1 million square kilometers from the year-to-year monthly average. The area covered by Antarctic sea ice has shown a small increasing trend. According to observations, both the thickness and extent of summer sea ice in the Arctic have shown a marked decline over the past thirty years.

Arctic Ice Circulation

The wind-driven Arctic ice circulation pattern has two primary components (Figure 4.25). The Beaufort Gyre is a clockwise circulation (looking from above the North Pole) in the Beaufort Sea. This circulation is driven by persistent high-pressure weather systems that spawn prevailing winds over the region. The second component is the Transpolar Drift Stream, where ice moves from the Siberian coast of Russia across the Arctic basin, exiting into the North Atlantic off the east coast of Greenland.



Figure 4.25 Arctic Ocean circulation (Image from Arctic Monitoring and Assessment Program (AMAP), Figure 3.29, AMAP (1998)).

Sea ice that forms or gets trapped in the Beaufort Gyre may circulate for several years. Sea ice in the Transpolar Drift Stream generally leaves the Arctic within one to two years. Thus, on average, sea ice in the Beaufort Sea has more time in the colder region so it is thicker. Also, because of the circular rotation of ice in the Beaufort Sea, ice floes are pushed into each other leading to ice deformation, which leads to thicker and more ridged ice. The Transpolar Drift Stream pushes some ice against northern Greenland and the Canadian Archipelago where the ice also compresses and forms into ridges.

In both the Beaufort Gyre and Transpolar Drift Stream, most of the ice follows a large-scale pattern when considered over a long period of time; however, within this long-term pattern of movement, there can be considerable variation. For example, the Beaufort Gyre may completely reverse directions--and often does for short periods of time, such as after a storm from a low-pressure system that moves across the region. Likewise, the Transpolar Drift Stream may also reverse direction. Thus, day-to-day variation in the large-scale circulation can be quite high.

Antarctic Ice Circulation

The Antarctic large-scale circulation of sea ice is generally in a clockwise direction (looking above the South Pole) around Antarctica, with gyres, or smaller rotations, in the Weddell and Ross Seas. There is an average northward component, so sea ice gradually moves to the northern ice edge after it forms. There is no northern land boundary for the northward flowing sea ice to run into, so the ice flows northward until it melts in warmer temperatures. Because of this, Antarctic sea ice is younger and thinner, on average, than ice in the Arctic.

4.9 Wave and Ice Interactions in Marginal Ice Zones

A Marginal Ice Zone is the transition region between an area of ocean ice cover and the open ocean. We are interested in Marginal Ice Zones because the ice there is subject to wind, wave and current forces; and these environmental forces greatly influence the characteristics of the ice in the zone. For example, a ship progressing through a Marginal ice Zone can quickly find that conditions change from loose pack ice and easy progress to heavily pressured ice and very difficult progress, based on a change in wind direction. The other characteristic of Marginal Ice Zones is that the concentration and characteristics of the ice influence the propagation of ocean waves through the zone.

The term Marginal Ice Zone (MIZ) is not very well defined, but the most common definition is by Wadhams (2000):

Marginal Ice Zone – that part of an ice cover which is close enough to the open ocean boundary to be affected by its presence.

This definition is generally applied to the region of pack ice that is noticeably affected by ocean waves. The affected region may, in some cases, extend from the ice edge right to the coast. The MIZ is highly variable in extent and characteristics and within all parts of the zone there is a complex interaction of waves, ice and wind.

Under energetic wave conditions the waves can break up ice such that the MIZ becomes tens of kilometers wide. The MIZ can also move tens of kilometers in a day; mainly in response to wind, but waves and currents also influence the movement. A MIZ often responds quite differently to on-ice wind as compared to off-ice wind. When wind blows over the MIZ towards the open ocean, the ice will drift towards the sea in separated bands, oriented normal to the wind direction, the waves generated by wind between the bands induces a pressure on the back side of an ice band, thus keeping the band of ice together [Wadhams, 2000]. When the wind blows in the on-shore direction the ice tends to pack closely together with the pressure between ice floes increasing in the shore-ward direction.



Figure 4.26 Marginal Ice Zone

There are some observations on the size distribution and geometry of ice floes in the MIZ. These suggest that there is a zonal distribution of ice floes, with small floes in the outer MIZ, medium sized floes in the interior zone and large floes near the solid ice edge [Lu, et al., 2008; Squire and Moore, 1980]. Lu, et al., 2008, proposed that the distribution of ice floe size and geometry follow a distribution law of the form:

$$\frac{N(< L)}{N_0} = 1 - \exp \left[- \left(\frac{L}{L_0} \right)^\gamma \right] \quad (4.1)$$

where: N is the cumulative number of floes with size smaller than L;
 N_0 is the total number of floes and
 L_0 is a scale coefficient and
 γ is a distribution shape coefficient
 L_0 and γ are both parameters that are selected based on observed data.

Characterization of sub-zones

Within a Marginal Ice Zone there are sub-zones that are essentially the gradation of wave effect and ice size as you move from the open water outside the ice edge into the MIZ to the point where the ice is no longer influenced by the surface waves. It is common to identify the following zones with respect to the relationship between the ice and the waves [Lu, et al., 2008; Squire and Moore, 1980; Wadhams, 2000]:

- **Open Ocean:** Well removed from the ice edge, is the open water, and the **ocean surface waves are not affected by any ice presence.**
- **Edge zone** with a low concentration of ice floes (i.e. the outer zone less than 5 km from the open ocean): In the outer MIZ region there is a relatively low concentration of ice such that the **floes do not interact with each other.** This would be less than 6/10 coverage. Individual ice floes are influenced by the wave action. If a floe is large enough (on the order of the wavelength), the wave will be locally altered due to reflection and diffraction. This gives rise to scattering of the wave energy. Waves tend to break large ice floes into smaller pieces and therefore only small floes are found in the edge zone in cases with energetic waves.
- **Transition zone** has frequent ice floes of intermediate size. The transition zone is characterized by higher concentrations of ice (>7/10). Wave induced floe-breaking is minimal. **Wave scattering due to wave ice-floe interaction is high** and the high concentration of ice floes means that additional energy is absorbed in collisions between ice floes.
- **Interior MIZ.** The interior zone is closest to the solid pack ice and contains the largest ice floes and generally high concentrations. Waves in this region are low

amplitude and long wavelength because shorter waves are scattered more efficiently in the earlier zones.

- **Solid ice.** In solid ice, waves can propagate almost undisturbed and can travel long distances. The major dissipation of wave energy comes from scattering due to leads and pressure ridges, and viscous dissipation at the ice-water interface [Liu and Mollo-Christensen, 1988; Wadhams, 1973]. The attenuation of waves in solid ice covers has not been as studied a problem as the wave ice-floe scattering process.

Although it is not really a zone in the sense of those identified above, ice that is just forming (*pancake ice*) or ice that has been pulverized by vigorous wave action (*slush*) can exist in Marginal Ice Zones. These features introduce slightly different wave propagation characteristics but still act to attenuate waves by scattering energy.

- **Slush ice or Pancake Ice:** During strong wave conditions ice floes are quickly broken into small pieces, and these pieces work to further crush each other. The result is a mixture of small ice floes and small ice particles dissolved in the water that form slush ice [Frankenstein, et al., 2001]. Pancake Ice is formed in the early stages of freeze-up and consists of small discs of ice completely covering the surface. Short waves are subject to scattering processes (essentially wave propagation in a viscous two-layer fluid) in either of these ice conditions, but long waves are not affected.

4.10 Ice accretion

Ice accretion is the formation of ice on structures or land features in or near the ocean but above the surface of the water. Ice accretion is also known as *icing*. For ships and structures operating in cold regions, ice accretion represents not only a load and stability hazard, but also an operational concern leading to slippery decks, ladders and handrails or interference with lifesaving and fire-fighting equipment. Ice accretion generally arises from sea spray or from atmospheric icing. In general sea spray is saltwater ice and atmospheric icing is freshwater ice.

Spray ice

Spray icing arises from wind driven sea spray accumulating on surfaces when the air temperature and the surface temperature are low enough to support freezing. Spray icing causes hazards and operational problems for ships, supply vessels and offshore drilling units in cold ocean areas.

It is worth noting that sprayed water has been put to good use creating barriers of artificial ice to protect offshore structures from the impacts of drifting sea ice. Spraying has also been used in constructing grounded ice platforms in shallow water for offshore oil drilling operations.

Spray icing of marine structures and effective artificial spray ice production occur under conditions in which the water flux to the icing surface exceeds the rate of ice growth. In this case of wet ice growth, only a portion of the impinging water is captured as ice, and the excess water leaves the surface as runoff, driven by wind drag or gravity. Because the impinging water spray is saline, part of the salt is trapped in the ice matrix in the form of brine pockets. This is somewhat similar to the formation of sea ice. The salinity of the growing spray ice accretion will be lower than that of the impinging spray water, so that some salt is rejected from the ice to the water film on the icing surface. The salinity of the water film will therefore be higher than that of the spray water. There is a direct relationship between the degree of salt entrapment and the sponginess (or porosity) of spray ice. Thus, spray ice is never as solid or as dense as pure ice.

Ice salinity also affects the growth rate of spray ice, and rejection of salt from the growing ice affects its adhesion strength on a surface. At temperatures typical of marine icing, the growth rate of saline spray ice is lower than that of freshwater spray ice.

Atmospheric icing

Atmospheric icing is the term used to describe accretion of ice on structures due to either freezing precipitation or freezing fog. Freezing fog is possible because the small water droplets in a cloud can often be super cooled liquid water. When these super-cooled droplets strike an object and break their surface, they immediately freeze and *rime ice* begins to form.

Rime ice – white ice forming on a surface from frozen fog.

Precipitation icing may result from freezing rain, wet snow, or even dry snow freezing to a surface.

Hoar frost is the result of a phase transition direct from vapour to solid, also referred to as “ice condensation” (i.e. *deposition* – the opposite of *sublimation*). Hoar frost is very light and has very little effect on structures but may be a hazard to operations.

Atmospheric icing occurs in most northern regions. Freezing rain is common in Canada. Wet snow is also an annual phenomenon in all circumpolar regions. Rime icing affects mostly high-altitude structures.

The accretion of ice on structures is a complex process that includes both receptor structural factors and driving meteorological parameters. In order to fully understand the icing phenomena, and to establish icing models for practical applications, it is important to examine both the physical accretion processes on structures exposed to the icing, and the meteorological environment that induces the icing.

Many researchers have studied the micro-scale processes of icing on objects of many kinds.

For in-cloud icing the most important parameters have been found to be:

- moisture content in the air
- droplet size
- air temperature
- wind speed
- wind direction
- humidity (degree of vapor saturation)

For precipitation icing (wet snow and freezing rain) the important parameters are:

- precipitation rate
- surface air temperature
- liquid water content of snow flakes
- wind speed
- wind direction
- temperature
- humidity

These parameters describe the immediate environment the structure undergoing icing. It is likewise important to consider the characteristics of the accreting object itself, such as surface property, shape, linear dimensions, etc.

Most research has been aimed at developing models that predict the incidence of icing and then the subsequent growth rates based on steady environmental conditions.

Chapter 4: Problems

4.1 Ice at Sea

Consider the egg code shown below. Sketch a possible ice cover that would have such an egg code. Give a scale in the sketch, with the view as seen from above.

7
1 4 2
4. 4 2
4 2 0

Egg

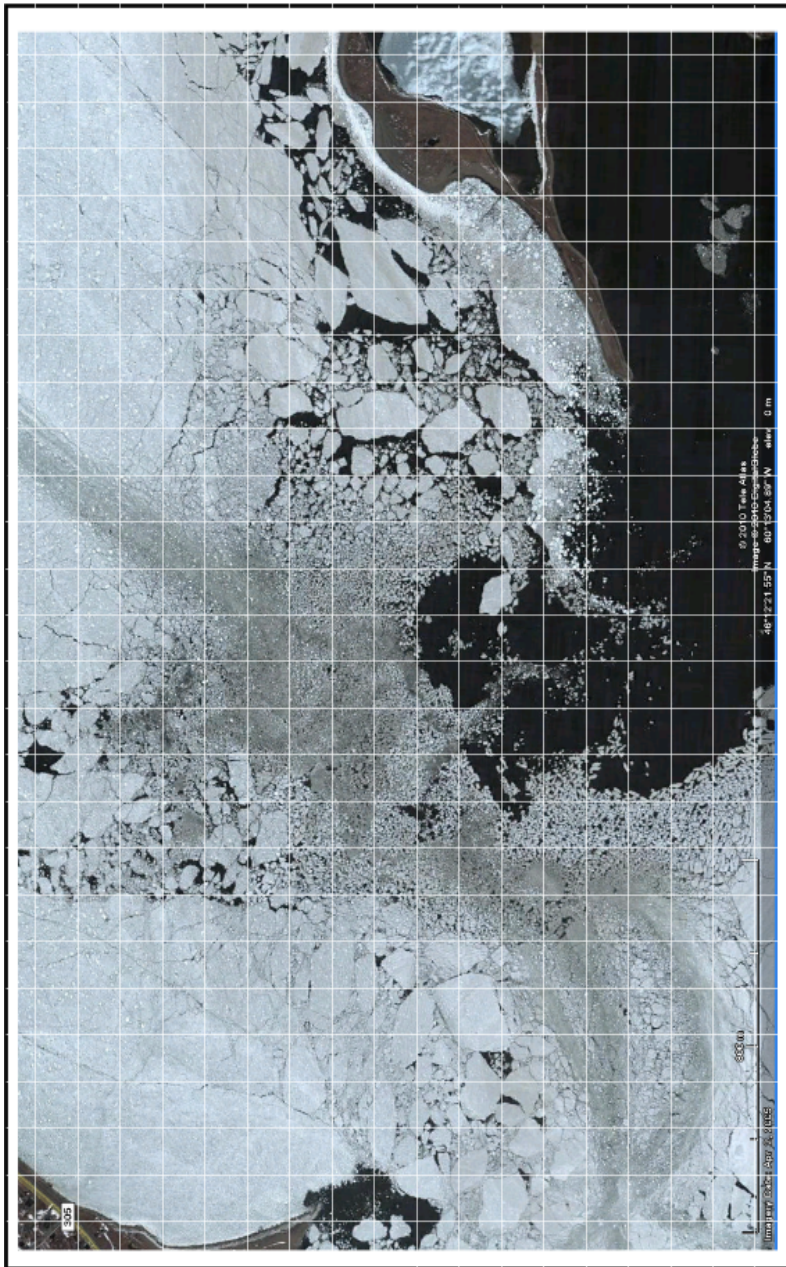


Sketch

4.2 Describe the ice in the photo shown below and estimate an egg code.



4.3 The image below is of the Sydney NS ferry harbor in winter. Divide the water into regions and give an egg code for each (about 4 egg codes).



4.4 Explain what Multi-year ice is and its importance to shipping.

5 Icebergs

5.1 Iceberg Formation

Although icebergs are found in the ocean, they are made up of freshwater ice. An iceberg is an ice mass that has broken off from a land-based glacier, or ice shelf. Glaciers are formed from the buildup and compression of layers of snow that fall on landmasses in the Polar Regions - generally Greenland or the Antarctic continent. The accumulation of snow over many years causes underlying layers to compress into solid ice and the additional weight of snow extrudes the glacier from the higher regions of the landmass towards the coast. The first stage of iceberg formation occurs when part of a glacier has moved to the coast and into the sea and starts to float on the water. Tides and wave action act on the exposed ice and lead to stress fractures, causing a piece of the glacier to break off. This process is called calving as sketched in Figure 5.1. Ice shelves are large floating glacial features that extend out to sea. They are typically hundreds of feet thick and can be thousands of years old. When the shelf breaks, large tabular icebergs, or ice islands can form, as sketched in Figure 5.2. These are most common in the Antarctic, but also exist in the Arctic.

An iceberg's blue and white coloration arises from the way glacial ice is formed. Glacial ice appears blue because pure ice absorbs other colors of light more rapidly than blue. This blue color indicates the deepest layers of the glacial ice, that have been under very high pressure thus compressing all air bubbles out of the ice. In contrast, the surface layers of an iceberg are white because air bubbles still trapped in the less compressed ice layers reflect the incident light. These air bubbles also result in iceberg fizz. As an iceberg melts, fizzing results from the release of trapped gas bubbles that have been held in the ice under pressure.

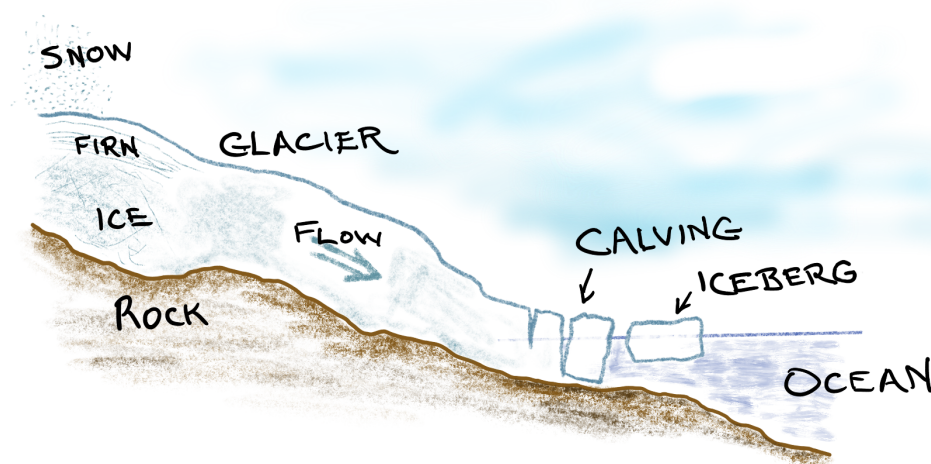


Figure 5.1 A section of a glacier breaks off to form an iceberg.

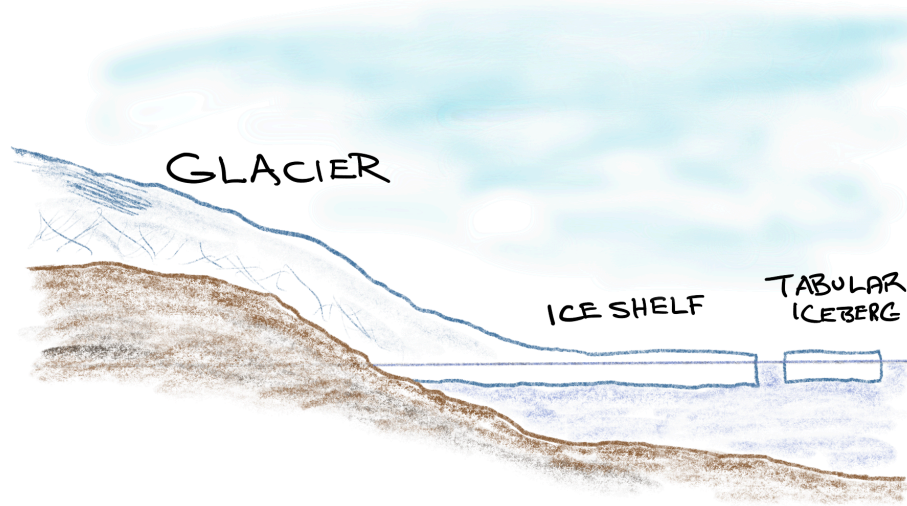


Figure 5.2 A section of a floating glacier, or ice shelf, breaks off to form an iceberg.

5.2 Antarctic Icebergs

Icebergs in the Antarctic calve from floating ice shelves, forming huge, flat “tabular” icebergs. Newly formed icebergs of this type have lateral dimensions that range from several to tens of kilometers, thicknesses of 200–400 m, and heights above the waterline (freeboards), of 30–50 m. The masses of a tabular icebergs range up to several billion tons.

Iceberg calving may be caused by ocean wave action, collisions from old icebergs, or the action of melting water on the upper surface of the berg. Breaking stress occurring near the ice front is most commonly associated with long storm-generated swells that may originate far away from the ice front. This bending stress is enhanced in the case of glacier tongues (long narrow floating ice shelves produced by fast-flowing glaciers that protrude far into the ocean). The swell causes the tongue to oscillate until it fractures.

A large production of icebergs from *Larsen Ice Shelf* in the period 1995 to 2002, was widely attributed to global warming, but is now thought to have occurred because summer melt water on the surface of the ice shelf filled many crevasses. As the liquid water refroze, it expanded and forced the crevasses to widen thus causing fractures lower in the ice shelf. This mechanism is called *frost wedging*, and caused the shelf to break in several places leading to a large number of icebergs.

Floating ice shelves are a continuation of the flowing mass of ice that makes up the Antarctic continental ice sheet. Floating ice shelves cover about 30 percent of Antarctica’s coastline, and the transition area where floating ice meets ice that sits directly on bedrock is known as the grounding line. Under the pressure of the ice flowing

outward from the centre of the continent, the ice in these shelves moves seaward at speeds in the range of 0.3–2.6 km per year depending on the location.

5.3 Arctic icebergs

Most Arctic icebergs originate from glaciers that extend from the Greenland Ice Sheet. These glaciers move towards the coast through gaps in the chain of mountains along the Greenland coast. The topographies of these mountain gaps influence the glaciers' flow speed and cause uneven stresses on the moving ice. These stresses lead to crevasses in the glaciers, which become part of the structure of the icebergs. Because of these built-in stresses and flaws, Arctic icebergs tend to be smaller and more randomly shaped than Antarctic bergs and also contain inherent areas of weakness, which lead to further fracturing after the berg is separated from the glacier.

Icebergs change shape, especially in summer as the seawater warms, through the action of differential melt rates occurring at different depths in the below water portion of the berg. Variations in melting, and the fracturing of parts of the berg, affect iceberg stability and cause icebergs to capsize regularly. This tendency to lose stability and capsize without warning combined with the tendency for large sections to break off, also without warning makes it dangerous to approach floating or grounded icebergs. The upper surfaces of capsized bergs may be covered by small scalloped indentations that are by-products of small convection cells that form when ice melts at the ice-water interface.

The Arctic Ocean's equivalent to the Antarctic tabular iceberg is the *ice island*. Arctic ice islands can be up to 30 km long but are only about 60 m thick. The main source of ice islands used to be the Ward Hunt Ice Shelf on Ellesmere Island, but this ice shelf has been reducing in production. Another more active source of ice islands is northeastern Greenland. The Flade Isblink, a small ice cap in the northeastern corner of Greenland, calves thin tabular ice islands with clearly defined layering into Fram Strait.

5.4 Iceberg structure

A newly calved Antarctic tabular iceberg retains the physical properties of the outer part of the parent ice shelf. The shelf has a similar layered structure to the continental ice sheet from which it flowed, with three major layers. The top layer is snow, which is older and denser with increasing depth. The next layer is the "firn", or a transitional form between the snow and solid ice below. The bottom layer is ice. All three layers are topped with recently fallen snow with older annual ice layers of increasing density underneath. Annual layers are often visible on the vertical side of a new tabular berg, which implies that the above water portion of the iceberg is composed of compressed snow rather than ice. Density profiles through newly calved bergs show that at the surface of the berg the density might be only 400 kg per cubic meter. Only when the density reaches 800 kg per cubic meter deep within the berg do the air channels collapse to form air bubbles. At this point, the material can be classified as ice. The lower density compressed snow above

the ice is called *Firn*. The firn layer is approximately 150–200 years old and the firn-ice transition occurs at about 40–60 m below the top surface of the iceberg.

As density and pressure increase, the air bubbles become compressed. Within the Greenland Ice Sheet, pressures of 10–15 atmospheres have been measured; the resulting air bubbles tend to be elongated, possessing lengths up to 4 mm and diameters of 0.02–0.18 mm. In Antarctic ice shelves and icebergs, air bubbles are more often spherical or ellipsoidal and possess a diameter of 0.33–0.49 mm. The size of the air bubbles decreases with increasing depth within the ice.

As soon as an iceberg calves, it starts to warm up. The rate of warming increases as the berg drifts into more temperate regions, especially when it drifts free of any surrounding pack ice. Once the upper surface of the berg begins to melt, the section above the waterline warms relatively quickly to temperatures that approach the melting point of ice. Melt water at the surface can percolate through the permeable uppermost 40–60 m and refreeze at depth. This freezing releases the berg's latent heat, and the visible part of the berg becomes a warm mass that has little mechanical strength; it is composed of firn and thus can be easily eroded. The remaining mechanical strength of the iceberg is contained in the “cold core” below sea level, where temperatures remain at -15 to -20 °C. In the cold core, heat transfer is inhibited owing to the lack of percolation and refreezing.

5.5 Iceberg size and shape

Arctic bergs are generally smaller than Antarctic bergs, especially when newly calved. The largest recorded Arctic iceberg (excluding ice islands) was 13 km long by 6 km wide and 20 m height above the waterline. Most Arctic bergs are much smaller and have a typical principal dimension of 100–300 m.

There have been many very large Antarctic icebergs in the Ross and Weddell seas with dimensions that have been measured by satellite. In 2000 an iceberg broke off the Ross Ice Shelf with an initial length of 295 km.

The international ice patrol that was created as a result of the Titanic sinking has established size categories for icebergs given in Table 5.1.

Table 5.1 Iceberg Size Categories.

Category	Height above wl (m)	Length (m)
growler	< 1	< 5
berg bit	1 - 4	5 - 14
small berg	5 - 15	15 - 60
medium berg	16 - 45	61 - 122
large berg	46 - 75	123 - 204
very large berg	> 75	> 204
Source: International Ice Patrol		

5.6 Erosion and melting

Most of the erosion of Antarctic icebergs occurs when the bergs move into the Southern Ocean. Melt and percolation through the firn layer brings the bulk of the above water portion of the berg to the melting point. Ocean wave action around the edges is then able to penetrate the above water portion of the berg. Erosion occurs by wave action and by the enhanced transport of heat, resulting in a wave cut that can penetrate several meters into the berg. The portion above the wave cut may collapse to create a growler or a bergy bit. The turbulence around cracks and crevasses is increased and waves cut deeper into these features, causing cracks to grow into caves that may also collapse. Through these processes, the iceberg can evolve into a dry-dock or a pinnacled berg with seemingly independent above water portions linked below the waterline.

Arctic icebergs, which undergo repeated capsizes, have no layer of firn. The entire berg melts at a rate dependent on the salinity and temperature in the water column and on the velocity of the berg relative to the water near the surface.

On the basis of observations, Weeks and Mellor proposed a rough formula for predicting melt loss:

$$-Z = K D \quad (5.1)$$

where Z = loss in meters per day from the walls and bottom of the iceberg,
 K = a constant of order 0.12, and
 D = mean water temperature in °C averaged over the draft of the iceberg.

This yields a loss of 60 m from iceberg sides and bottom during 100 days of drift in water at 5 °C, a rate that corresponds reasonably well to survival times of icebergs in waters off the coast of Newfoundland although the water temperature is perhaps a bit overestimated.

In Arctic icebergs, erosion often leads to a loss of stability and capsizing. For an Antarctic tabular berg, complete capsize is uncommon, although some long, narrow bergs may roll completely over a very long period. More common is a shift to a new position of stability, which creates a new waterline for wave erosion. When tabular icebergs finally fragment into smaller pieces, these smaller individual bergs melt faster, because a larger proportion of their surface relative to volume is exposed to the water.

5.7 Iceberg distribution and drift trajectories

In the Antarctic, a freshly calved iceberg usually moves westward in the Antarctic Coastal Current. Since its trajectory is also turned to the left by the Coriolis force, arising from the Earth's rotation, it may run aground and remain stuck in place for years before moving on. If a berg can break away from the coastal current, it enters the Antarctic Circumpolar Current, or West Wind Drift. This eastward-flowing system circles the globe at latitudes of 40°–60° S. Icebergs tend to enter this current system at four well-defined longitudes or “retroflexion zones”: the Weddell Sea, east of the Kerguelen Plateau at longitude 90° E, west of the Balleny Islands at longitude 150° E, and in the

northeastern Ross Sea. These zones reflect the partial separation of the surface water south of the Antarctic Circumpolar Current into independently circulating gyres, and they imply that icebergs found at low latitudes may originate from specific sectors of the Antarctic coast.

Once in the Antarctic Circumpolar Current, the iceberg's track is generally eastward, driven by both the current and the wind. Also, the Coriolis force pushes the berg slightly northward. The berg will then move in a northeasterly direction so that it can end up at relatively low latitudes and in relatively warm waters before disintegrating. Under extreme conditions, such as its capture by a cold eddy, an iceberg may succeed in reaching extremely low latitudes. Icebergs have been responsible for the disappearance of ships off Cape Horn.

In the Arctic (See Figure 5.3), the most northerly sources of icebergs are the Svalbard archipelago north of Norway and the islands of the Russian Arctic. Iceberg production from these areas is not large. Icebergs from these sources tend to move directly into the Barents or Kara seas, where they run aground. Other bergs pass into the East Greenland Current. As these icebergs move down the eastern coast of Greenland, the population is increased by bergs produced by coastal glaciers,

As the increased flux of icebergs reaches Cape Farewell, most bergs turn into Baffin Bay, although some icebergs move directly into the Labrador Sea, especially if influenced by strong weather patterns. Icebergs entering Baffin Bay first move northward in the West Greenland Current. At this point they merge with a large population of bergs from the productive West Greenland glaciers. About 10,000 icebergs are produced in this region every year. Bergs then cross to the west side of the bay, where they move south in the Baffin Island Current toward Labrador. At the northern end of Baffin Bay, in Melville Bay, lies an especially active iceberg-producing glacier, the Humboldt Glacier, the largest glacier in the Northern Hemisphere.

Some icebergs take only 8–15 months to move from Lancaster Sound to Davis Strait, but the total passage around Baffin Bay can take three years or more. The flux of bergs that emerges from Davis Strait into the Labrador Current is extremely variable. On average, approximately 500 icebergs per year cross the 48° N parallel and enter the zone where they are a danger to shipping—though numbers vary greatly from year to year.

Much work has gone into modeling iceberg drift, but it is difficult to predict an iceberg's drift speed and direction. An iceberg is affected by the wind drag on its above water surfaces, skin friction drag and form drag. Similarly, the current drag acts on the below-water portion of the berg. However, currents change with increasing depth. Another factor influencing an iceberg's velocity is the Coriolis force, which pushes icebergs toward the right of their track in the Northern Hemisphere and toward the left in the Southern Hemisphere. This force is typically stronger on icebergs than on sea ice, because icebergs have a larger mass.

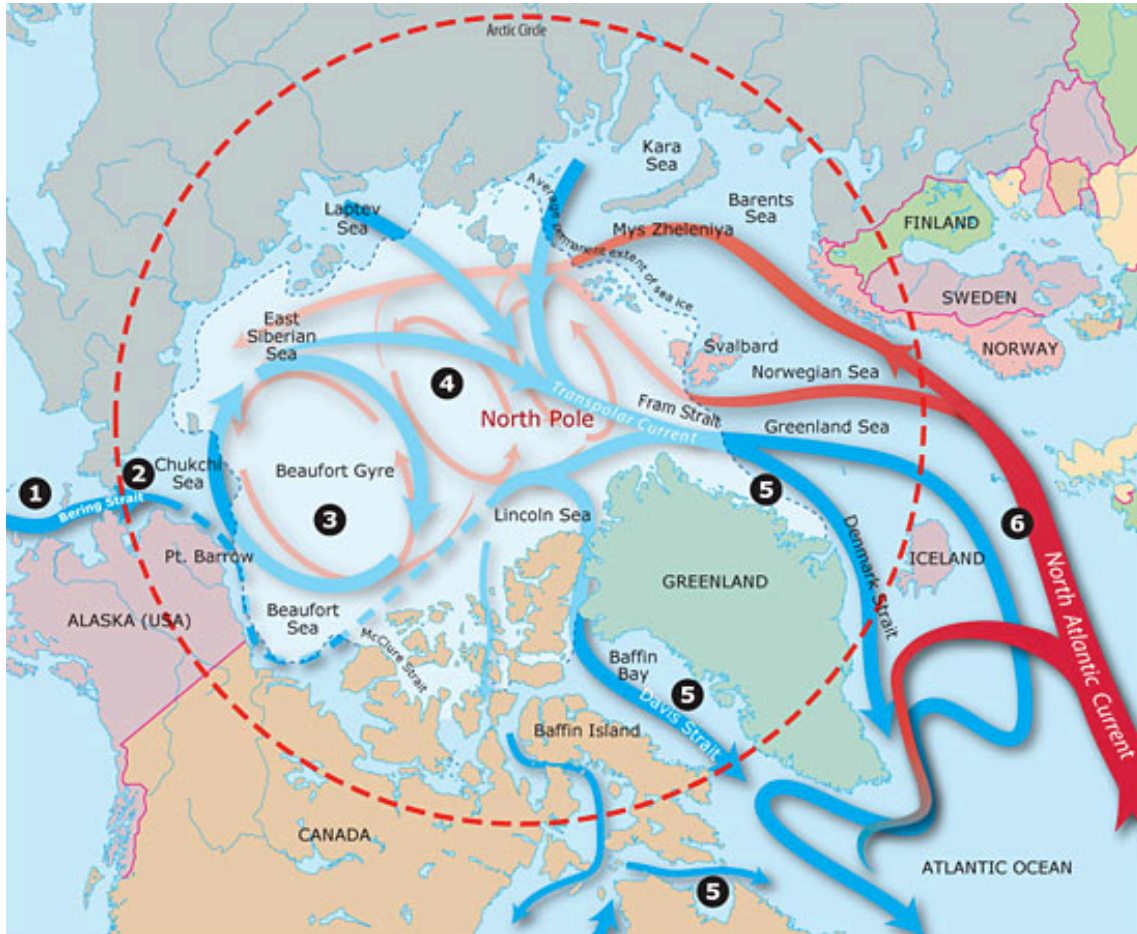


Figure 5.3 Arctic Ice Drift Current Patterns

Chapter 5: Problems

6 Mechanical strength of sea ice

6.1 Uniaxial Compressive Strength of Ice

The simplest measure of the *compressive strength* of ice can be found by crushing an ice core sample. The test is performed by applying a compressive force to a cylindrical sample of ice, in a manner similar to a test on a sample of concrete. The test is done in a cold room, in a hydraulic press. However, ice is a complex material and the test can result in a variety of *failure modes*. Figure 6.1 shows the common modes of failure. The particular failure mode depends on several factors, including the *type* and *orientation* of the ice, the *strain rate*, the *temperature* and the *specific test arrangement*, especially the end-cap arrangements.

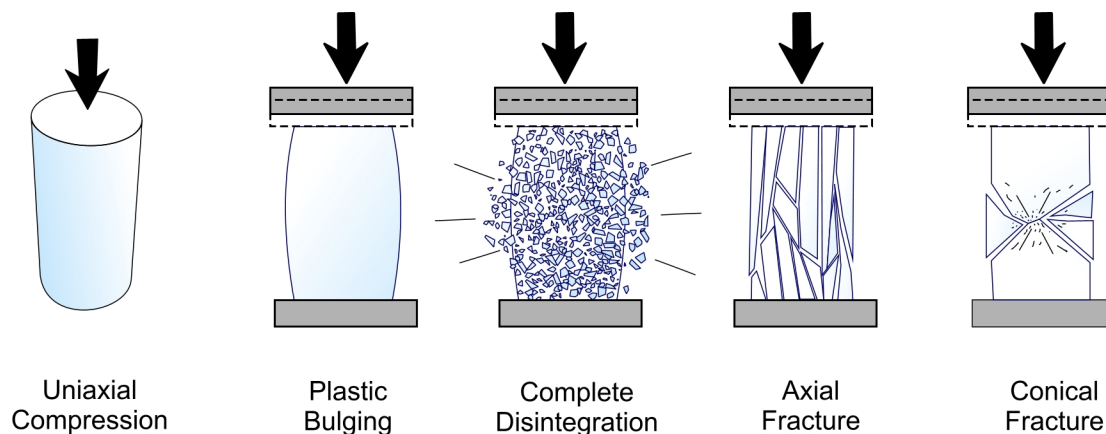


Figure 6.1 Compressive Failure in cylindrical ice samples.

The variety of the failure modes, and the complexity of some of the modes, raises what should be an important concern. The ‘simple’ compressive strength test is really not so simple, and the resulting value (the strength expressed as the peak force divided by the cross-section area) is not a material property in the usual sense of providing a fundamental continuum property, like density. Nevertheless, the test is useful and has been performed often enough to provide considerable insight into the process of ice failure. Besides the ice characteristics (e.g. temperature, salinity, grain size and orientation) that affect the strength, the details of the test are also important. It is important to note how the ends of the ice were held in the apparatus (the boundary conditions). The rate of load application (relating to strain-rate) also influences the results.

Figure 6.2 shows a sketch of 3 different end conditions that can occur. The first two are similar, with friction in one case and a ring in the other acting to prevent the ice from expanding or shifting at the cap. This provides a restraining stress at the caps, which can change the failure mode and the apparent strength. In the third case the confining stress is released and the ice can fail more easily. Axial splitting is much more likely to occur without restraint. It is important to know which of these test conditions were used. The simple friction situation is the least controlled and results in the most variation.

To understand ice behavior, it helps to remember that in all cases of practical interest, ice is very close to its melting temperature, in an absolute sense. Absolute temperature is measured in Kelvin ($^{\circ}\text{K}$). Ice melts at 0°C or 273°K . Even at -20°C , ice is at 93% of its melting temperature. At -2°C ice is at over 99% of its melting temperature. What is surprising is that ice maintains its strength and brittle behavior even at such relatively high temperatures. When steel is at 93% of its melting temperature, (steel melts at 1511°C so 93% is 1380°C), it is very soft. So it is not surprising that ice is described as a *visco-elastic solid*. In simple terms, this means that ice is brittle when loaded quickly and ductile (plastic) when loaded slowly. The slow long-term deformation is called *creep*.

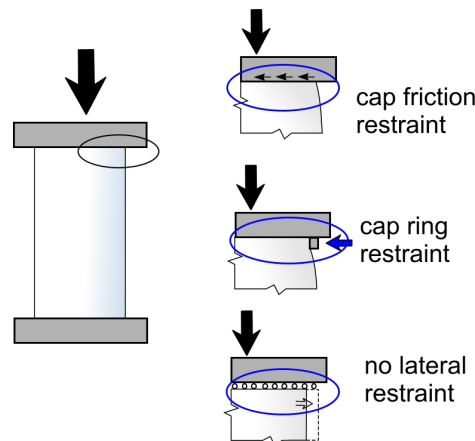


Figure 6.2 Compressive test end conditions.

The following sections describe various factors that affect the measured strength of ice.

Influence of strain rate

Strain is the relative stretch or contraction that a sample feels when subjected to a stress. Strain is non-dimensional, because it is a ratio of length to length (e.g. $\epsilon = \text{mm of compression per mm of sample length}$). The *strain rate* is the change in strain per unit time, and so strain rate has units like speed, but without the length unit (i.e. $1/\text{s}$ instead of m/s). For example, if a 1m long sample were fixed on one end, and subjected to a powerful moving boundary, moving at 0.01mm/s at the other end, the sample would experience a constant strain rate of 0.00001 s^{-1} (or 10^{-5} s^{-1}).

When an ice sample is subjected to a very low, but long acting stress, it strains very slowly, but it does experience permanent deformation. This is called creep and is illustrated in Figure 6.3. In this case the maximum stress reaches a plateau, and the ice continues to steadily strain. As the strain rate increases, the maximum stress (σ_c) also increases, up to a strain level of about 10^{-4} . For higher strain rates, the ice behavior changes to brittle fracture, and is no longer dependent on the strain rate. Figure 6.3 shows what appears to be a slight drop in strength for strain rates above 10^{-3} .

On the right-hand side in Figure 6.3 are three examples of the stress-time record from uniaxial tests. In each case, the sample is subjected to a constant strain rate, and the stress is measured. For very low strain rates, the stress builds slowly up to a plateau. On the plateau, the ice is slowly flowing under constant stress. The maximum stress is the 'strength' as reported on the graph to the left. When the strain rate is high (above 10^{-3} s^{-1}) the failure mode changes from ductile to brittle. In brittle failure, the ice responds elastically until it fails by sudden fracture.

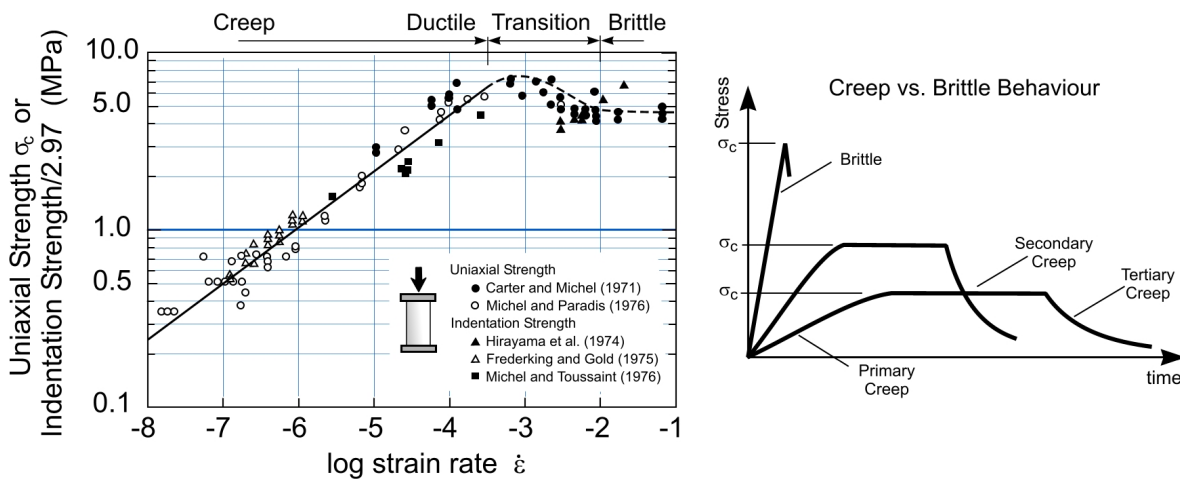


Figure 6.3 Influence of strain rate on uniaxial strength.

Influence of temperature on creep

The influence of temperature depends on the type of failure. In creep behavior, there is a strong dependence of the secondary creep stress (plateau stress) and temperature. The data in Figure 6.3 is for relatively warm ice (-2°C). At a temperature of -50°C , ice exhibits much higher stress (8 to 10 times) for any given strain rate. Conversely, for a constant stress, the colder ice has a strain rate of 3 orders of magnitude less (1000 times less). These issues are quite important when studying the slow movement of glaciers, or the slow settlement of objects resting on or buried in ice. In offshore ice engineering situations, the strain rates tend to be in the transition or brittle range, so creep behavior will not be explored any further here.

Influence of grain size

The size of the ice grains plays a significant role in the strength of ice. Figure 6.4 shows how grain size can influence strength quite significantly. The particular study was aimed at comparing the strength of spray ice to natural ice. Spray is a construction material that is created by spraying water through cold air and onto a surface. This is quite similar to the techniques used to make snow at ski hills, but the results are different. At ski hills the result should be as light and dry as possible. Spray ice for construction is intended to be as dense and solid as possible. It is put down in layers that can freeze between applications. One of the advantages of spray ice is the small size of the grains, which

tends to increase the strength. On the other hand, spray ice has many voids, and so is of lower density than natural ice. Figure 6.4 shows the combined effects of grain size and density. The spray ice is generally stronger than the natural ice. The trend lines show that both types of ice are stronger when the density is higher.

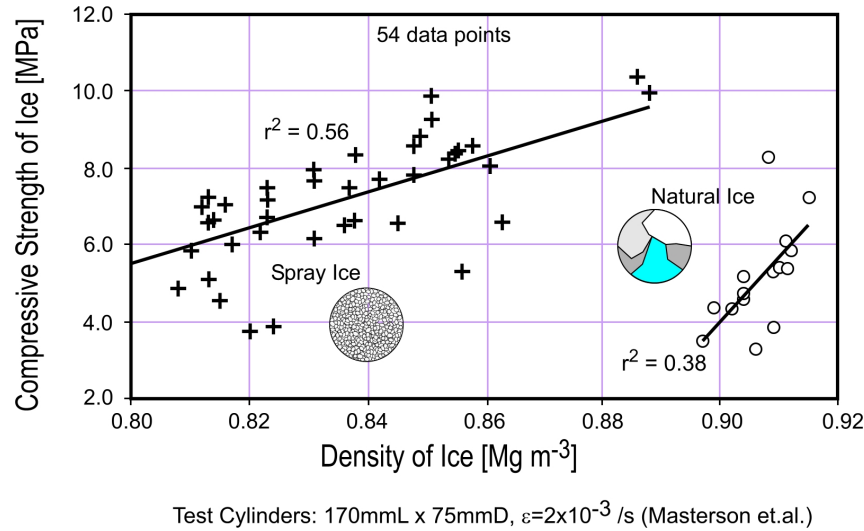


Figure 6.4 Comparison of strength of fine-grained spray ice with natural ice.

Influence of temperature on strength of sea ice

In sea ice, temperature not only affects the movement of dislocations and grain boundary slip, but it also has a significant effect on the volume of trapped brine. The brine volume, and thus the porosity of sea ice, is directly affected by temperature (see equation (3.13) in Section 3.8). Strength σ has been empirically related to brine volume as follows:

$$\sigma = A \left(1 - \sqrt{\frac{v_b}{B}} \right) \quad (6.1)$$

Where A and B are constants and v_b is the brine volume ratio.

Various authors have suggested values for A and B. Peyton (1966) proposed the following for the compressive strength of sea ice in Cook Inlet (south of Alaska):

$$\sigma = 1.65 \left(1 - \sqrt{\frac{v_b}{275}} \right) \quad (6.2)$$

The above values would be considered quite low for compressive strength. Frederking and Timco (1980) report much higher values from their study of ice in the Southern Beaufort Sea. The data is shown in Figure 6.5 and the dashed envelope trend line has been added. The equation for this envelope line is:

$$\sigma = 24 \left(1 - \sqrt{\frac{\nu_b}{33}} \right) \quad (6.3)$$

Which is more than 10X higher than Peyton's formula, which was for mean values. Clearly there is considerable variability and uncertainty in ice compressive strength. The key reason is likely because of the direct temperature effects. The Beaufort Sea data was measured for a range of -20°C to -27°C, while the Cook Inlet ice was likely much warmer. Notice also in Figure 6.5 that the mode of failure appears to influence the strength quite strongly, with brittle fractures showing higher strength. Why would this be? It may be that if the ice crystals happen to be aligned in a way that they interlocked better, they would strain elastically without slipping (which is the essence of ductile behavior). At a high strain, the system of crystals would then fail in a brittle manner (i.e. fast fracture). Brittle failure is unstable, while ductile failure is stable. This point is again emphasized in the results presented in Figure 6.6, for pure polycrystalline ice.

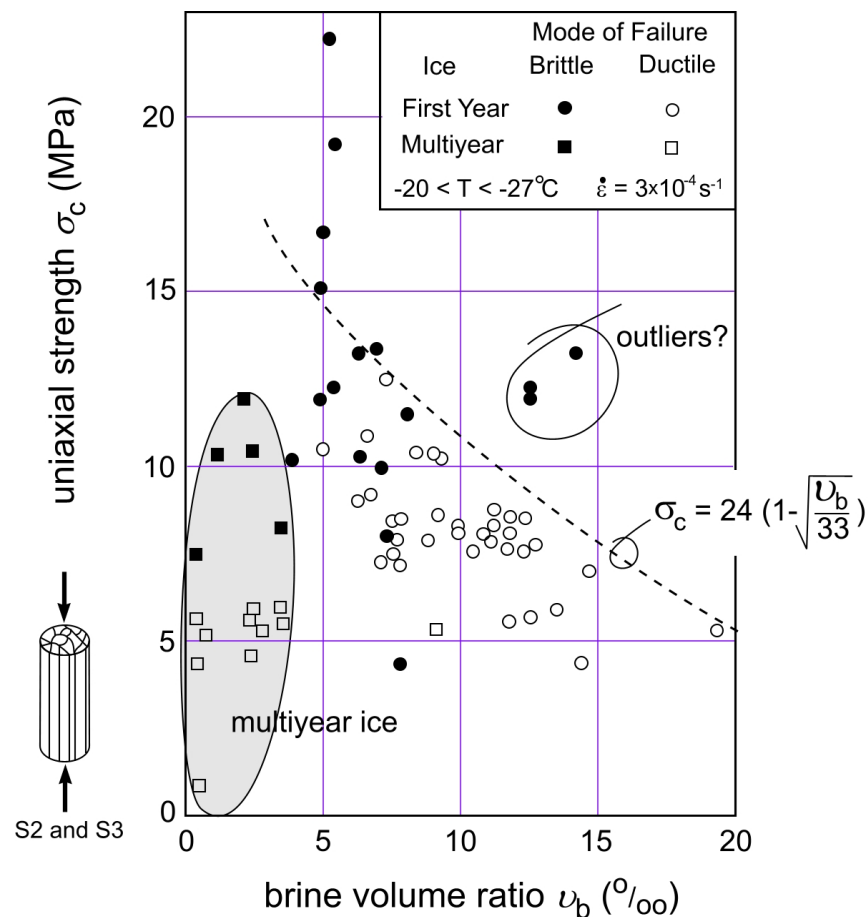


Figure 6.5 Compressive strength of Beaufort Sea ice.

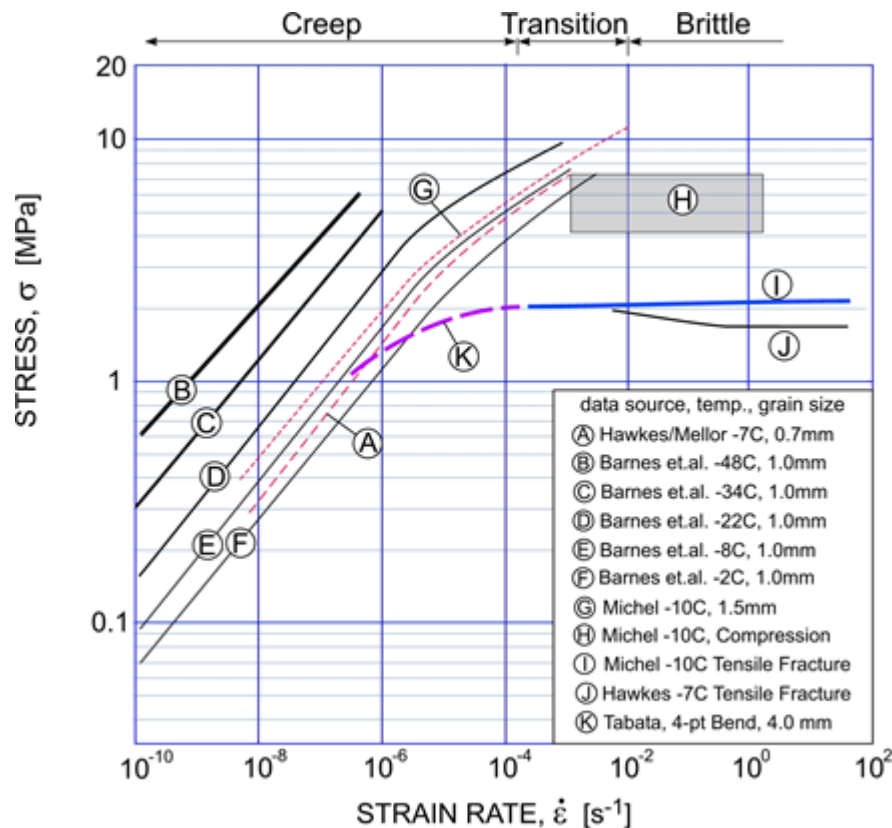


Figure 6.6 Various strengths of pure polycrystalline ice, showing the influence of strain rate, temperature and loading direction.

6.2 Fracture of Polycrystals

The dependence of ice strength on grain size has to do with the polycrystalline nature of ice. Each crystal is anisotropic, in that it is stiffer in some planes than in others. Thus, when the crystals are stressed, they tend to form stress concentrations at boundaries and especially at intersections (where 3 crystals intersect). An overall compressive stress produces shear along some of the grain boundaries. This causes the boundary to slide and then stress concentrations occur at the intersections. Figure 6.7 illustrates the process. Once the cracks start, they tend to grow in a direction aligned with the main compressive stress. Figure 6.8 shows how *wing cracks* form at the ends of a *shear crack*, in the tension region on one side of the shear crack tip. The wing cracks continue to grow and turn so that they point at the main compressive stress. This is because the maximum compression is a principal stress. The 2nd principal stress is the highest tension (or smallest compression), and the cracks tend to be at right angles to the tension (or least compression).

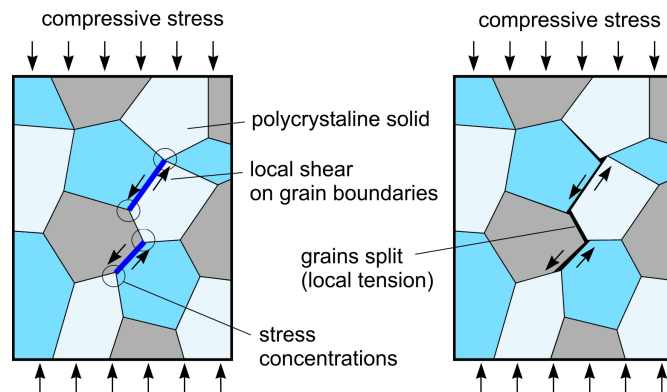


Figure 6.7 Grain boundary slip and cracking in polycrystalline ice.

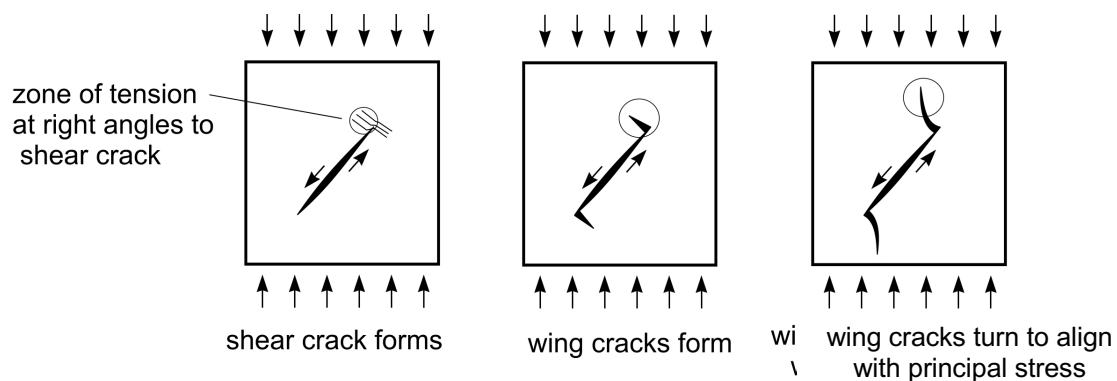


Figure 6.8 Formation and growth of wing cracks from an initial shear crack in polycrystalline ice.

6.3 Tensile and Flexural Ice Strength

Tensile Strength

Direct tension is not a typical state of stress for ice. However, because tension occurs when ice is broken in flexure, there is interest in tensile strength. The two most common arrangements for determining tensile strength are shown in Figure 6.9. The direct tension tests produce uniform tension and are unambiguous. The ring tension tests cause tensile failure in the inside of the 'donut'. Ring tension tests are somewhat easier to prepare, as they only require an auger to drill a hole in a core sample. Also, the test is performed with a compressive load, so the same equipment used to do compression test can be easily used. Ring tension test would be the easiest (of these two) to conduct in the field.

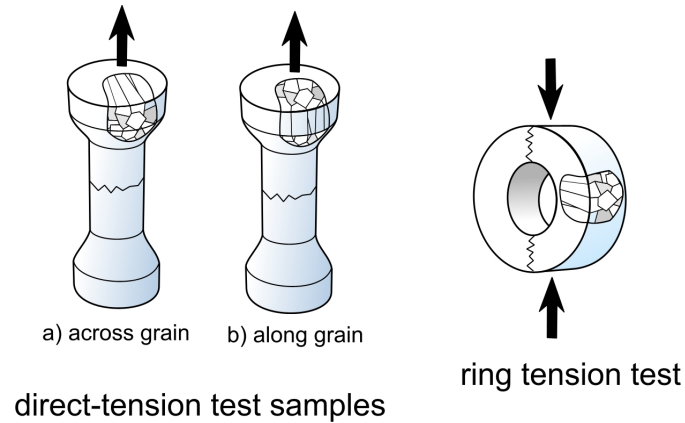


Figure 6.9 Tensile strength tests.

Peyton (1966) suggested the following mean (regression) values for tensile strength:

$$\sigma_t = 0.82 \left(1 - \sqrt{\frac{v_b}{142}} \right) \text{ case a) across grain} \quad (6.4)$$

$$\sigma_t = 1.54 \left(1 - \sqrt{\frac{v_b}{311}} \right) \text{ case b) along grain} \quad (6.5)$$

Dykins (1970) reported tensile strengths from 5 to 12 MPa (along grain) with the lower values for -5°C ice and the higher values for -27°C ice, which are again considerably higher values than reported by Peyton.

Figure 6.10 shows the geometry of a ring tension test. The maximum stress in the ring is tensile and is on the inside surface just below the applied load. The maximum stress is;

$$\sigma_t = \frac{K \cdot P}{w \cdot b} \quad (6.6)$$

Where the constant K has been derived by fitting an equation to the values for this case as presented in Roark (6th ed).

$$K = 34.37 \left(\frac{a}{b} \right)^3 + 2.16 \quad (6.7)$$

The K value is valid over the range of 0.2 to 0.5 for a/b . This result is new and so may not be in agreement with the methods used previously. It should be noted that the stress state for the ring is complex and would depend on the grain orientation and sample length. More study of these issues would be warranted if such tests would be employed.

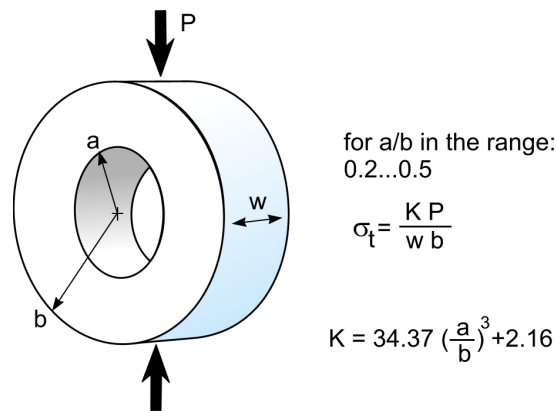


Figure 6.10 Ring Tension calculations.

Flexural Strength Tests

The flexural strength of ice can be found by conducting a *four-point bending test* (see Figure 6.11). With two roller supports and two load points, the whole beam between the two load points is subjected to constant bending moment, and this region is not affected by the direct compression directly below the load. This is preferable to a three-point bending test, where the maximum bending occurs at only one point and that point is compromised by the local direct stresses. The four-point bending test is a lab test, conducted with a machined (or at least cut) sample of ice. The strength value from such a test is;

$$\sigma_f = \frac{3 \cdot P \cdot a}{w \cdot h^2} \quad (6.8)$$

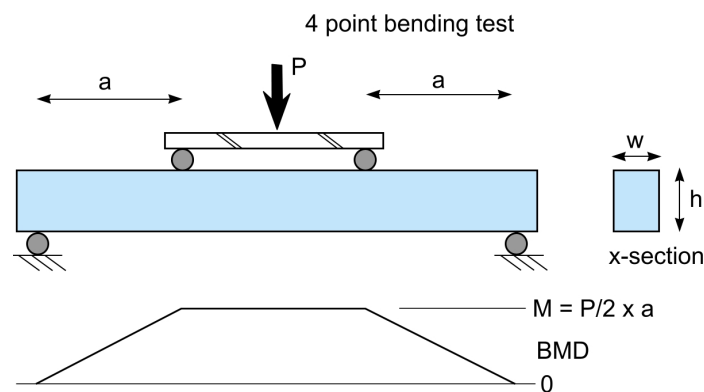


Figure 6.11 Four-point bending test.

The *cantilever beam test* is an in-situ test, rather than a lab test and is the most common strength test, next to uniaxial compression. This test is conducted at both model and full scale. The advantage of the cantilever beam test is that it measures the net strength of the whole cross section of an ice sheet, and so averages over the various layers and

temperatures. Figure 6.12 shows the basic arrangement for conducting a cantilever beam test. To prepare the cantilever in the field, it is usual to cut a U shaped slot in the ice and set the loading apparatus on the ice as shown in Figure 6.13. Downward flexure is most common, although upward flexure is possible as well. The choice will depend on the eventual use of the data. Ships break ice downward, while most fixed offshore structures break ice upward.

In the simplest case the flexural strength is found from the formula;

$$\sigma_f = \frac{6 \cdot P \cdot L}{w \cdot h^2} \quad (6.9)$$

Note that this formula ignores the effect of the fluid foundation. As long as L is relatively short, the formula is reasonable. This issue will be discussed further in the section on beams on elastic foundations.

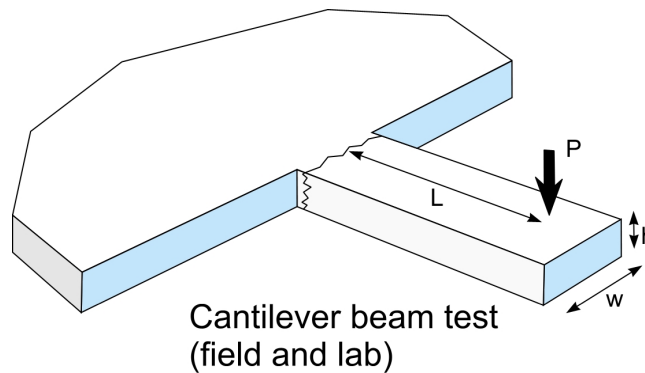


Figure 6.12 Sketch of Cantilever beam test.

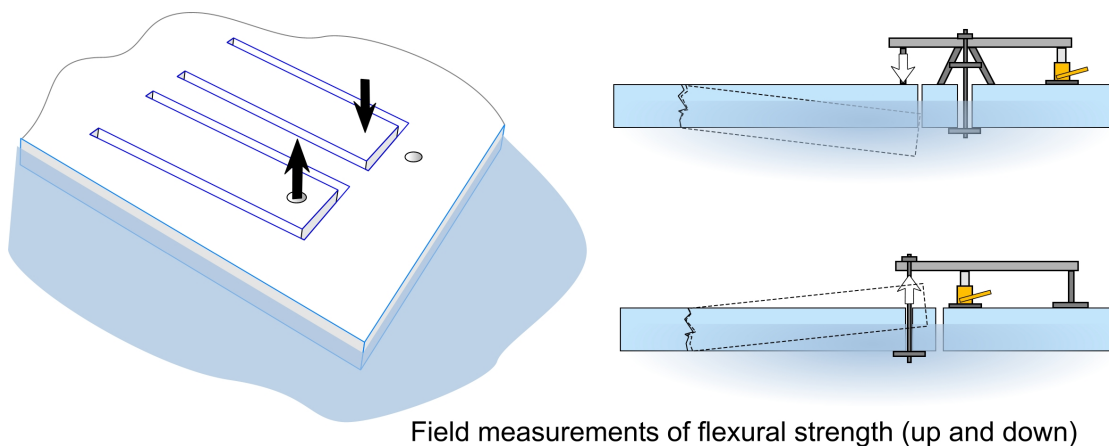


Figure 6.13 Sketch of cantilever test arrangements (down and up).

6.4 Cantilever Beam Test Calculations

To be considered semi-infinite, a beam of 1m thick ice would need to be 60 to 65m long. Typically, cantilever beam samples are cut to be 5-10x the ice thickness. At these lengths, the water has little effect and the test can be considered as an ideal cantilever.

Table 6.1 lists the steps in calculating the force required to break a cantilever beam cut in lake ice. The ice is assumed to be 0.2m thick. The beam is planned to be 0.4m wide and 2m long. E, k and I are estimated to check the characteristic length, which is found to be about 7m. The flexural strength is estimated to be E/5000, putting it at 1.8 MPa. This gives an estimated force at failure of 2.4 kN, and a deflection of 2.7 mm. With this information, a test can be planned. For sea ice the Modulus and strength would be less, and be a function of the brine volume.

Table 6.2 lists the calculations made when an actual test is performed. The flexural breaking force is easy to measure accurately, such that strength is accurately determined. Greater care is needed to measure deflection accurately, without which the modulus will not be accurate.

Table 6.1 Estimating force to break cantilever beam of freshwater ice.

Test quantities are estimated from planned beam size and estimated strength

Item	variable	source	value	units	formula
Modulus of ice	E	estimate	9.0	GPa	
ice thickness	h	planned	0.2	m	
width of cantilever	w	planned	0.4	m	
I of beam	I	calculated	0.00027	m ⁴	= 1/12*w*h ³
Z of beam	Z	calculated	0.00267	m ³	= 1/6*w*h ²
length of beam	L	planned	2	m	
water density	rho	standard	1025	kg/m ³	
gravity	G	standard	9.8	m/s ²	
foundation stiffness	k	estimate	4018	N/m/m	= rho*g*w
Char. Length	λ	estimate	6.991	m	= (4*E*I/k) ^{1/4}
flex strength of ice	σ _f	estimate	1800000	Pa	= E/5000
failure moment	M _f	estimate	4800	N-m	= σ _f Z
failure force	P _f	estimate	2400	N	= M _f /L
failure deflection	df	estimate	0.002667	m	= P _f L ³ /(3*E*I)

Table 6.2 Calculating ice flexural strength and modulus from measurements.

Maximum force and deflection are measured

Item	variable	source	value	units	formula
failure force	P	measured	2500	N	
failure deflection	d	measured	0.004	m	
failure moment	Mf	calculated	5000	N-m	= P*L
flex strength of ice	σf	calculated	1875000	Pa	= Mf / Z
Modulus of ice	E	calculated	6.25E+09	Pa	= P*L^3/(3*d*I)

6.5 Young's Modulus Data

Young's modulus is a measure of the elastic stiffness of an elastic material. At most practical engineering strain rates, ice is an elastic material. At very low strain rates (and very large scales), ice creeps and can be thought of as a viscous or visco-elastic material. However, at strain rates and scales involved with most sea ice engineering problems, ice is elastic. Measurement of Young's modulus can be done with a mechanical test, but such tests are prone to measurement error. A more precise way to measure Young's modulus is by measuring the speed of sound and inferring the modulus based on elasticity theory (Langleben, 1962). The speed of a compression wave in an elastic solid is;

$$C_B = \left[\frac{E}{\rho} \frac{(1 - \nu)}{(1 + \nu)(1 - 2\nu)} \right]^{0.5} \quad (6.10)$$

The speed of a shear wave in an elastic solid is;

$$C_S = \left[\frac{E}{\rho} \frac{1}{2(1 + \nu)} \right]^{0.5} \quad (6.11)$$

where

C_B is the velocity of compressional waves in an extended solid, sometimes called the bulk velocity,
 C_S , the velocity of shear waves,
 ρ , the density of the material,
 E , Young's modulus, and
 ν is Poisson's ratio.

Langleben (1962) published an extensive set of results for sea ice of various salinities. Pure ice has a Young's modulus in the range of 9-10 GPa, while sea ice can range down to 7 GPa. Even lower values are possible as the ice warms and deteriorates.

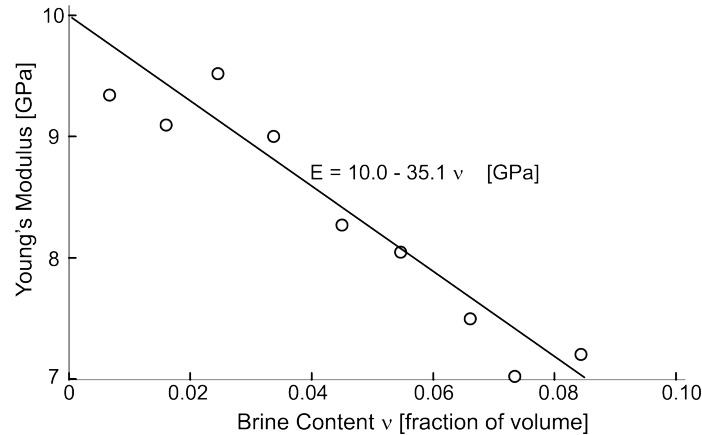


Figure 6.14 Young's modulus plotted against brine content by volume. Each point is a group average of E and v in intervals of v of 0.01. (Langleben 1962).

6.6 Flexural Strength Data

Sea ice is a natural material with highly variable strength. The brine channels weaken the ice, and the size of the brine channels depends on temperature and thickness as well as the freezing history. Timco and Obrien (1994) published an extensive set of data on the flexural strength of sea ice. Figure 6.15 shows the strength data as a function of brine volume. High brine volumes are associated with thinner, and warmer ice (see equation (3.13)). It is noteworthy that while pure ice (freshwater ice) can have flexural strengths in the 1.5-2.0 MPa range, sea ice can be much weaker, even as low as a few hundred kPa. Figure 6.16 shows an even larger data set with strength as a function of temperature.

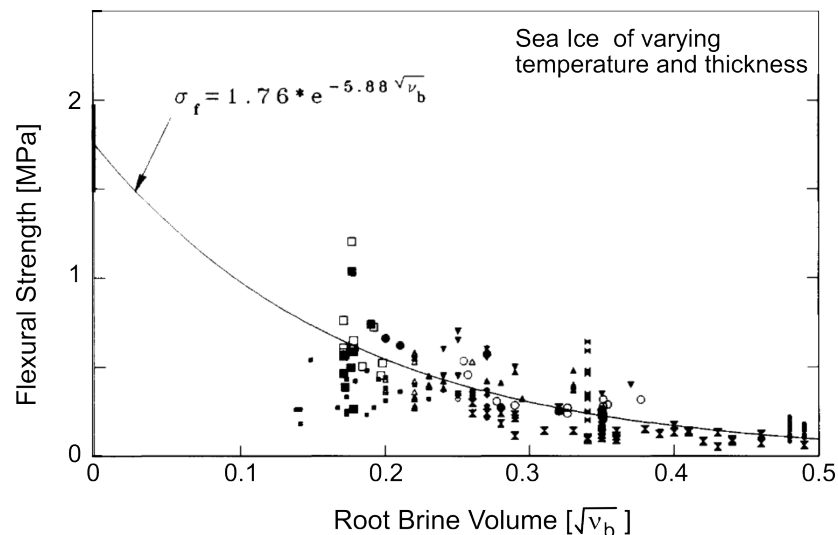


Figure 6.15 Flexural strength versus brine volume for sea ice. The tests were conducted using simple beams (open symbols) and cantilever beams (solid symbols). (Timco and Obrien 1994).

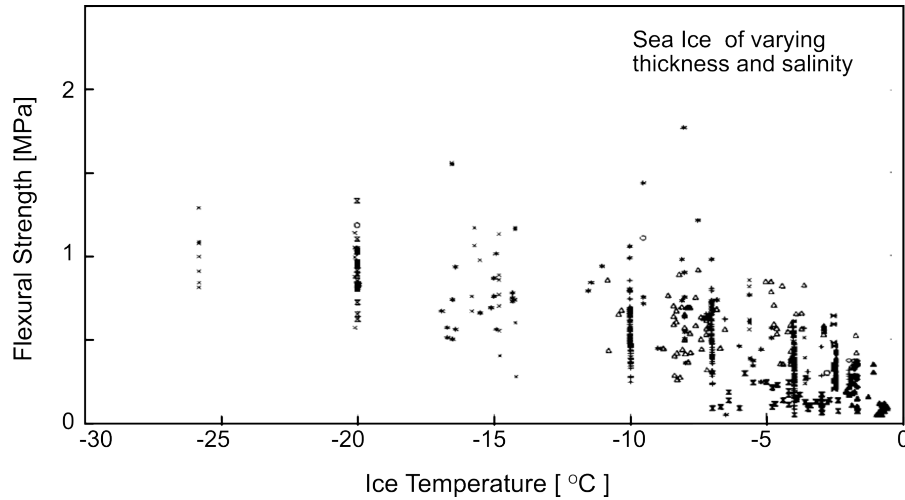


Figure 6.16 Flexural strength versus temperature for all data for sea ice (Timco and Obrien 1994).

6.7 Mechanics of Beams on Elastic Foundations

Sea and lake ice floats on water. The water provides a foundation material, which exerts a (net) pressure on the ice in proportion to the vertical movement of the ice. This becomes significant in bearing capacity and ice-structure interaction. Here the concern is with the effect on the cantilever beam test. As the beam deflects, the water exerts a load (buoyancy) directly proportional to the deflection. Figure 6.17 illustrates the situation. The case can be modeled with a modified form of the beam equation;

$$EI \frac{d^4 w}{dx^4} + k w = 0 \quad (6.12)$$

Where w is deflection, EI is the beam stiffness and k is the foundation modulus. For water density ρ and beam of width d , $k = \rho g d$. For later convenience we define a term called the characteristic length λ ;

$$\lambda = \left(\frac{4EI}{k} \right)^{\frac{1}{4}} \quad (6.13)$$

Checking the units, it can be shown that λ has units of length.

To find the influence of the water foundation, the solution of the differential equation (6.12) is needed. For the case of a semi-infinite beam, with an end load P (see Figure 6.17), the solution of the system is;

$$\text{Deflection} \quad w = \frac{2P}{\lambda k} e^{-\frac{x}{\lambda}} \cos\left(\frac{x}{\lambda}\right) \quad (6.14)$$

Slope $\theta = -\frac{2P}{\lambda^2 k} e^{-\frac{x}{\lambda}} \left[\cos\left(\frac{x}{\lambda}\right) + \sin\left(\frac{x}{\lambda}\right) \right] \quad (6.15)$

Moment $M = -\lambda P \cdot e^{-\frac{x}{\lambda}} \sin\left(\frac{x}{\lambda}\right) \quad (6.16)$

Shear $Q = -P e^{-\frac{x}{\lambda}} \left[\cos\left(\frac{x}{\lambda}\right) - \sin\left(\frac{x}{\lambda}\right) \right] \quad (6.17)$

The maximum bending moment occurs at a distance x_c from the free end:

$$x_c = \frac{\pi}{4} \lambda \quad (6.18)$$

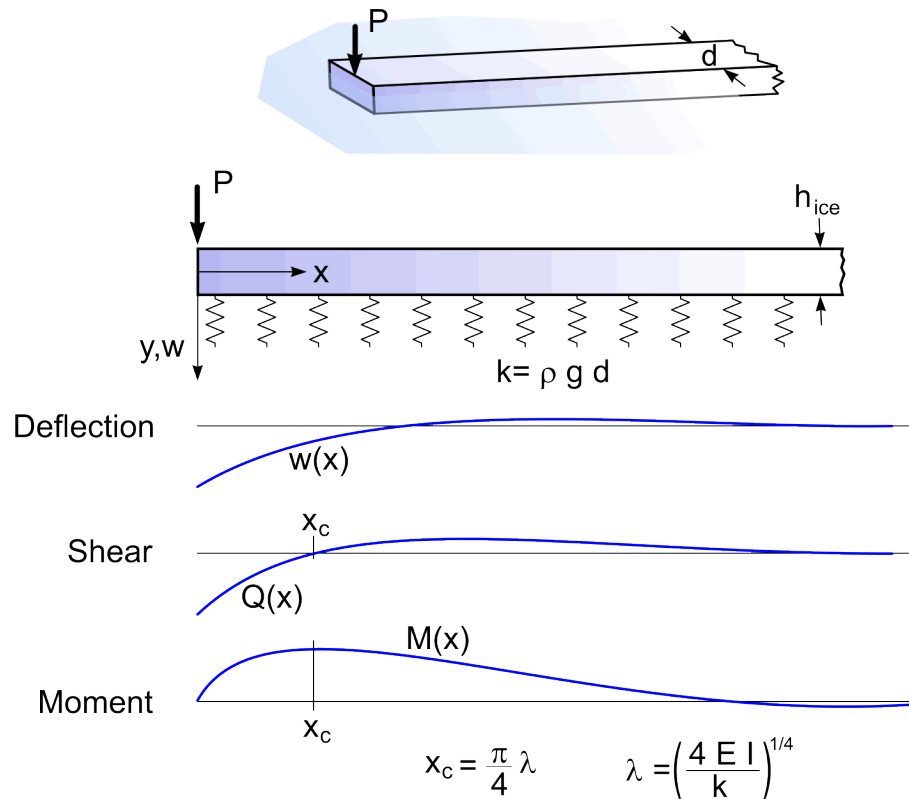


Figure 6.17 Sketch of semi-infinite beam on an elastic foundation.

To achieve this semi-infinite condition, a cantilever beam would need to be at least 3 characteristic lengths long. This is usually impractical. The characteristic length formula (eqn. (6.13)) can be re-expressed as;

$$\lambda = \left(\frac{E}{3 \rho_w g} \right)^{\frac{1}{4}} h^{\frac{3}{4}} \quad (6.19)$$

Which for typical ice properties is;

$$\lambda = C \cdot h^{\frac{3}{4}} \quad (6.20)$$

Where C ranges from 18 to 24 (soft to hard ice). So, for 1m of ice, λ ranges from 18 to 24 m.

If equations (6.16) and (6.18) are combined, the maximum bending moment is;

$$\begin{aligned} M_{max} &= \lambda P \cdot e^{-\frac{\pi}{4}} \cos\left(\frac{\pi}{4}\right) \\ &= 0.322 \lambda P \end{aligned} \quad (6.21)$$

Chapter 6: Problems

6.1 Sea ice has a salinity of 4 ppt, and is at -8C. What is the brine volume ratio, and what is the uniaxial crushing strength likely to be? What is the Flexural strength likely to be?

6.2 There is a large sheet of freshwater ice that is 0.5 meters thick. You take a chainsaw and cut a long cantilever beam in the ice. The beam is 100 meters long and 1m wide.

Assume $E = 3 \text{ GPa}$, $\rho = 900 \text{ kg/m}^3$, $\sigma_{flex} = 2 \text{ MPa}$

- What force applied vertically to the free end to deflect the ice 5cm (which is the freeboard of the ice).
- What force would you expect to be at the flexural limit (beam breaks)?
- What is the vertical deflection at the load location ?
- If the vertical deflection at (nominal) failure is more than 5cm, how would you explain the effect of the water flooding? What load do you think would break the beam?

6.3. Sea ice has a salinity of 3 ppt, and is at -10 C.

What is the brine volume ratio?

What is the uniaxial crushing strength likely to be?

7 Ice Sheet Bearing Capacity

7.1 Infinite plate on an elastic foundation

There are many situations when an ice cover is subjected to a vertical force (Figure 7.1). When a person walks on the ice, when a car drives on an ice road or when a submarine attempts to surface through an ice cover, the ice feels a local vertical force. In most situations, the load is applied over a relatively small area and acts effectively as a point load.

The ice response to a point load can be modeled as an axially symmetric problem Figure 7.2, which results in simpler equations and solution. In this way, the problem can be treated as 2D, with ordinary differential equations, rather than 3D with partial differential equations.

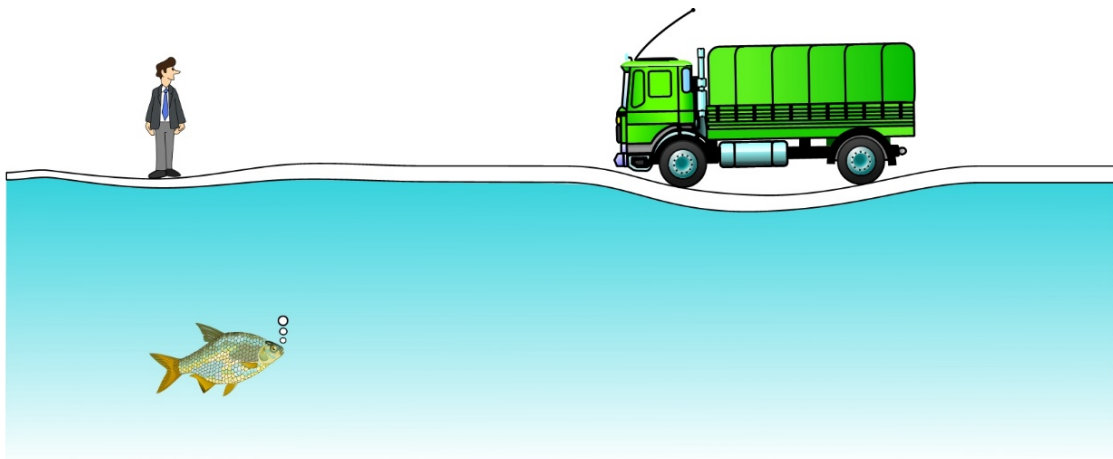


Figure 7.1 Ice as an infinite plate on an elastic foundation.

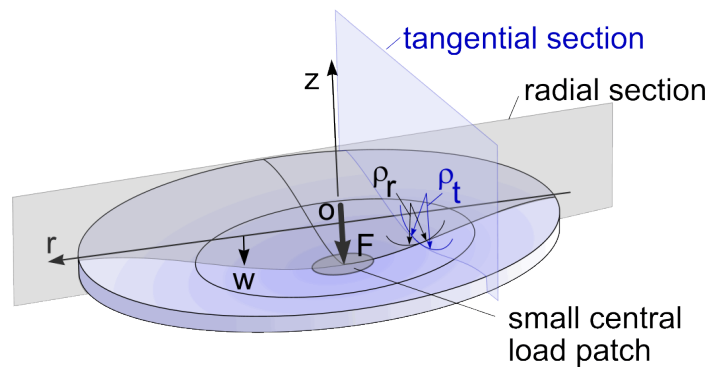


Figure 7.2 Axially symmetrical response of a plate to a local force

Consider the situation shown in Figure 7.2. The ice is loaded at the origin, and the largest deformation occurs there. In order to estimate the bearing capacity of this ice sheet to this load, we first need to determine the curvatures of the deformed shape. There are two principal curvatures that define the axisymmetric deformation shape: one in the radial direction, and one in the tangential direction.

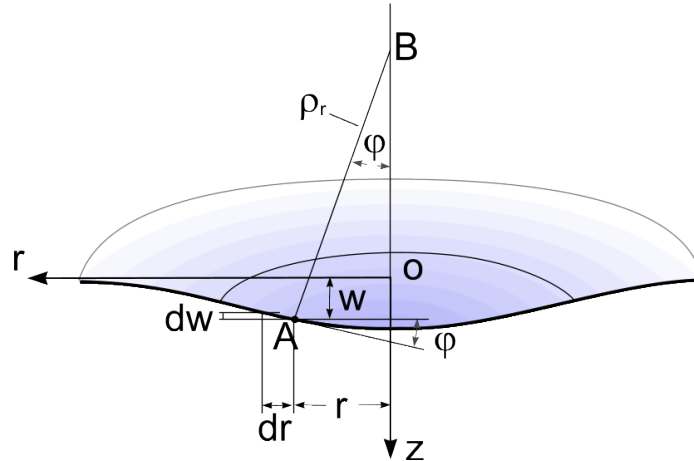


Figure 7.3 Radial cross section of a plate (after Timoshenko).

First, let's determine the curvature in the radial direction. Figure 7.3 shows a radial section of the deformed shape through the origin (as shown in Figure 7.2). At any radius, r , from O there is a deflection w . The slope of any point A is equal to:

$$\varphi = -\frac{dw}{dr} \quad (7.1)$$

and the curvature in the radial direction is:

$$\frac{1}{\rho_r} = \frac{d\varphi}{dr} = -\frac{d^2w}{dr^2} \quad (7.2)$$

where: φ is the small angle between AB and the axis of symmetry OB
 ρ_r is the *radius of curvature*

Symmetry implies that this is one of the principal curvatures of the deformed surface at A . The second principal curvature is in the section through the normal AB and perpendicular to the rz plane. Imagine you are looking along line AB . If line AB is revolved about the vertical axis (i.e. the axis of symmetry for this surface), it will describe a cone with a base radius, r , with its apex at B . The length of the line AB is the second principal curvature, which is given by:

$$\frac{1}{\rho_t} = -\frac{1}{r} \frac{dw}{dr} = \frac{\varphi}{r} \quad (7.3)$$

The above equations are very similar to the 2D equations for beam bending. The equations only relate some of the deformations, and don't (yet) contain any description of stresses or forces.

In a manner similar to beam bending, we will assume that the ice has a constant thickness and uniform properties (which we know is not quite right). The bending strains in the radial and tangential directions are:

$$\varepsilon_r = \frac{z}{\rho_r} \quad (7.4)$$

$$\varepsilon_t = \frac{z}{\rho_t} \quad (7.5)$$

where: z is the distance from the neutral surface of the plate.

Hooke's Law (notably one of Hooke's minor accomplishments, but the only one to bear his name) lets us convert these two strains to stresses:

$$\sigma_r = \frac{E \cdot z}{1 - \nu^2} \left[\frac{1}{\rho_r} + \nu \frac{1}{\rho_t} \right] \quad (7.6)$$

$$\sigma_t = \frac{E \cdot z}{1 - \nu^2} \left[\frac{1}{\rho_t} + \nu \frac{1}{\rho_r} \right] \quad (7.7)$$

Imagine a small element of the ice sheet, bounded by two radial edges (lines da and cb) and by two tangential edges (lines ab and cd). Figure 7.4 shows the forces and moments on this element. The only in-plane forces come from *bending*. M_r and M_t are the moments per unit length of plate, acting in the radial and tangential directions:

$$M_r = \int_{-\frac{h}{2}}^{\frac{h}{2}} \sigma_r \cdot z \cdot dz \quad (7.8)$$

$$M_t = \int_{-\frac{h}{2}}^{+\frac{h}{2}} \sigma_t \cdot z \cdot dz \quad (7.9)$$

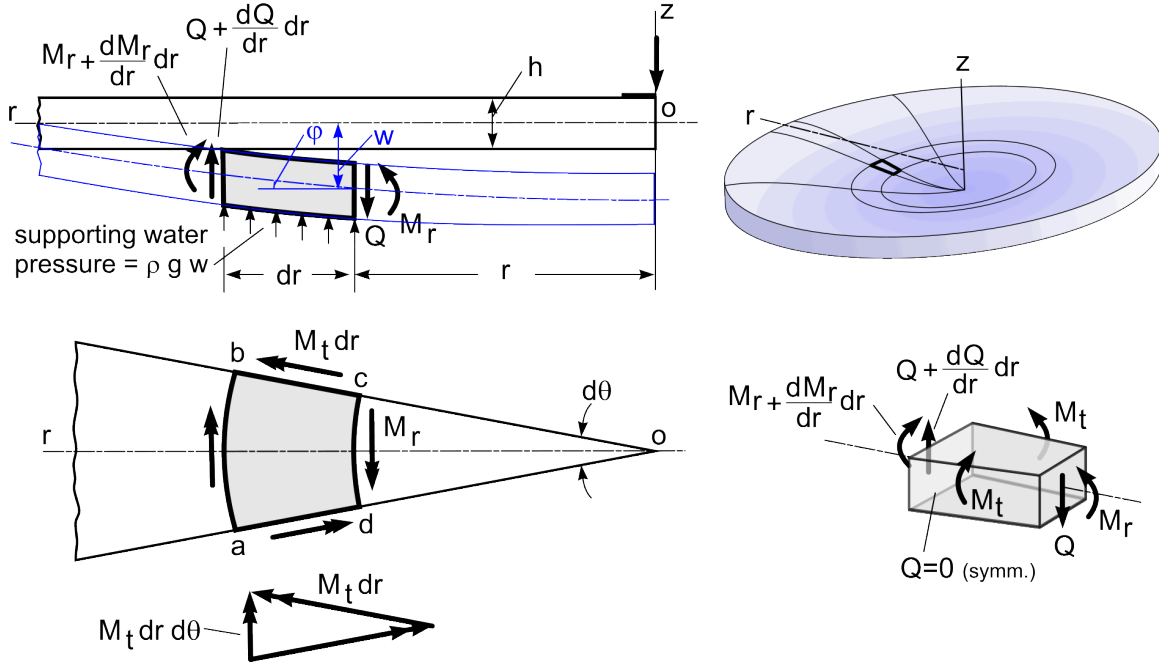


Figure 7.4 Forces and moments on an element of an ice plate (axial symmetry).

By substituting equations (7.2) and (7.6) into (7.8), and (7.3) and (7.7) into (7.9), we get the differential equations:

$$M_r = -D \left(\frac{d^2 w}{dr^2} + \frac{\nu}{r} \frac{dw}{dr} \right) = D \left(\frac{d\varphi}{dr} + \frac{\nu}{r} \varphi \right) \quad (7.10)$$

$$M_t = -D \left(\frac{1}{r} \frac{dw}{dr} + \nu \frac{d^2 w}{dr^2} \right) = D \left(\frac{\varphi}{r} + \nu \frac{d\varphi}{dr} \right) \quad (7.11)$$

where D is the plate's *flexural rigidity*:

$$D = \frac{E \cdot h^3}{12(1 - \nu^2)} \quad (7.12)$$

Equations (7.10) and (7.11) have only one dependent variable, w (or φ), and one independent variable, r . The dependent variable w (or φ) can be determined by considering the equilibrium of the element $abcd$.

The moment acting on the side cd is:

$$M_r \cdot r \, d\theta \quad (7.13)$$

The corresponding moment on side ab is:

$$\left(M_r + \frac{\delta M_r}{\delta r} dr\right)(r + dr)d\theta \quad (7.14)$$

The moments on each of the sides ad and cb are:

$$M_t \cdot dr \quad (7.15)$$

These moments are not quite at right angles to the radial moments, M_r , and consequently there is a resultant moment in the radial direction of:

$$M_t \cdot dr \cdot d\theta \quad (7.16)$$

Now let's consider shear. Q is the shear force per unit width. We note that there is no shear on the radial faces ad and cb (due to symmetry). The shear force on face cd is;

$$Q \cdot r \cdot d\theta \quad (7.17)$$

Neglecting the small difference between the shearing forces on the opposite ends of the element, the shear gives a radial moment of:

$$Q \cdot r \cdot d\theta \cdot dr \quad (7.18)$$

Summing up the moments with proper signs gives:

$$\left(M_r + \frac{\delta M_r}{\delta r} r\right)(r + dr)d\theta - M_r \cdot r \cdot d\theta - M_t \cdot dr \cdot d\theta + Q \cdot r \cdot d\theta \cdot dr = 0 \quad (7.19)$$

We divide through by $dr \cdot d\theta$ and collect terms to get:

$$M_r + \frac{\delta M_r}{\delta r^2} r^2 + \frac{\delta M_r}{\delta r} \cdot r - M_t + Q \cdot r = 0 \quad (7.20)$$

We note that $\frac{\delta M_r}{\delta r^2} r^2$ is a higher order term (negligible magnitude) and so we have:

$$M_r + \frac{\delta M_r}{\delta r} \cdot r - M_t + Q \cdot r = 0 \quad (7.21)$$

and substituting in eqns. (7.10) and (7.11) gives:

$$\frac{d^2 \varphi}{dr^2} + \frac{1}{r} \frac{d\varphi}{dr} - \frac{\varphi}{r^2} = -\frac{Q}{D} \quad (7.22)$$

or in another form:

$$\frac{d^3w}{dr^3} + \frac{1}{r} \frac{d^2w}{dr^2} - \frac{1}{r^2} \frac{dw}{dr} = -\frac{Q}{D} \quad (7.23)$$

We can replace the Q term (a shear per unit length of cut) with a q term, where q represents the total vertical shear force per radial unit, such that:

$$2\pi r \cdot Q = \int_0^r 2\pi r \cdot q \, dr \quad (7.24)$$

This enables us to re-write the differential equation in polar coordinates as (steps not shown):

$$\left(\frac{d^2}{dr^2} + \frac{1}{r} \frac{d}{dr} \right) \left(\frac{d^2w}{dr^2} + \frac{1}{r} \frac{dw}{dr} \right) = \frac{q}{D} \quad (7.25)$$

In rectangular coordinates this becomes:

$$\frac{d^4w}{dx^4} + 2 \frac{d^4w}{dx^2 dy^2} + \frac{d^4w}{dy^4} = \frac{q}{D} \quad (7.26)$$

The above value q represents all loads, including the water pressure (from the ‘foundation’). Its preferable to separate the downward loads on top of the ice, from the buoyancy forces from below. So, let’s define p as the loads on top and separate the water support reaction, k_w . This lets us re-write (7.25) as:

$$\frac{d^4w}{dx^4} + 2 \frac{d^4w}{dx^2 dy^2} + \frac{d^4w}{dy^4} = \frac{p - k_w}{D} \quad (7.27)$$

Which in Hamilton operator shorthand is:

$$\Delta \Delta w = \frac{p - k_w}{D} \quad (7.28)$$

This is our load-response differential equation for our ice plate with axi-symmetric loads.

We can non-dimensionalize this using:

$$\ell = \sqrt[4]{\frac{D}{k_w}} \quad (7.29)$$

$$\omega = \frac{w}{\ell} \quad (7.30)$$

$$x = \frac{r}{\ell} \quad (7.31)$$

$$p' = \frac{p}{k} \quad (7.32)$$

and so write:

$$\Delta\Delta\omega + \omega = p' \quad (7.33)$$

ℓ is called the characteristic length of the sheet, similar to the λ value, as given in Chapter 6.

7.2 Response to concentrated load

In most situations, a person standing on ice can be treated as a point load (though not so if the person is lying down or wearing skis). The solution to the above differential equations for the point load case is somewhat complex, and requires the use of Bessel functions.

For a point load the solution is:

$$w = \frac{p\ell^2}{2\pi D} \text{kei}\left(\frac{r}{\ell}\right) \quad (7.34)$$

where: w is the deflection at location $\left(\frac{r}{\ell}\right)$ (units of length (e.g. [m]))
 p is the point load (units of force (e.g. [N]))

The function $\text{kei}()$ (pronounced like 'pie') is a Bessel function. In Maple $\text{kei}(x)$ is the same as $\text{KelvinKei}(0,x)$.

If we realize that $\left(\frac{r}{\ell}\right)$ is a location on the deformed surface, and that the maximum deflection occurs at the point of application of the load (i.e. $\frac{r}{\ell} = 0$), then $\text{kei}(0) = -\pi/4$ and (choosing down as positive):

$$w_{\max} = \frac{p\ell^2}{2\pi D} \text{kei}(0) = \frac{p\ell^2}{2\pi D} \left(\frac{\pi}{4}\right) \quad (7.35)$$

or:

$$w_{\max} = \frac{p\ell^2}{8D} \quad (7.36)$$

By using equation (7.33b) we can replace the D in equation (7.27) and isolate ℓ . This lets us estimate the characteristic length, based on the deflection of a sheet under a concentrated load:

$$\ell = \sqrt{\frac{p}{8 k_w w_{\max}}} \quad (7.37)$$

The displacement is plotted in the example below. The ice conditions are;

modulus:: $E_{ice} = 6 \text{ GPa}$
 thickness: $h_{ice} = 0.1 \text{ m } (\sim 4'')$
 rigidity: $EI = D = \frac{E \cdot h^3}{12(1-\nu^2)}$
 foundation: $k_w = 10045 \frac{\text{N}}{\text{m}^3}$
 char. length: $\ell = \left(\frac{EI}{k}\right)^{\frac{1}{4}} = 2.72 \text{ m}$
 load: $p = 10000 \text{ N}$

The example is solved using Maple to calculate ice plate bending;

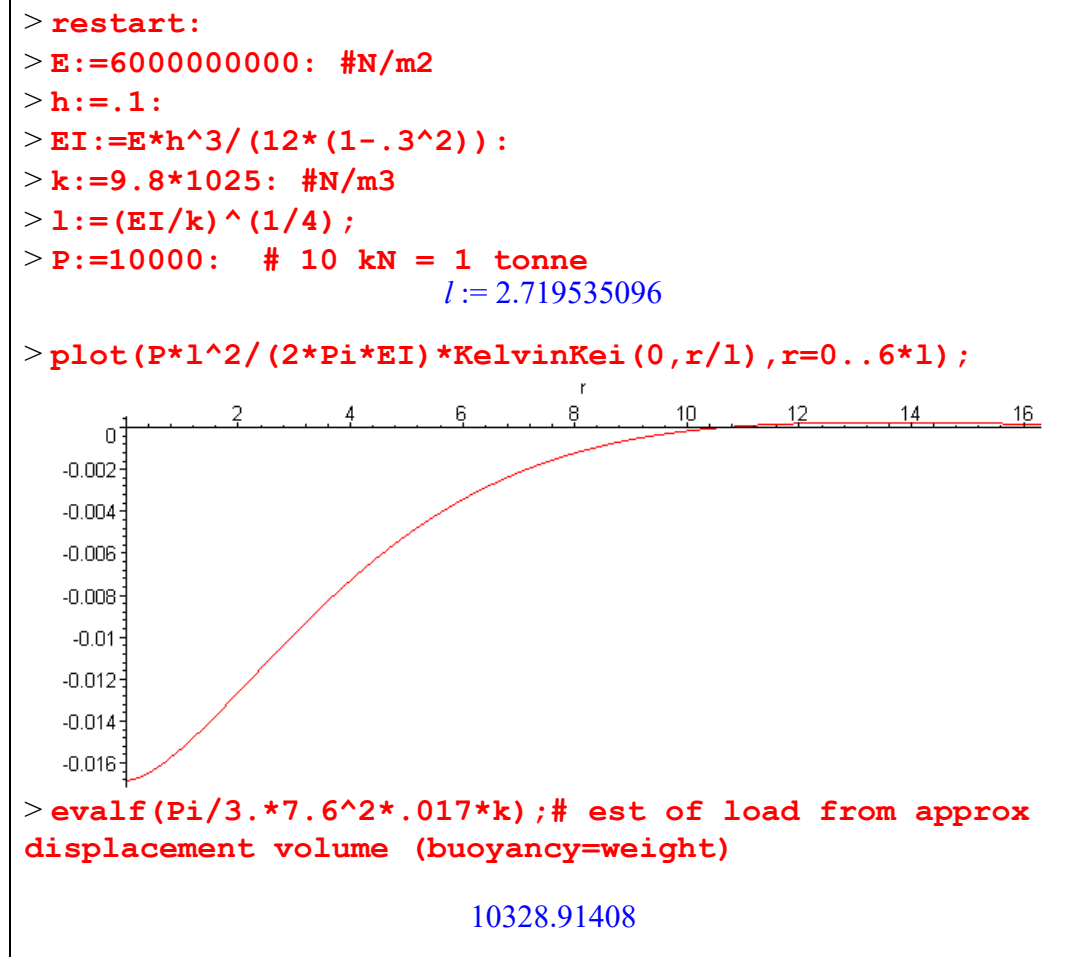


Figure 7.5 Maple example of calculating response to point load.

The last line in the example above is the estimation of the displacement of the ice, by equating the displaced shape to a cone of base diameter 7.6m, and height of .017m (est. from the plot). With the water density k , the displacement is estimated at close to the force of 10kN, confirming the solution. The shape of the plot by maple is generally

similar to the expected response as shown in Figure 9.2. Notice that for an infinite plate, the active region extends out to about three characteristic lengths from the load.

The bending moments in the radian and tangential directions are:

$$M_r = \frac{P}{4\pi} \left[(1 + \nu) \left(\ln \frac{2\ell}{r} - \nu \right) - \frac{(1 - \nu)}{2} \right] \quad (7.38)$$

$$M_t = \frac{P}{4\pi} \left[(1 + \nu) \left(\ln \frac{2\ell}{r} - \nu \right) + \frac{(1 - \nu)}{2} \right] \quad (7.39)$$

For the above example, the two bending moments are plotted in Figure 7.6. The drawback with this solution is that the stresses are very high right at the point load. Loads in practice are distributed over a small or large finite area and this diminishes the peak bending moment.

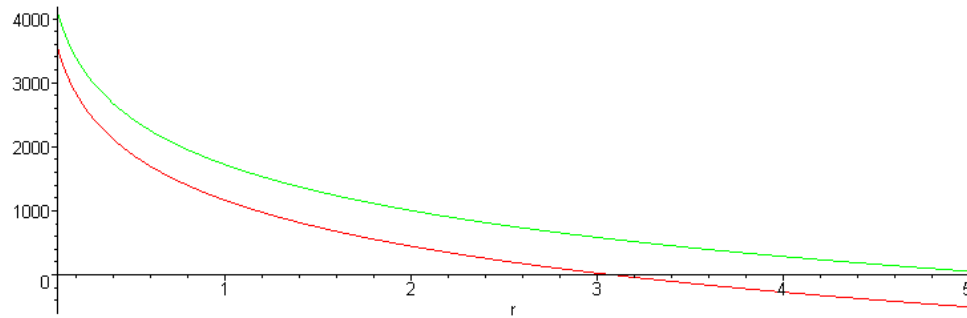


Figure 7.6 Radial (red) and tangential (green on top) bending moments for point load.

7.3 Response to circular load

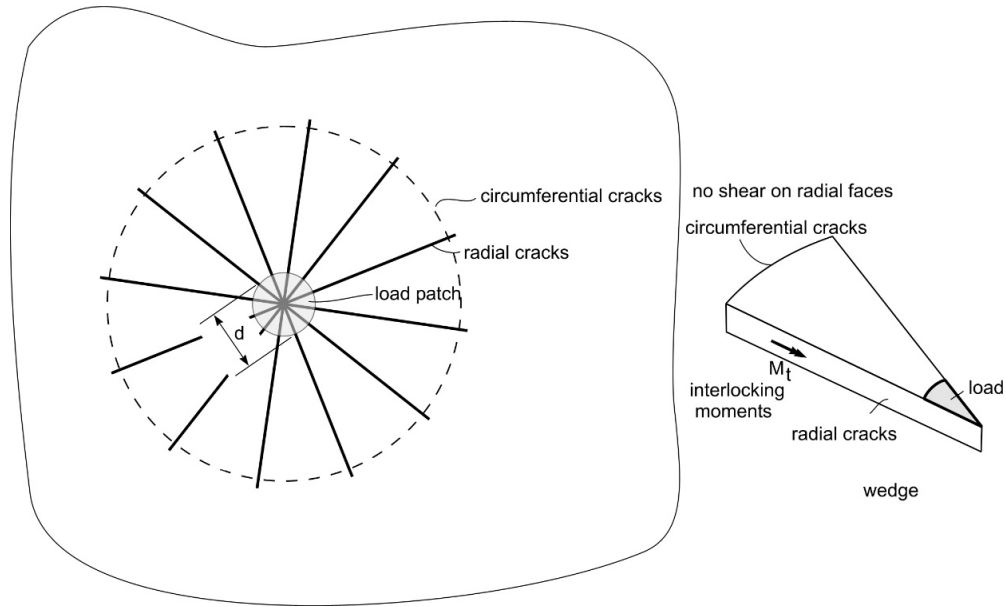


Figure 7.7 Radial and circumferential cracks for a small circular load.

For plates with the load applied over a small circular patch of diameter d , the maximum stress (acting circumferentially, so that radial cracks will form) was found by Westergaard (see Timoshenko and Wionowsky-Kreiger 1959, p. 275):

$$\sigma_{max} = 0.275(1 - \nu) \frac{P}{h^2} \log_{10} \left[\frac{E \cdot h^3}{k \cdot c^4} \right] \quad (7.40)$$

$$\sigma_{max} = 0.275(1 - \nu) \frac{P}{h^2} \log_{10} \left[12(1 - \nu^2) \frac{\ell^4}{c^4} \right] \quad (7.41)$$

Where P is the load on the sheet and c is a function of load diameter:

$$c = \sqrt{1.6 \left(\frac{d}{2} \right)^2 + h^2} - 0.675h \quad \text{for } \frac{d}{2} < 1.724h \quad (7.42)$$

$$c = \frac{d}{2} \quad \text{for } \frac{d}{2} > 1.724h$$

This can be re-expressed as a bearing capacity that as:

$$P = \frac{4}{\log_{10} \left[\frac{E \cdot h^3}{k \cdot c^4} \right]} \sigma_{flex} \cdot h^2 \quad (7.43)$$

$$\cong 0.5 \cdot \sigma_{flex} \cdot h^2$$

Equation (7.41) represents the load when the first radial cracks form. The ultimate capacity is larger, but not double. Calculating the strength of an ice sheet with radial cracks involves checking the strength of ice wedges, in a manner similar to the beams considered earlier. One complicating factor is that the wedges tend to interlock, providing additional capacity. Regardless, equation (7.41) is a good starting point for estimating the bearing capacity. The capacity vs ice thickness is plotted in Figure 7.8 for two assumed ice strengths (1000kPa for strong ice and 400 kPa for typical ice). The values are plotted together with some field measurements (see CRREL web site) showing measured capacities in thick ice. Thickness limits for various activities are shown. These thicknesses are somewhat on the conservative side and assume only moderate ice strength. However, decaying ice can be very weak, and ice thickness can be uncertain, especially near streams or other water (runoff) sources. Great care must be taken if there is any concern about the ice. Individuals should test the ice by cutting or coring. Any vehicular use of ice should only take place after much planning and study by experienced people.

Ice plate failure by bending will be examined further in the chapters on icebreaking and loads on sloping structures.

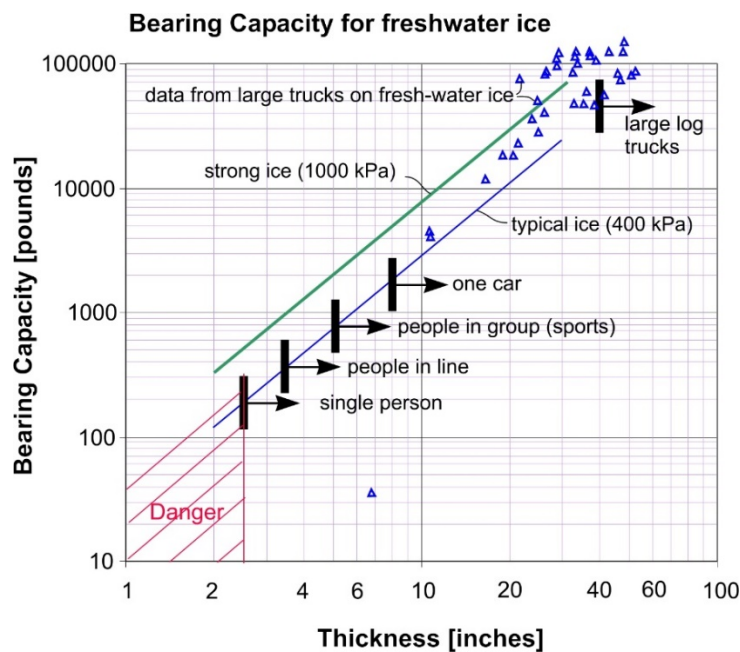


Figure 7.8 Bearing capacity of freshwater ice.

7.4 Dynamic behavior

Moving loads create a pressure wave in the water under the ice, similar to the wave created by a moving ship. The wave will influence the ice cover, which will amplify deflections and thus stresses. Although in theory the wave can be quite large at resonance, in practice the dynamic amplification is limited to a factor of about 1.5. Wave creation is most problematic when approaching a shoreline. In this case the pressure wave created by the moving vehicle is either augmented by the shallowing bottom profile or it reflects off the shoreline. In either case the wave profile is increased and the stress in the ice can lead to ice failure. Also, vehicles travelling a narrow passage or inlet covered by ice can create a standing wave which reflects from the shorelines, causing increased wave amplitudes and damage to the ice cover.

In general, speed limits are imposed on moving loads on ice to avoid dynamic effects. This is more critical as the load levels approach the maximum allowed for the particular ice thickness. The speed of the underlying water wave is primarily dependent on the depth of the water, the thickness of the ice cover and the elasticity of the ice. In deep water, the greatest deflection and the most severe stresses occur when the vehicle on top of the ice and the wave below it are travelling at the same speed. If the ice sheet is highly stressed because the ice is too thin or severely cracked, the stress from the wave plus the stress from the load can be enough to cause failure in the ice cover.

The critical vehicle velocity for maximum dynamic magnification, V_C (km/h), is determined principally by the water depth and can be expressed as:

$$V_C = 1.3d^{0.5} \quad (7.44)$$

where: d is the water depth in metres

At or near to the critical speed, the ice deflection and the ice stress/ strain can be 1.5 times the values when the vehicle is travelling slowly. At a speed of less than 70% of the critical velocity, field measurements have indicated that the dynamic magnification factor is not significant.

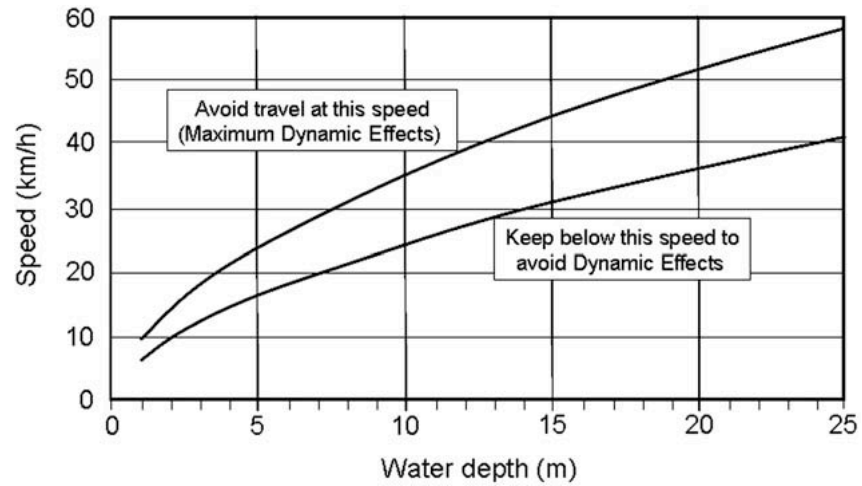


Figure 7.9 Safe transit speeds on ice

Chapter 7: Problems

7.1 Ice Growth and Bearing Capacity

Consider the following scenario. Late in the evening on Jan. 11th a man on a snow machine was crossing a bay in the ocean covered by fast sea ice (no snow). The total weight of man and machine was 750 lb. He broke through the ice and barely managed to save himself and get home. He returned with friends on January 18th, when the ice thickness in the bay was 25cm. The weather records for mean daily temperature are tabulated below.

- c) From this data, estimate the ice thickness when the man fell through the ice.
- d) Estimate which day could he have safely crossed the ice? (assume the flexural strength was 0.5MPa)

Date	Mean Daily Temperature C
Jan 12	-8
Jan 13	-10
Jan 14	-12
Jan 15	-9
Jan 16	-18
Jan 17	-22
Jan 18	-12

- 7.2. Consider columnar sea ice, with thickness of 29 cm and brine volume of 8 o/oo. What would be the heaviest weight that you could temporarily place on the ice? Assume the load patch is small.
- 7.3 You are standing on level fast ice, 2m thick, and you are 1 km from shore. The ice extends 50km further offshore and the wind is blowing towards shore. The shore is a vertical flat rock cliff. You have an accurate measurement of your position, and you determine that you are moving towards shore at 1mm/min. Estimate the ice pressure on the rock face at the shore.

8 Ice load processes - crushing, bending, rubble formation

8.1 Developing ice load models

This chapter will begin a discussion of ice loads. The earliest models of ice forces involved loads on vertical bridge piers. However, before considering specific cases, a general discussion of model development will be presented.

The development of ice load models follows a process of successive refinement and validation of a description of the loading process. This is not unique to ice loads. Similar issues arise in all branches of knowledge. In engineering situations involving the natural world the following discussion is especially appropriate

Generally in natural processes, for example ice crushing against a stone pier, the situation is more complex than it first appears. In time certain patterns emerge and we can develop a mental model of the various things going on. We call this a “perceptual” model. Such models are descriptive and can often be full of special cases and interactions. The observer perceives events that are nonlinear and difficult to describe in a mathematical way

The next stage in developing a workable description is to create a relatively simple descriptive model of the main aspects of the process. This is called the “conceptual” model. This concept can be expressed as one or more simple mechanical events (processes) that can be expressed mathematically. The creation of a conceptual model is an important aspect of creating an engineering model or solution. Conceptual models must be relatively simple so they can be expressed mathematically and solved. The challenge is to capture the essence of the complex reality so that the final model is reasonably accurate. Once a conceptual model is finished it is transformed into an algorithm for solution by an appropriate method. The best models are analytical with algebraic (closed form) solutions. Often this is not possible and numerical solutions are required. Another alternative is to create a physical analog of the conceptual model and study it (e.g. in a towing tank). This later step is common in modeling complex fluid and other natural problems because it has historically proven difficult to provide sufficiently descriptive analytical or numerical models.

The algorithmic model must be a complete implementation of the conceptual model, though this is not always easy to accomplish. The algorithmic model may have its own challenges (e.g. instabilities).

Once a working engineering model is available, the next step is validation. The model must be explored for the sensitivities it shows. The output should be reasonably well correlated with field and experimental observations. Field and lab data is relatively sparse, scarce and subject to uncertainty. The uncertainty may be an inherent result of the natural process or may arise from the inadequacy of the observations (e.g. sensors may give wrong or no data).

The validation is almost always “partial” in the sense that only certain cases can be checked and validated. As well, the validation phase often shows that the model does not agree all that well with the observations. Nevertheless, the models are used for various practical purposes. Any uncertainty is handled by employing some form of safety net (safety factor, backup systems, risk assessment) to protect against the consequences of inaccurate predictions.

The above discussion applies to many situations. When considering the process of breaking ice with a ship, Enkvist (1972) described a perceptual model in the first part of a doctoral thesis. He recognized the challenge of implementing a full mathematical model that addressed all aspects of his field observations. As a partial solution, he proposed a relatively simple conceptual model that he then converted to an algorithm to calculate a result. The passage of time has tended to validate his concept but has also led many to feel that the concept reflects the totality of the problem. While common, this kind of thinking impedes progress. Enkvist hoped that others would build on his perceptual model, not his conceptual one.

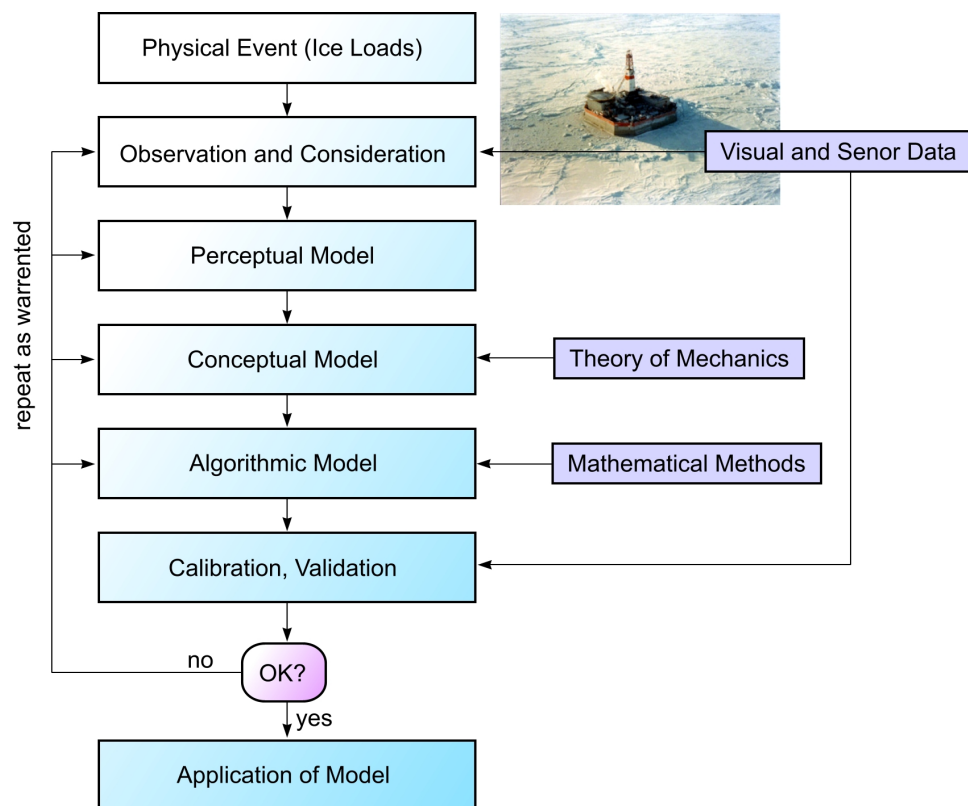


Figure 8.1 Illustration of the sequence and of model development

8.2 Vertical structures in ice

There are a variety of vertical structures that experience ice loads. The first types, that gained attention, were bridge piers and coastal structures (light houses, wharves). Consider the situation as shown in Figure 10.2. The ice is 'h' thick and strikes the structure of 'w' width. The simplest of 'perceptual' models would describe the interaction as smooth crushing, with uniform pressure over the contact area. The force would be expressed as;

$$F = \sigma_c w h \quad (8.1)$$

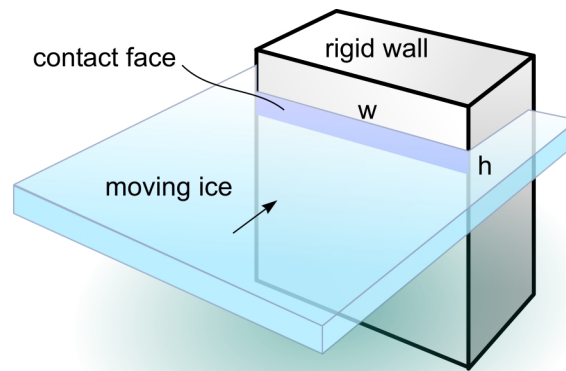


Figure 8.2 Ice load on vertical face

For very slow interactions, in the creep range, an equation of the form of (8.1) may well apply, though for many cases, a biaxial stress state requires that the stress is higher than the uni-axial strength. The increase is 2.97x for ideal Von-Mises plasticity.

When strain rates are in the transition or brittle range, the process changes considerably. In general, the contact force can be expressed as;

$$F = p_{ice} w h \quad (8.2)$$

Where p_{ice} is the effective pressure on the nominal contact area ($w \times h$). The first important ice load model was developed by Korzhavin (1962). Korzhavin studied the effect of the shape of the indenter and noticed that it had a significant effect. He studied flat, round, and wedge shaped indenters as shown in Figure 8.3. He observed the following:

- The shape of the crushed zone depends on the shape of the indenter.
(larger for flat indenters, vanishes for $2\alpha = 60^\circ$),
- Ice pressure varies irregularly, dropping with formation of cracks
- Generally, the process is brittle

- Suggested shape factors ($m=1$ for flat, $m=0.9$ for circular, $m = 0.85 \sqrt{\sin \alpha}$ for $2\alpha = 60^\circ$ to 120°) for wedge shaped structures.

He observed time-histories of the forms shown in Figure 8.4. Korzhavin proposed the equation;

$$p_{ice} = I m k \sigma_c \quad (8.3)$$

Where

I - indentation (confinement) factor, say 2.5 – 3.0 for narrow indenters

m - shape factor (above)

k - contact factor (starts at 1 for full contact and drops to .6 with loss of contact for spalling)

σ_c – uniaxial crushing strength

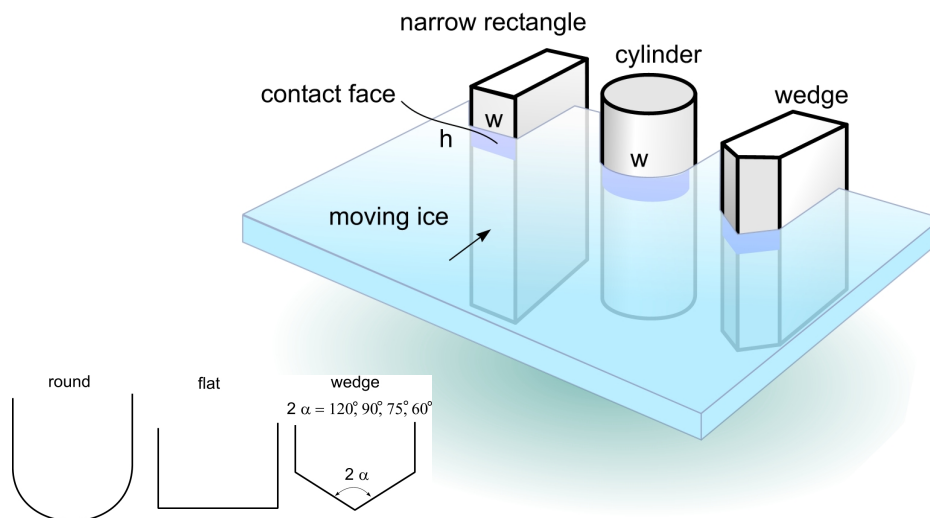


Figure 8.3 Ice indenter shapes

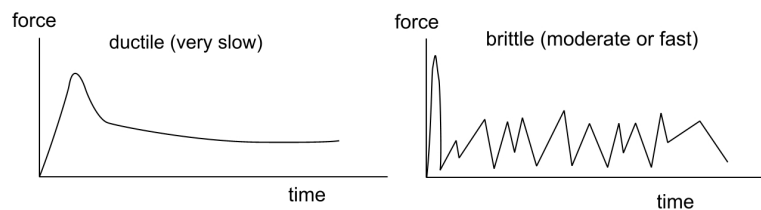


Figure 8.4 Ice indentation time-histories

Saeki et.al. (1978) conducted a series of slow speed indentation tests in sea ice and plotted the data as shown in Figure 10.5.

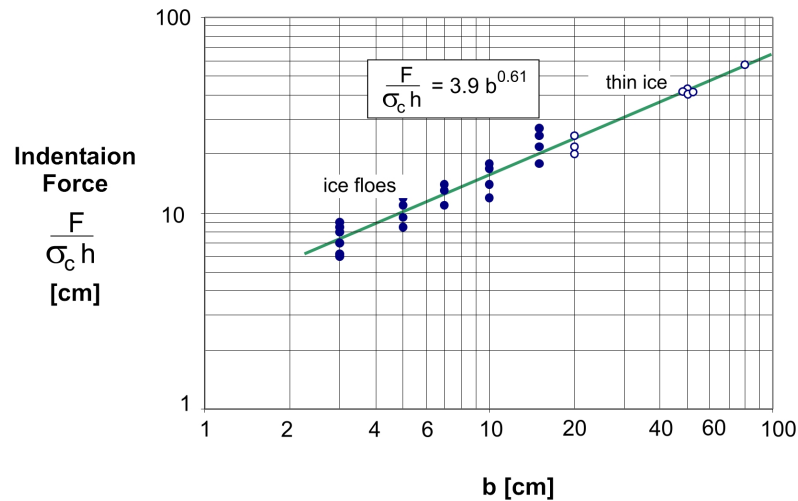


Figure 8.5 Ice indentation with flat indenter in sea ice

Saeki's force equation can be converted to show that effective pressure decreases with contact width;

$$\bar{p} = \frac{F}{b h} = 3.9 \sigma_c b^{-.39} \quad (8.4)$$

This is one of the first expressions that ice pressure depended on size of contact.

8.3 Limit Load Concept

The basic Korzhavin model is an empirical description of the factors that affect the crushing pressure. Developing this pressure requires that the ice does not fail in some other way first.

The maximum ice force on a structure can be governed by several different factors with local crushing only one. Croasdale [1984, OTC] described a number of different factors that limit the total force on a stationary offshore structure;

Limit stress: This is the case where local contact pressure on the structure reaches a maximum (e.g. crushing) and this sets a limit on the total force. There are several local failure modes that would also fall into the "limit stress" category: creep, buckling, rubble formation (ridge formation) as well as 'crushing'.

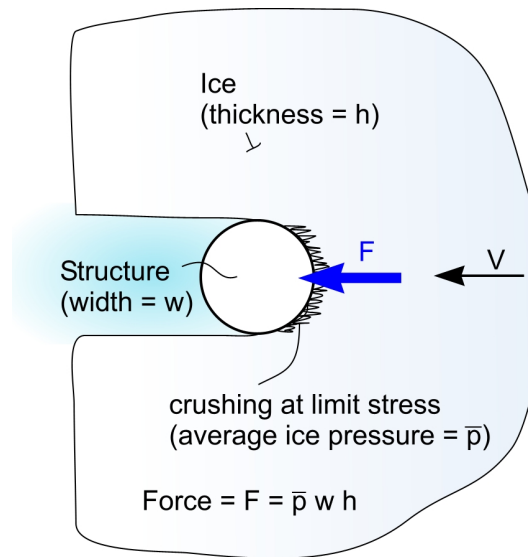


Figure 8.6 Sketch of limit-stress condition.

Limit force: This is the case where the total force that can be transmitted to the structure is less than the limit stress (local crushing) force. This is the result of failure in the ice sheet, remote from the structure, or the result of limited environmental driving forces. Normally this is caused by the formation of pressure ridges in thinner floes in the ice pack, remote from the structure, or the result of limited environmental driving forces (limited fetch, limited wind or current force).

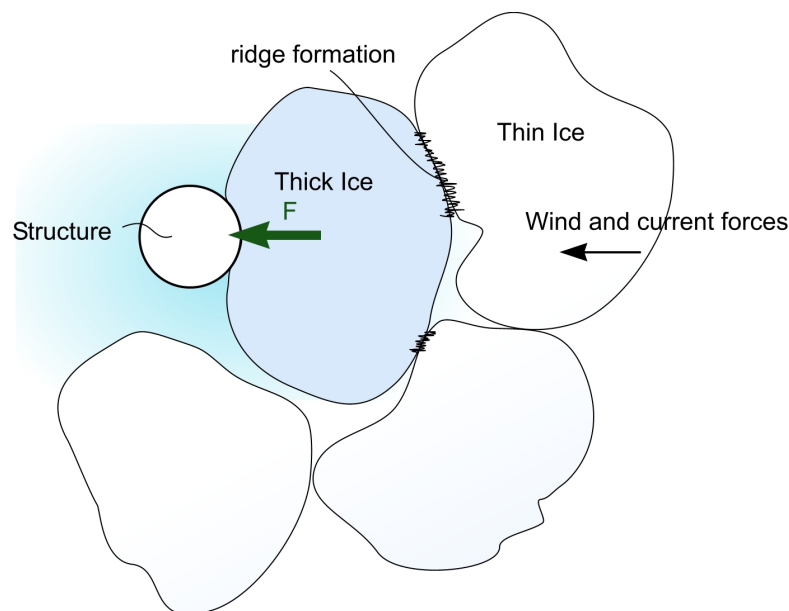


Figure 8.7 Sketch of limit-force condition.

Limit momentum: There are situations where the ice load arises from an impact with a free floating ice floe. The maximum force is limited by the available momentum, which is a product of the mass and the impact velocity.

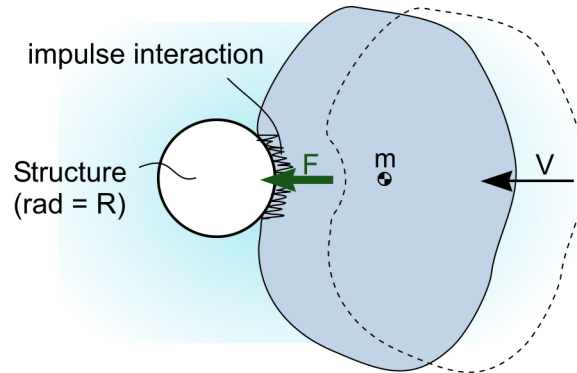


Figure 8.8 Sketch of limit-momentum condition

The force can be determined by equating the kinetic energy of the ice flow (usually all lost in the collision) with the ice crushing energy (indentation energy):

Kinetic energy (KE):

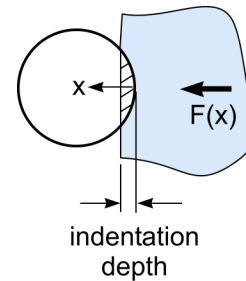
$$KE = \frac{1}{2} m v^2 \quad (\text{for head-on collisions}) \quad (8.5)$$

$$KE = \frac{1}{2} m_e v_n^2 \quad (\text{for oblique collisions}) \quad (8.6)$$

where

m_e is the 'effective' mass

v_n is the 'normal' velocity



Crushing energy (IE):

$$IE = \int_0^x F(x) dx \quad (8.7)$$

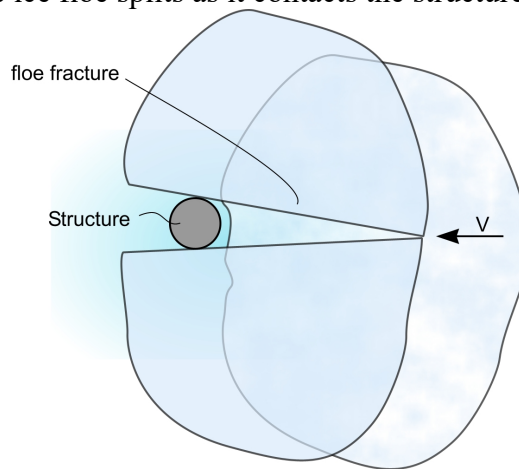
A description of the indentation process is required so that $F(x)$ can be found. A common way to do this is with a 'pressure-area' equation and the shape of the structure (actually the shape of the ice/structure overlap) expressed in terms of $A(x)$, which is contact area as a function of indentation depth.;

$$F(x) = p(A(x)) \cdot A(x) \quad (8.8)$$

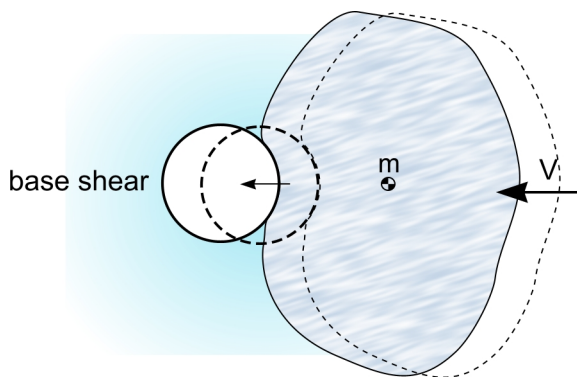
Other limit conditions.

As well as limit stress, force and momentum, there are other situations that can result in a limit to the ice force. These might be considered as other forms of limit force.

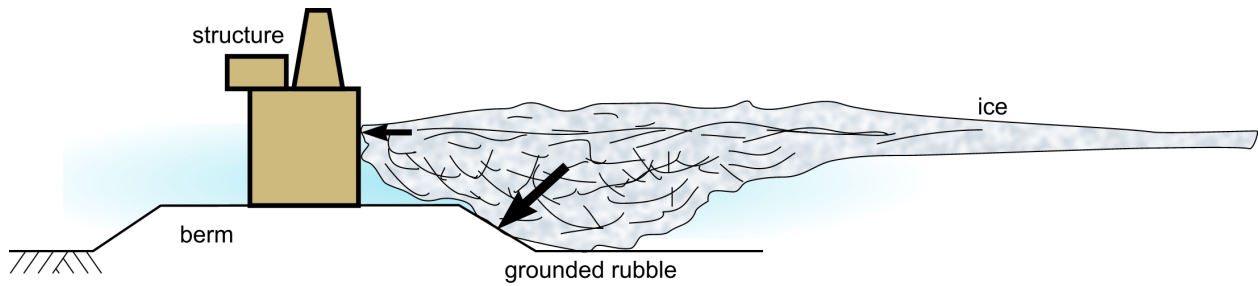
Limit fracture - the ice floe splits as it contacts the structure.



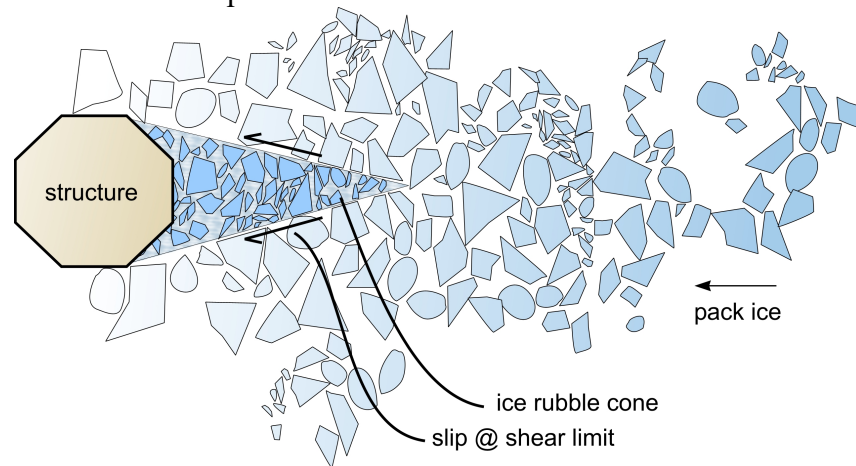
Limit base shear – on bottom founded structures, the base can slide, limiting the ice load.



Ice grounding – the ice force can be limited by the grounding of rubble ice on the underwater berm.



Limit rubble shear – ice forms a rubble cone upstream of a structure. The pack ice moves past the cone and applies a shear force to the ice, which is then transmitted to the structure. In shallow water the rubble cone may be grounded and so further protect the structure.



8.4 Loads on upward sloping structures

Upward sloping structures are used for a variety of applications. Bridge piers can be wedge shaped or conical and tend to be sloped if ice is a concern. As sloped surface forces the ice to fail in bending which generally results in a lower load than cases where the ice fails in crushing. Offshore artificial islands tend to be wide sloping structures. Figure 10.9 shows some examples of upward sloping structures. Bottom founded structures are normally designed to break ice upward, which increases the downward ice forces, and stabilizes the structure. On the other hand, floating structures normally break up downwards, to clear the ice under the structure and raise the structure (ship) out of the water. Sloping structures work by causing flexural failure in the ice.

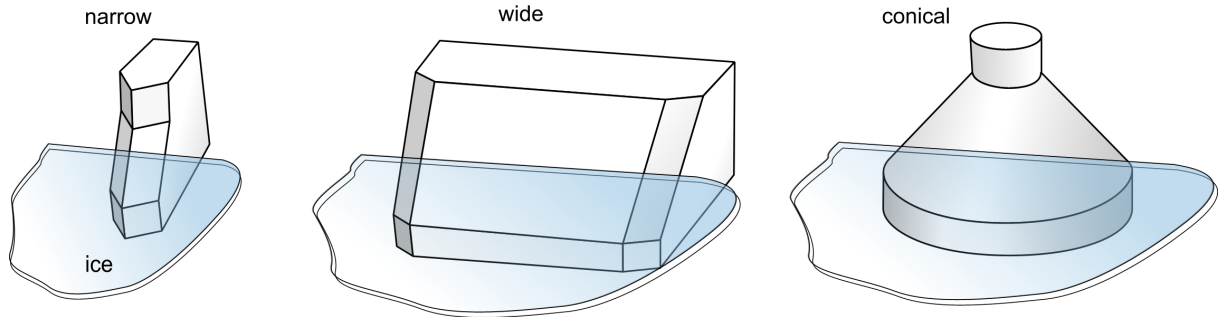


Figure 8.9 Examples of upward sloping structures.

Let's examine the case of a wide sloping structure (Figure 8.10 and Figure 8.11). In such a case, we can consider the interaction 2D and use the equations from section 6.7 (beams on elastic foundations). The ice creates a normal force as it crushes against the slope. A frictional force also develops. The vertical and horizontal forces (per unit width) can be expressed in terms of the normal force;

$$V = N_c(\cos\theta - \mu \sin\theta) \quad (8.9)$$

$$H = N_c(\sin\theta + \mu \cos\theta) \quad (8.10)$$

Combining gives the ratio of horizontal to vertical force;

$$\frac{H}{V} = \frac{\sin\theta + \mu \cos\theta}{\cos\theta - \mu \sin\theta} \quad (8.11)$$

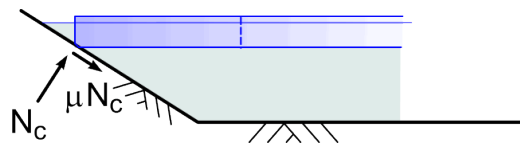


Figure 8.10 First contact between ice and a sloping structure.

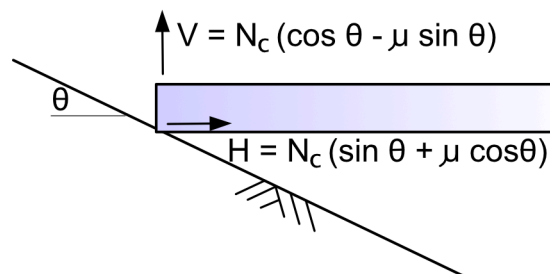


Figure 8.11 Free body diagram of contact on a sloping structure.

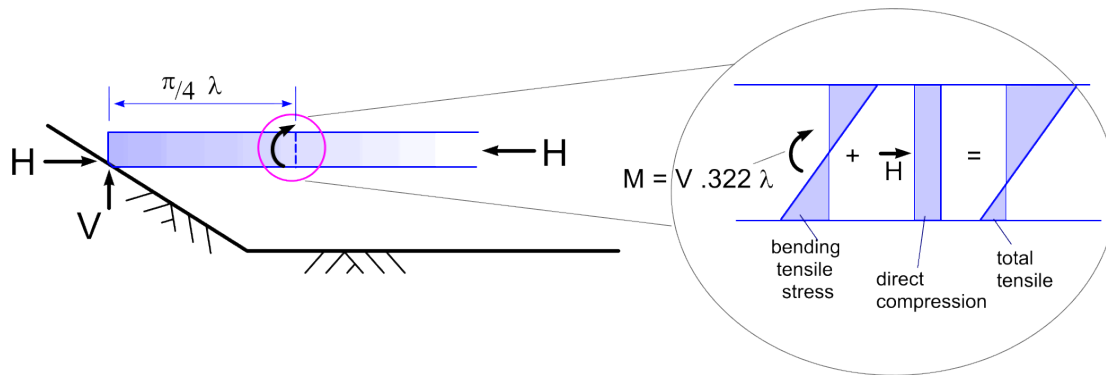


Figure 8.12 Free body diagram of contact on a wide sloping structure.

This ratio is plotted in Figure 8.13 for a range of slopes and friction factors. It is clear that, except for small angles and low friction factors, the horizontal force greatly exceeds the vertical force.

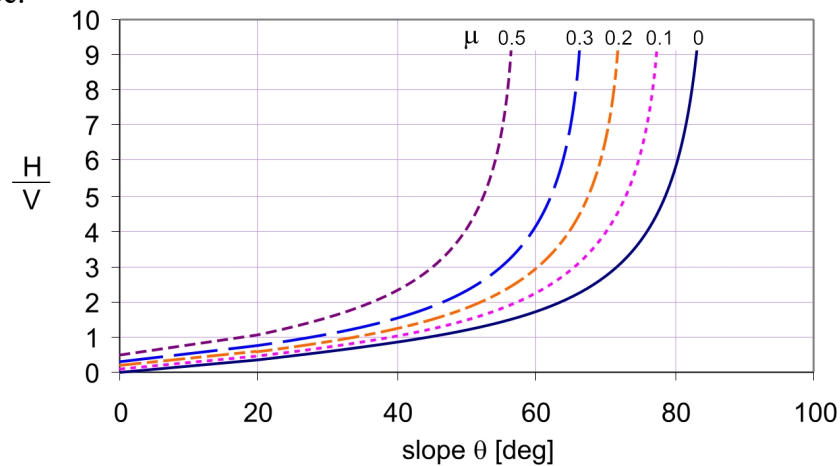


Figure 8.13 Ratio of horizontal to vertical force on sloping structures.

The forces are limited by the load required to cause some form of ice failure. At low slope angles this is likely to be flexural failure. The vertical force causes a tensile stress on the bottom of the ice sheet. The horizontal force compresses the whole sheet, and so decreases the tensile stress. This increases the required vertical force to cause flexural failure.

Refer back to section 6.7. The maximum bending stress is given by equation (6.21) and the distance to the maximum bending (point of fracture) is given by equation (6.18). The flexural stress is found using the standard beam formula, where both M and Z (section modulus) are per unit width of ice;

$$\sigma_{flex} = \frac{M}{Z} \quad (8.12)$$

So, we have;

$$\sigma_{flex} = \frac{0.322 V \lambda}{\frac{1}{6} t^2} \quad (8.13)$$

Referring to Figure 8.12 the tensile stress at the bottom of the ice is;

$$\sigma_t = \sigma_{flex} - \frac{H}{t} \quad (8.14)$$

Combining the above and letting $\lambda = C t^{.75}$ gives;

$$\sigma_t = \frac{V}{t} \left(\frac{1.932 C}{t^{.25}} - \frac{\sin\theta + \mu \cos\theta}{\cos\theta - \mu \sin\theta} \right) \quad (8.15)$$

Note that;

$$C = \left(\frac{E}{3 \rho g} \right)^{.25}$$

With C generally in the range of 22.6 to 24.6 (units are m^{1/4})

Therefore, the vertical, horizontal and normal forces (per unit width), become;

$$V = \frac{\sigma_t t}{\left(\frac{1.932 C}{t^{.25}} - \frac{\sin\theta + \mu \cos\theta}{\cos\theta - \mu \sin\theta} \right)} \quad (8.16)$$

$$H = \frac{\sigma_t t}{\left(\frac{1.932 C \cos\theta - \mu \sin\theta}{t^{.25} \sin\theta + \mu \cos\theta} - 1 \right)} \quad (8.17)$$

$$N_c = \frac{\sigma_t t}{\left(\frac{1.932 C}{t^{.25}} \cdot (\cos\theta - \mu \sin\theta) - (\sin\theta + \mu \cos\theta) \right)} \quad (8.18)$$

A purely vertical load causes failure at a load of;

$$V_{vert} = \frac{\sigma_t t^{1.25}}{1.932 C} \quad (8.19)$$

Figure 8.14 plots the initial normal force per meter, on a wide up-sloping structure. Slopes above 40° tend to have much higher loads. While icebreaking ships are downward breaking, this shows why ship tend to have very low slope angles (25°-35°).

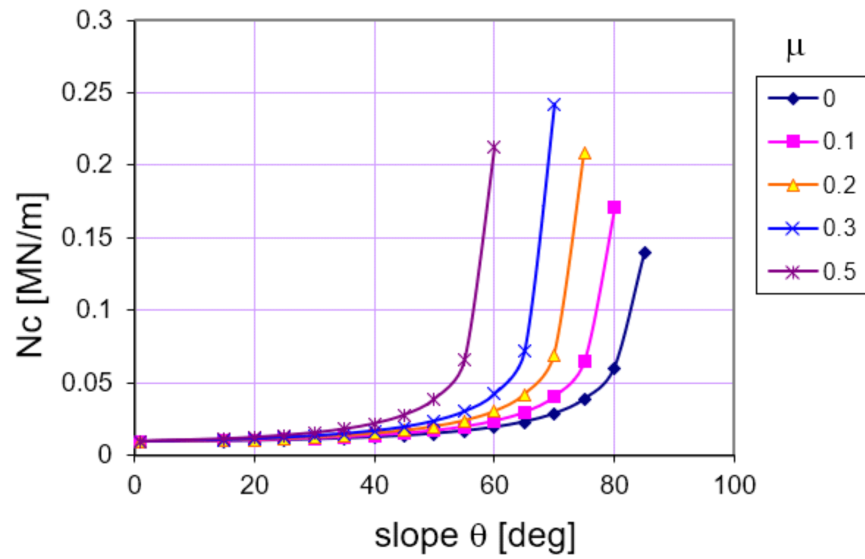


Figure 8.14 Normal force vs. slope for 0.8m sea ice.

After the ice fails as shown in Figure 8.12, a new phase of interaction begins. The broken ice piece is required to slide up the structural face. This is illustrated in Figure 8.15 and Figure 8.16.

The net forces applied to the ice are;

$$V = N_c(\cos\theta - \mu \sin\theta) - W \sin\theta (\sin\theta + \mu \cos\theta) \quad (8.20)$$

$$H = N_c(\sin\theta + \mu \cos\theta) + W \cos\theta (\sin\theta + \mu \cos\theta) \quad (8.21)$$

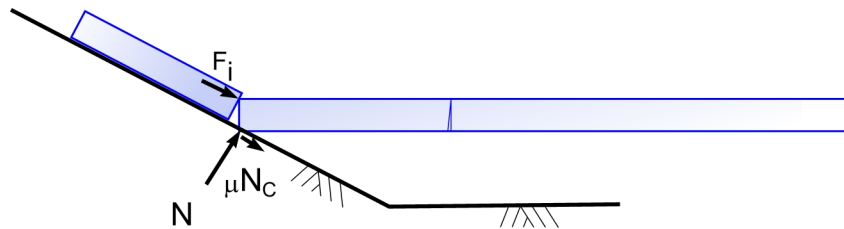


Figure 8.15 Ice sheet pushing block up sloping structure.

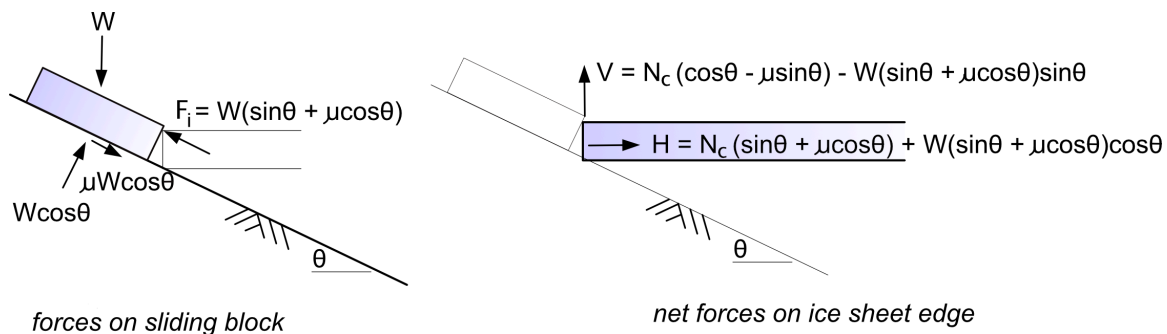


Figure 8.16 Free-body diagrams of ice failure on a sloping structure with sliding ice.

Once ice starts to ride up a sloping structure, a complex process begins, with various results. The ice on the slope loses its buoyancy and so exerts its full weight on the slope, increasing the potential frictional forces. Adfreeze can occur, further increasing the forces. At some point the horizontal loads get high enough to cause crushing, buckling and/or rubbing to occur. Figure 8.17 sketches this sequence. With wide structures the ice continues to build up in front of the structure with no way to clear. Only a change in the ice drift direction can possibly clear the ice. If the rubble is heavily grounded, even a change in the ice drift may not clear the ice rubble.

Figure 8.18 shows a case of an upward cone. Relatively narrow cones allow the ice to ride up and around the cone. While some rubble may form on the leading edge, the ice clears around the cone. This ice clearing is a significant issue. Without clearing, ice rubble can become a significant issue.

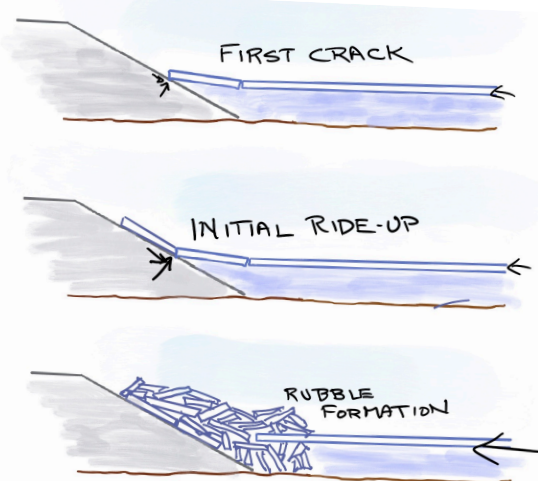
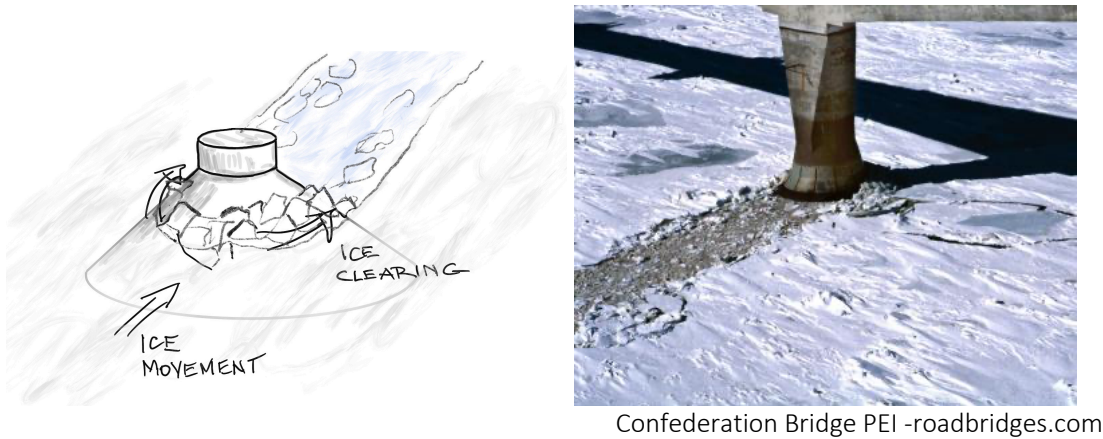


Figure 8.17 Sequence of 2D ice failure on a sloping structure.



Confederation Bridge PEI -roadbridges.com

Figure 8.18 Ice failure and clearing on an upward conical structure.

Ships break ice downwards. The mechanics are similar to upward icebreaking on fixed structures, with the differences being buoyancy, a lubricated interface, and generally higher speed. The icebreaking process on ships is examined in a later Section.

8.5 Ice Induced Structural Vibrations

Ice acting on a fixed structure often gives rise to global and local responses that fluctuate in time. The fluctuation arises because of the cyclic nature of ice failure. The frequency of load fluctuation depends on the mode of ice failure and the speed of the ice interaction with the ship or structure. These speeds of interaction can range from very slow, as ice drifts past a fixed structure, to relatively fast, as a ship breaks ice. In any of these interactions there is a cyclic loading and the potential for a resulting vibration in the structure depending on the speed of interaction, the breaking pattern of the ice, and the natural frequencies in the structure and /or its foundations or moorings.

If vibrations arise from an ice-structure interaction, the responses experienced by the structure are magnified. Even if the vibrations do not damage the structure, the vibrations often create noise that disrupts working conditions on the structure. Long term vibration may, in some extreme cases, be a critical loading condition in the design due to fatigue.

Historically such vibrations have been most evident in light piers and oil production structures. Steady-state vibrations were measured in oil production structures located in Cook Inlet (Blenkarn 1970). Later, the same problem was the subject of four field measurement programs on light piers in the Baltic Sea (Engelbrektson 1977; Määttänen 1978; Nordlund et al. 1988). The issue became much more important when a number of Jacket structures were subject to high levels of ice induced vibration with at least one failure in Bohai Bay in the 1980s. In addition the Molikpaq caisson structure experienced severe events of time-varying ice loading in the Beaufort Sea in March 1986. The evidence shows that all kinds of structures, with varying stiffnesses and frequencies can be subject to ice induced vibrations.

Cyclic Characteristics of Ice Failure Modes

In general ice can fail against a structure in one of three different modes, **crushing**, **buckling or bending**. Each of these modes induces a different type of load cycle. The situation is also complicated by the **strain-rate dependence** of ice failure in that slow speed interactions lead to ductile failures in the ice and high-speed interactions lead to brittle failures in the ice. As a general rule there is less cyclic loading associated with **ductile failures** because the plastic nature of the ice failure results in lower peak loads and a smoother transition from low load levels to failure levels due to the plastic behaviour of the ice. **Brittle failures** on the other hand are more inclined to be cyclic as the load increases rapidly and the consequent fracturing acts to reduce the load.

Ice Failure and Structural Vibration Characteristics

The basic process of ice induced vibrations arises when moving ice-structure interaction results in loading and deformation of both the ice and the structure in either of the modes identified above. Eventual failure of the ice at some finite stress level results in a reduction of the load on the structure. Depending on the speed of the interaction, the spring-back response of the structure may affect a few cycles of damped vibrations at the structural natural frequency. When contact between the structure and the intact ice is re-established, the process repeats itself, as the ice and structure come together again.

Full-scale measurements and laboratory tests have shown that there are differing modes of interaction between an ice sheet and a structure that depend largely on ice conditions and the speed of interaction. Four basic ice failure modes may occur as analysed by Blanchet et al. (1988).

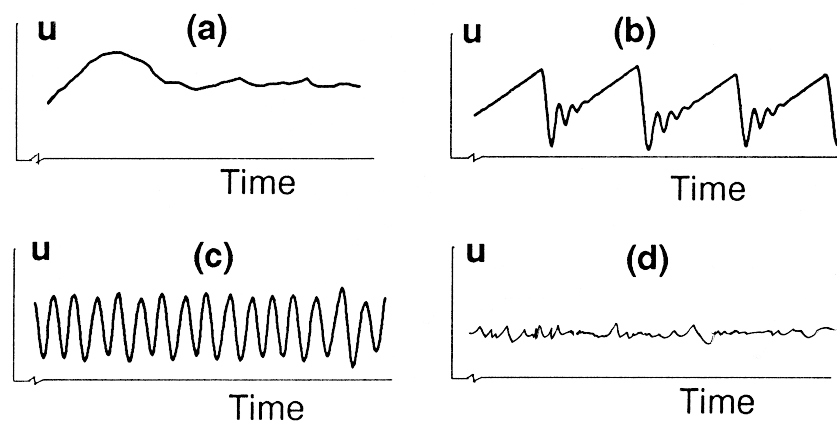


Figure 8.19 Ice interaction excitation modes (Karna 2009)

Considering the structural response at different ice velocities, the following modes of loading arising from ice failure can be identified (Figure 8.19):

(a) Ductile ice failure load characteristic, (at very low ice velocities)

In this case the ice failure is not very cyclic and the cycling happens at a very slow rate. Thus structural vibration is not likely to be excited.

(b) Quasi-static cyclic loading, (at low ice velocities).

Figure 8.19 (b) illustrates conditions where the ice load increases slowly and releases relatively quickly in a regular pattern. Transient vibrations are initiated when the peak ice force is released as part of the cycle. This kind of response is quasi-static because it is not amplified by the dynamics of the structure. Simple static calculations are theoretically sufficient to yield the maximum response to the peak load. However, evaluation of the total peak force is a problem because it can be significantly magnified by the time-varying interaction between the structure and the ice floe.

(c) Steady-state cyclic loading in conditions where the ice fails by crushing and horizontal splitting, (at medium ice velocities)

The relevant feature of steady-state vibrations (Figure 8.19 (c)) is that accelerations occur at almost constant amplitude. The effects of ice forces are magnified by the dynamics of the structure. The time signal is relatively uniform and near sinusoidal.

(d) Random load cycling due to non-simultaneous ice crushing (at high ice velocities)

In this case the ice failure pattern is random and occurring at very high frequencies. The excitation in this case has the appearance of noise and may induce vibrations if the noise signal has appreciable energy in a frequency band that can excite some structural vibration mode.

If we neglect consideration of the extremely low speed first case (a), which does not really cover a case of vibration, we are left with three basic types of vibration arising from ice failure, depending primarily on the speed of the interaction. These descriptions are based on analysis of relatively narrow structures leading to relatively uniform ice behaviour across the face of the structure leading to global excitation of the structural member. For wide structures the excitation may occur in local areas of the structure due to non-simultaneous ice failure across the face of the structure.

Intermittent vibrations: When the relative velocity of the ice sheet/floe is very slow, the force time period is much longer than the structure natural period. In this case, the ice fails simultaneously across the (relatively narrow) width of the structure as the ice forces and responses are synchronized. Ice deforms as a ductile solid or under creep behaviour, and the stress in the ice increases with the deformation of the structure until the deformation of the structure and ice stress reach their maximum at that loading rate. Following failure in the ice the load falls sharply, which induces transient ‘impulse-response’ vibrations in the structure.

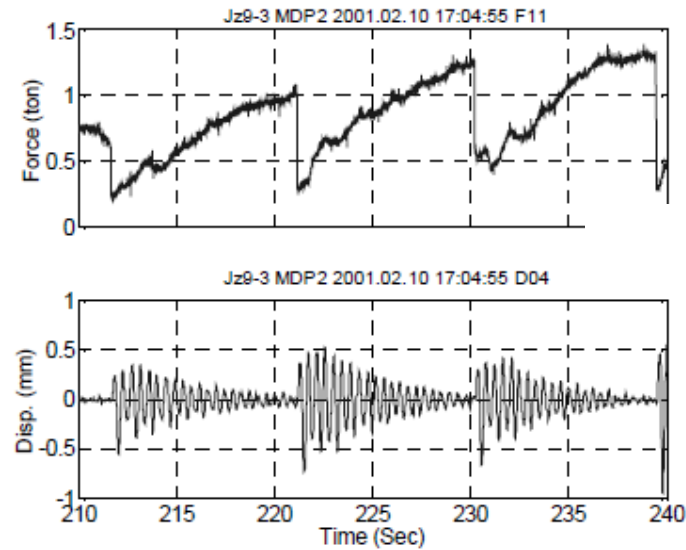


Figure 8.20 Force and Displacement traces for Intermittent Vibrations [Yue et al 2002]

Steady-state vibrations

This type of interaction occurs at slightly higher speeds than the quasi-static vibrations. The amplitudes of responses remain nearly constant in this case. The ice force remains in phase with the structure vibration and usually simultaneous ice failure across the face of the structure is observed. Ice failure mode is usually in the ductile-brittle transition range.

When the ice stress reaches the maximum value, the structure reaches maximum amplitude and starts to return as the ice fails and the load reduces. In this way the ice failure occurs at the same frequency as the structural vibrations and the two mechanisms tend to reinforce each other.

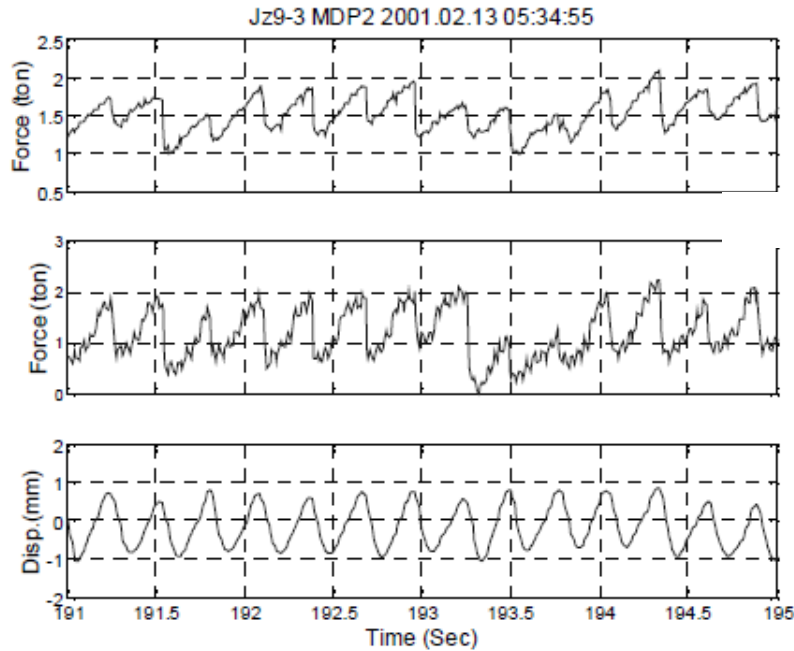


Figure 8.21 Force and Displacement traces for Steady State Vibrations [Yue et al 2002]

Kärnä and Turunen (1990) maintained that the structural response during steady-state vibration can be given by a simple formula:

$$\dot{u}_{ca} = \beta v \quad (8.22)$$

Where:

- $\dot{u}_{ca}$ is the amplitude of the structural velocity at the ice contact,
- v is the ice interaction velocity
- β is a constant factor in the range of 1.0 - 1.4.

The fact that β is equal to or greater than 1 implies that the structural response is magnified for cases where the vibration is steady-state and near the natural frequency of the structure.

Figure 8.22 from the same paper shows experimental results confirming this relationship.

Outside the range of the structural natural frequency the vibration does not occur.

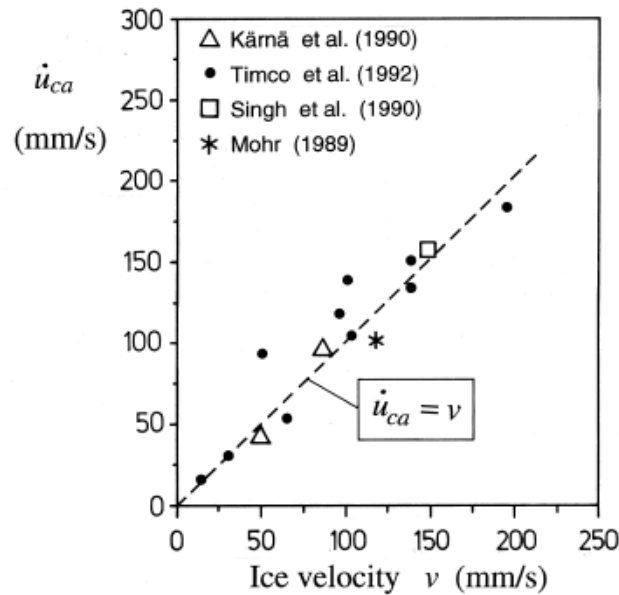


Figure 8.22 Ice Velocity vs structural velocity for Steady State Vibrations [Kärnä 2009]

For steady state vibrations, the structural motion is essentially harmonic vibration and thus the displacement (vibration) amplitude u_{ca} , at the point of ice contact can be approximated by:

$$u_{ca} = \frac{\beta v}{2\pi f_n} \quad (8.23)$$

where: u_{ca} is the vibration amplitude (not the velocity), and
 f_n is the natural frequency of the structural vibration

These equations are only valid for steady-state vibration that arises when the combination of interaction velocity and the failure pattern in the ice excite vibrations at a natural mode in the structure. At lower excitation frequencies the structural response would be quasi-static (covered previously) and there would be no magnification. At higher ice interaction frequencies (covered below) the structure will filter the excitation and will not vibrate at the natural frequency but a higher natural mode of vibration might be triggered.

Random vibrations: These occur at higher interaction speeds. Ice forces in this mode produce a wide band of different frequencies and the forcing function looks like a noise signal. Generally the ice fails in the brittle mode. The breaking period and force amplitude is random. In this case the vibration signal looks like noise and the structure may respond if there is sufficient energy in the noise signal at frequencies close to the natural frequencies of the structure.

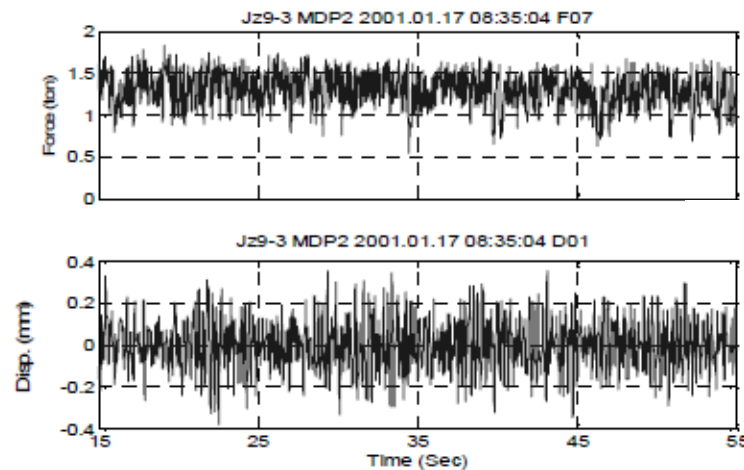


Figure 8.23 Force and Displacement traces for Random Vibrations [Yue et al 2002]

Other features of ice induced vibrations

Vibration Lock-in Some data shows that the steady-state vibration occurs at a frequency, which is 5% to 15% lower than the natural frequency of the structure. This is a form of so-called lock-in where the loading frequency excites a vibration in the structure which then reinforces the failure pattern in the ice. The two phenomena act in concert to give a resonance-like response over a wider range of frequencies than would be evident if we just considered the natural frequency of the structure.

Non-simultaneous Failures on wide structures In general, ice failure may not occur simultaneously across the face of a structure, particularly if the structure is wide. Thus the cyclic loading may be a local phenomenon in such cases. Most of the structures that have been subject to (and studied for) ice-induced vibrations have been relatively narrow structures such as the tubular elements of a jacket structure. In these cases the scale of the ice failure zone is on the same order as the dimensions of the structure and thus the vibration is a global occurrence.

8.6 Ice Crushing Forces and Pressures – History of Developments

It is challenging to design a structure that efficiently and completely breaks ice in flexure. In most cases there is some significant element of ice crushing. In very thick ice, crushing represents the limit process that defines the maximum ice load. Crushing is a complex process and is still not fully understood. What is now well understood is that ice crushing is not a continuous process and is not a simple continuum process. Crushing is a combination of several processes, including elastic contact, damage to the solid, fracture, re-breaking of trapped ice, and extrusion of granular material.

The earliest model of solid-solid contact was the Hertzian elastic contact model (see Figure 8.24a). Of course, this is not a model of crushing, but rather a model of touching. A simple crushing model, as used with soils, is shown in Figure 8.24b. The ice is assumed to be a plastic medium, with slip planes forming to cause the ice to flow. At very slow loading rates (creep) this may be a reasonable model. The first model that explicitly recognized that ice is pulverized when crushed quickly was developed in Russia by Khesin and Kurdymov (Figure 8.24c). Their model postulated the formation of a pulverized layer of approximately uniform thickness, which had to be extruded. The ice was presumed to pulverize along the solid-to-granular boundary as the indenter penetrated the ice. The resulting ice pressures are quite dependent on the mechanics of extruding a granular material between parallel plates. The Khesin-Kurdymov model was the standard model of ice crushing for many years. The experimental evidence for the model was based on ‘ball-drop’ tests, where a steel ball was dropped onto ice. At contact, the accelerations were measured, and the force was estimated ($F=ma$). The model parameters were adjusted to agree with the measurements. The contact was examined and appeared to show a layer of pulverization. The Khesin and Kurdymov model predicted a number of ice load and ice pressure aspects that were not measurable until the 1980s. At that time the model started to unravel.

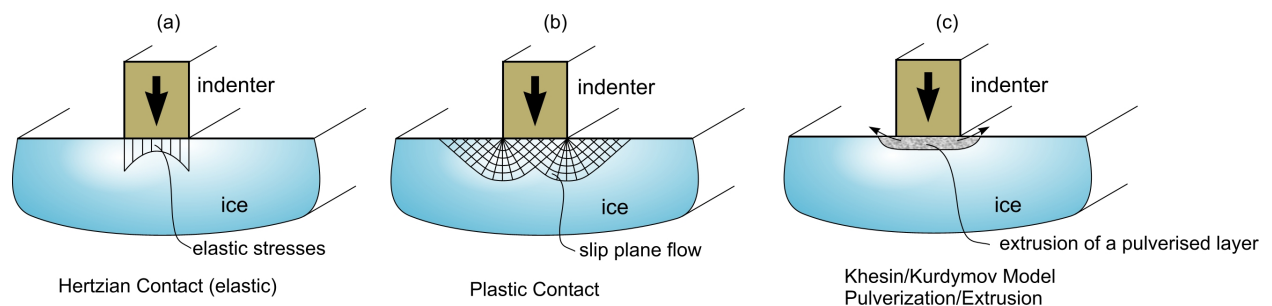


Figure 8.24 Contact Models: a) elastic b) ideal plastic c) Kheysin-Kurdumov extrusion.

In 1977 the Canadian Coast Guard icebreaker *Louis S. St. Laurent* was instrumented with small through-hull pressure sensors. Ice pressures were measured to be as high as 70 MPa, far higher than expected. The data was somewhat ‘spotty’ and left much

uncertainty about what was happening. In 1979/80, The *Canmar Kigoriak* was instrumented with several hull pressure sensors to measure the ice pressures during operations in heavy ice (see Figure 8.25). Rather than seeing the relatively uniform pressures as expected by the Kheysin-Kurdymov model, the pressures were noted to be quite localized (peaky), though none were as high as observed on the *Louis*. The *Kigoriak* pressure data was plotted vs. area and a trend was noticed; the smaller the measurement area, the higher the maximum pressure. This helped explain why the *Louis* data was so high (the areas of the *Louis* pressure sensors were tiny - .0001 m²)

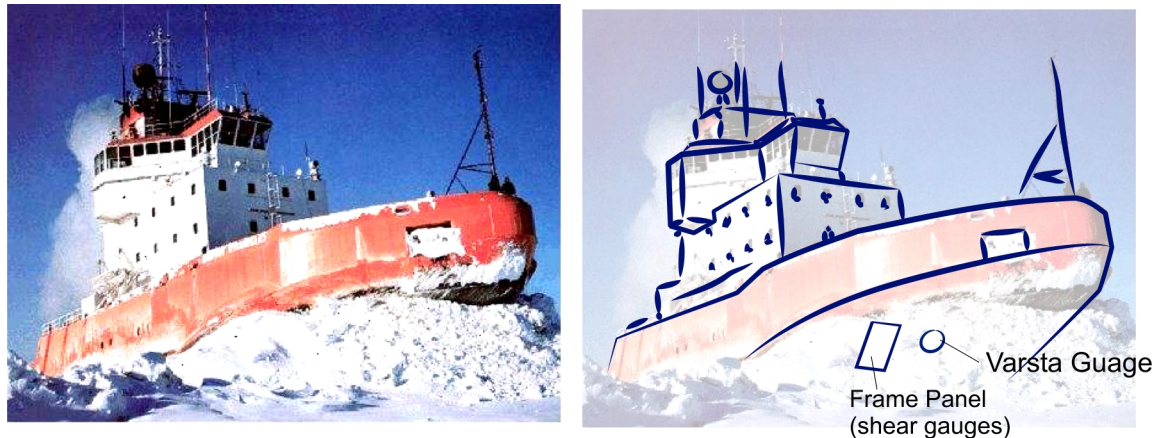
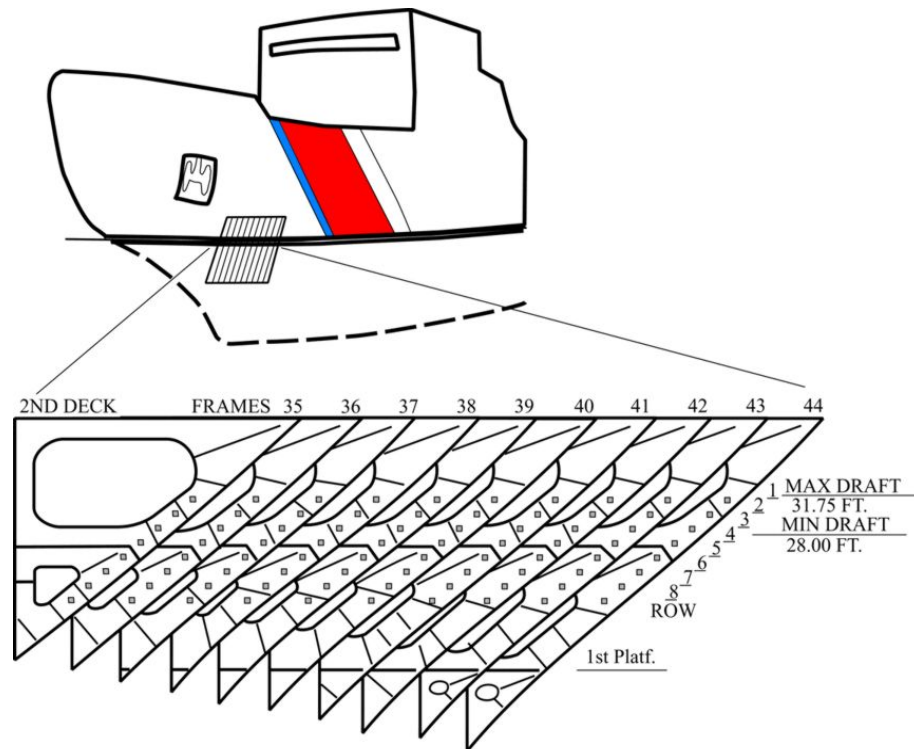


Figure 8.25 *Canmar Kigoriak* Ice Pressure Trials in 1980.

Next came the *USCGC Polar Sea* Measurements. The *Polar Sea* was fitted with a load panel of 9m², with a resolution of 0.15m². (see Figure 8.26) This permitted a good look at the pressures on single plate panels and frames and the whole contact patch. The *Polar Sea* data showed a strong trend of pressure vs. area, with high peaks in the pressures. Unfortunately there was no possibility of seeing how the ice failed in order to understand what was causing the high local pressures. When the data from trials were analyzed, data such as Figure 8.27 were presented. This showed that at every instant, the pressures at smaller areas were greater than average pressures on larger areas. The *Polar Sea* data along with most other available data was compiled and published by Sanderson in 1988, (Figure 8.28) with the speculation that there might be a universal relationship between pressure and area for ice, of the form;

$$P = C \cdot A^{-0.5} \quad (8.24)$$

The C value for heavy polar ice would possibly be in the range of 8MPa according to the Sanderson compilation.



Overview of the instrumented panel on the bow of the USCGC Polar Sea. Strain gage locations are indicated on frame expansion.

Figure 8.26 Instrumentation System on The USCGC Polar Sea

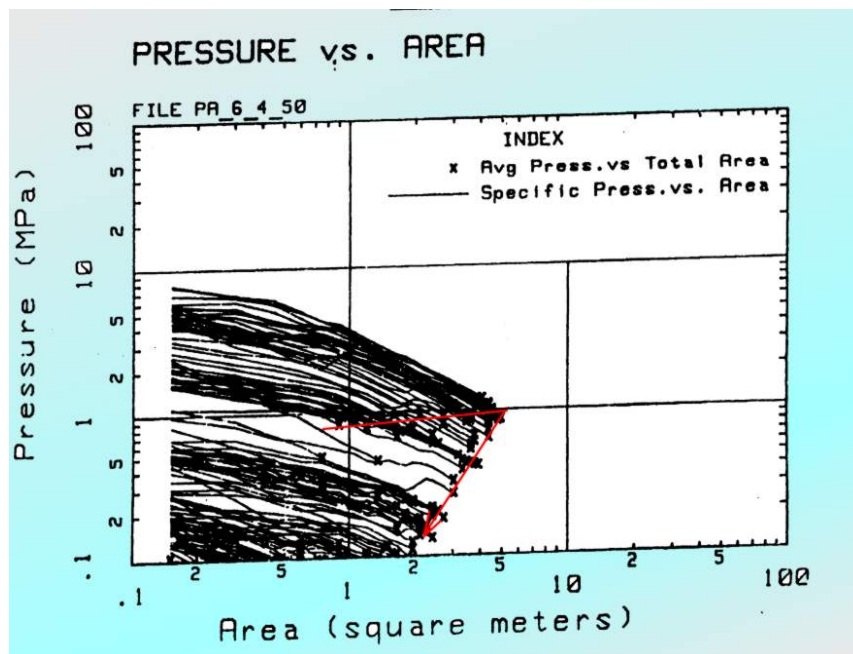


Figure 8.27 Pressure-Area data from one impact on the USCGC Polar Sea (1982)

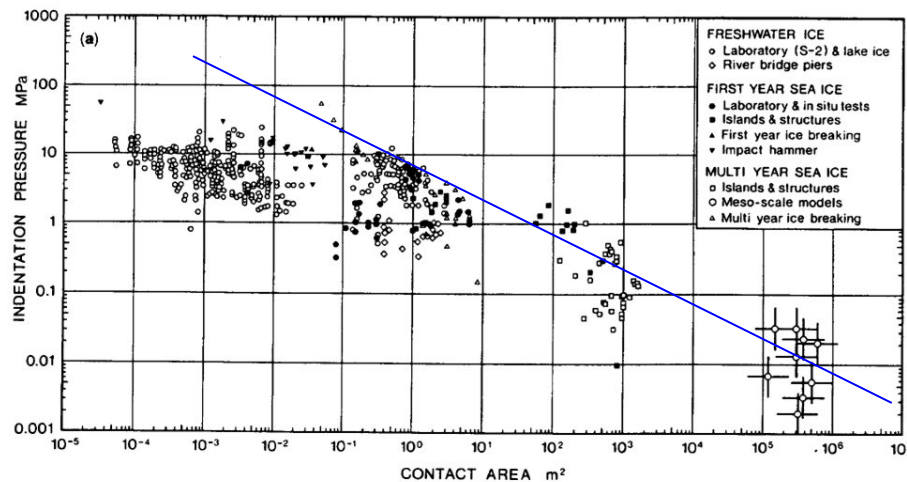


Figure 8.28 Pressure-Area data compiled in Sanderson (1988)

The next significant development in understanding ice crushing process, came in 1988, with test conducted by Joensuu and Riska in Helsinki (at the Wartsila Arctic Research Center). The crushing tests were conducted with a high-resolution force measurement system and a clear indenter (Figure 8.29). Two surprising observations were made. One was that the ice in contact with the indenter was very thin and line-like. The other aspect was that the force record was a series of triangular ‘teeth’ with large load drops and a kind of ‘staircase of small load drops (Figure 8.30). A simple model by Daley (1991) was able to reproduce most of the key aspects of the Riska-Joensuu tests (Figure 8.31 and Figure 8.32) (line of high-pressure contact, pressures area effects, force time history, distribution of crushed ice piece sized and ‘uncertainty’ in the observed values. The Daley model showed that non-linear mechanics explained much of the apparent randomness in the data, where little true randomness existed. The non-linear phenomena tended to produce ‘chaos’ which has some of the appearance of randomness, while being purely deterministic. The Daley (1991) model was simple and did not contain any treatment of extrusion, a behavior that is important in many full-scale situations.

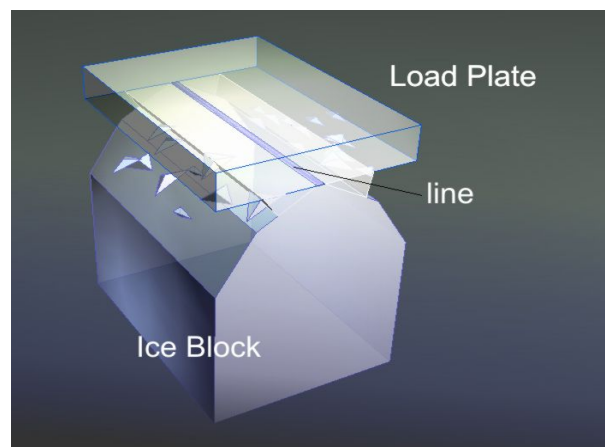


Figure 8.29 Sketch of ice block tests by Riska and Joensuu (1988)

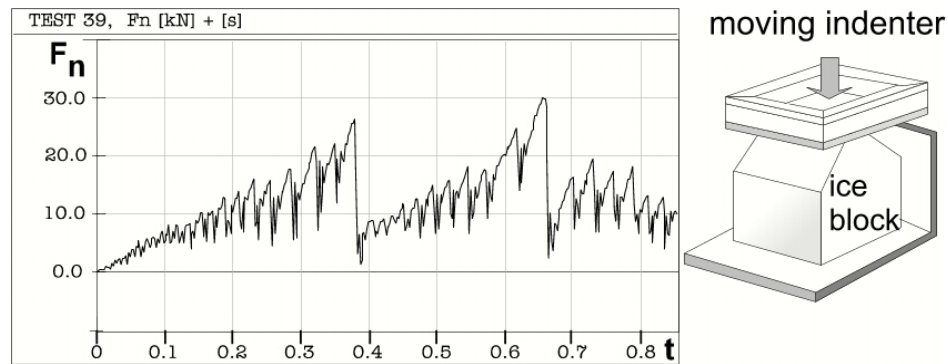


Figure 8.30 Force vs time in ice block tests by Riska and Joensuu (1988)

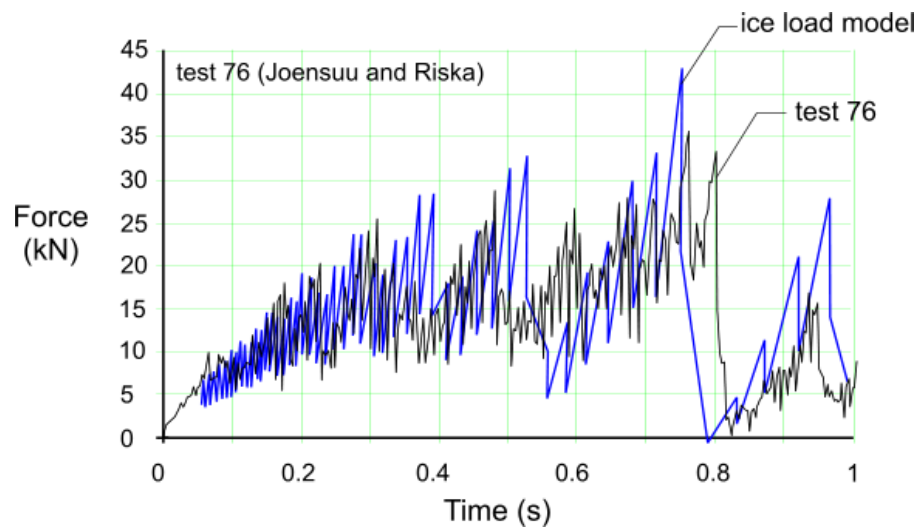


Figure 8.31 Force-time data by Riska and Joensuu compared with model by Daley (1991)

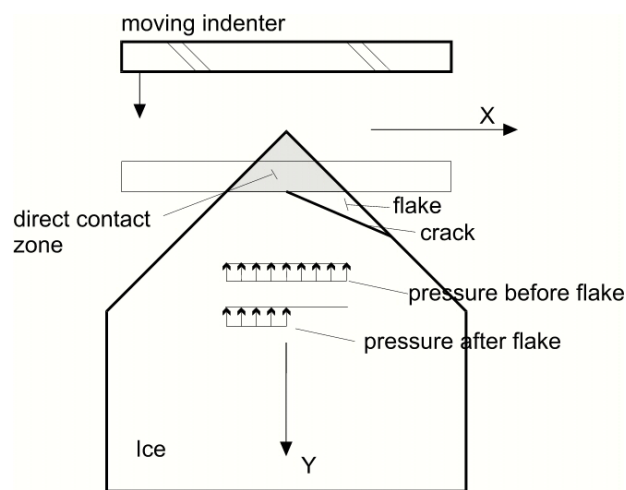


Figure 8.32 Contact model concept by Daley (1991)

The next significant development in the understanding of ice pressure came with the Medium Scale Indenter tests, and the Hobson's Choice Ice Island test in particular. Figure 8.33 shows the general setup of the tests. A large trench (approx 10 x 10 x 100 feet) was excavated in a multi-year ice island. The walls of the trench were prepared and crushed with a large hydraulic indenter system. A variety of shapes were crushed and a variety of force and pressure measurements were made. One significant aspect is shown in Figure 8.34. The crushing showed a pattern of contact that was partly line-like (similar to the Joensuu-Riska tests) but formed more complex branching patterns, in the shapes of Xs, and double-Ys. The central part of the ice was solid (translucent blue) and transmitted very high pressures (up to 70 MPa). These tests confirmed and extended the observations of Joensuu-Riska to large and more realistic ice conditions, though still in a prepared situation.

Another key feature of the tests is shown in Figure 8.35. There are two pressure-area plots from two similar but different tests. The nominal area was increasing in time as the indenter was forced into the ice (crushing a wedge), and the force in the ram was measured. This is therefore also a kind of force vs. time plot. The odd thing is that the various peaks and valleys, seemingly random 'variations', are almost perfectly matched between the two tests. This is likely not a random variation of pressure. The pattern arises from the specific failure (flaking) of the ice edge, and that pattern repeats itself almost perfectly in two tests. This confirms a finding by Daley about the Joensuu-Riska tests, that ice crushing is a sequence of specific failures, non-linear (and thus chaotic) in character, but strongly deterministic. Patterns arising in such cases are not absolutely certain, but neither are they random.

Figure 8.36 summarizes the main aspects of ice crushing. The contact contains a small central zone of direct contact, where the solid ice can transmit very high pressures to the structure. The area of this zone is constantly being adjusted (reduced) by flaking (local cracking) of the ice edge. The ice released by these cracks enters into the crushed ice rubble trapped between the ice and the structure. This rubble is further broken (a process called comminution) as it is extruded to the edges. The rubble layer transmits some stress, but far less than the solid contact. The main effect of the rubble is to apply a confining back-pressure on the ice, which tends to inhibit crack formation (due to compressive stresses at potential crack tips). When the rubble becomes larger, the size of the direct contact and associated force must grow to overcome the confining stresses and crack the ice. As the ice is indented it must fail and move out of the way.

This last point raises the possibility that average pressures may actually have to rise (not fall) as contact areas get large (see end of Figure 8.35). This will be discussed next in a pressure-area description.

HOBSON'S CHOICE INDENTOR TESTS APRIL, 1989

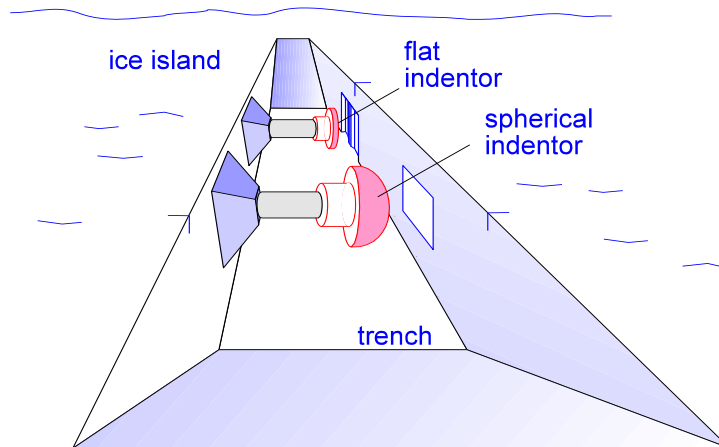


Figure 8.33 Hobson's Choice Ice Tests (1990)

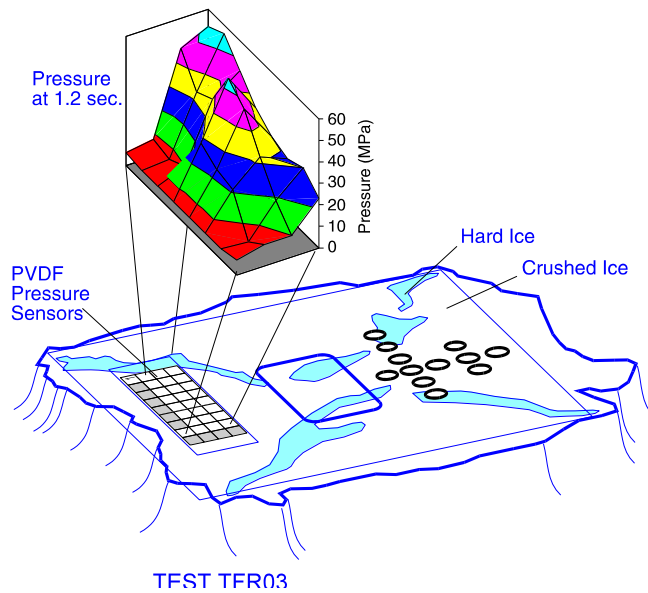


Figure 8.34 Hobson's Choice Ice Pressure Pattern Measurements (1990)

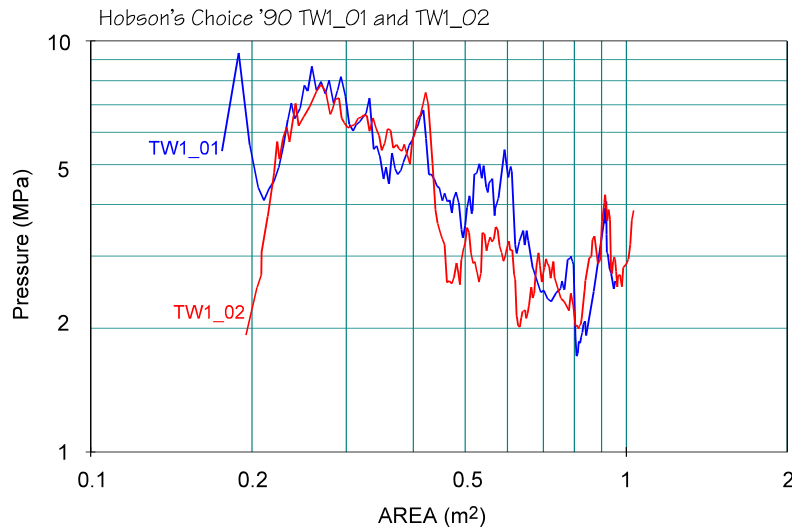


Figure 8.35 Hobson's Choice Ice Pressure Measurements (1990)

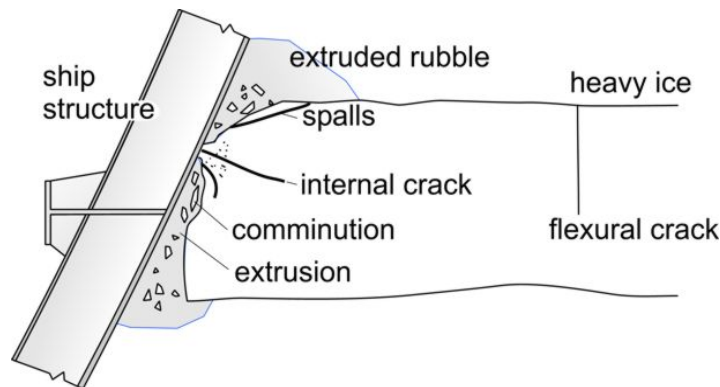


Figure 8.36 Sketch of Key components of ice-structure contact.

8.7 Pressure-Area Data

There are essentially two ways to measure pressure on a structure. These are interior and exterior measurements. Exterior measurements find an average pressure by dividing the total force on the structure by the nominal contact area. The nominal contact area is the area of overlap between the ice and structure. The total force is usually obtained by some form of global (exterior of the contact zone) measurement. Determination of nominal contact area requires the measurement of the ice/structure overlap area. This has only ever been accomplished with precision during indenter tests, where the ice edge was prepared into a known shape, and the indenter movement was measured (e.g. Frederking 1989). Some ships trials, for head-on rams, have attempted to gather such data by integrating acceleration data (Ghoneim 1984).

To determine actual pressures, and the actual contact area, the pressure must be measured directly on the surface of the structure. These are interior measurements (interior of the contact zone). There are many ways to do this, though all involve some form of array of

pressure panels. The resolution of the pressure panels will determine the resolution of the measurements of the surface pressure. Figure 8.37 shows a sketch of three variations of the meaning of the word pressure, and associated area. On the left, ‘nominal pressure’ is defined. If there is an independently measured total force and overlap area (nominal area) of the ice and structure, dividing one by the other will give the nominal pressure. This is a useful value but gives no information on the local pressure distribution. In the central sketch the true pressure distribution is postulated. To observe this, it would be necessary to measure pressure contiguously over the entire surface with high spatial resolution. This type of data is practically non-existent. The right-hand sketch shows the situation normally faced. The pressure has been measured on a rather coarse array and may be subject to noise and other forms of error. Consequently, the coarseness of the array and the data collection/reduction algorithms can influence the estimates of the local pressures. There are always some pressure and areal resolution limits to deal with. These points should be kept in mind when thinking about ice load data.

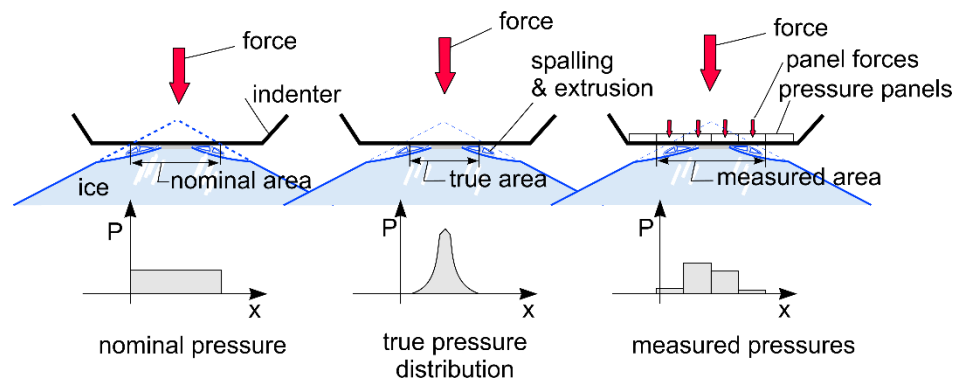


Figure 8.37 Types of areas and pressures related to pressure-area data.

Types of Pressure-Area Data

There are two distinct kinds of pressure-area data. One describes the way that pressure is distributed within the area of the contact zone, termed spatial pressure-area. The other describes how the average pressure within the nominal area changes as the indentation grows, termed process pressure-area. If there were one universal pressure-area relationship (as hypothesized by Sanderson), local ice pressures would only depend on the area over which they act. They would tend to be independent of the total area or the total force. This does not appear to be the case. Local pressures appear to depend on the total contact area. The two kinds of pressure-area data will be described, and then the connection between the two will be discussed.

Spatial Pressure Distribution

The spatial pressure distribution describes the variation of pressure in an ice contact at one instant in time. Figure 8.38 illustrates the idea. The pressure varies within the contact, forming one or more peaks. The highest pressure occurs on a small area at the peak. The average pressure within larger areas will necessarily be smaller than the peak pressure. Average pressures over progressively larger areas (each containing all the smaller areas

and more) will decline. Consequently, spatial pressure-area plots will always show an inverse relationship between pressure and area. Typically, such relationships take the form of equation (8.24). C is typically in the range of 0.5 to 5 MPa and the exponent is typically in the range of -0.25 to -0.7 . The values vary among datasets.

There are several ways to define both pressure and area, and then the meaning can be affected by the measurement procedure. Rarely is it possible to measure with both fine spatial resolution and large areal coverage. As a result, the data tends to be coarse, which may obscure some trends.

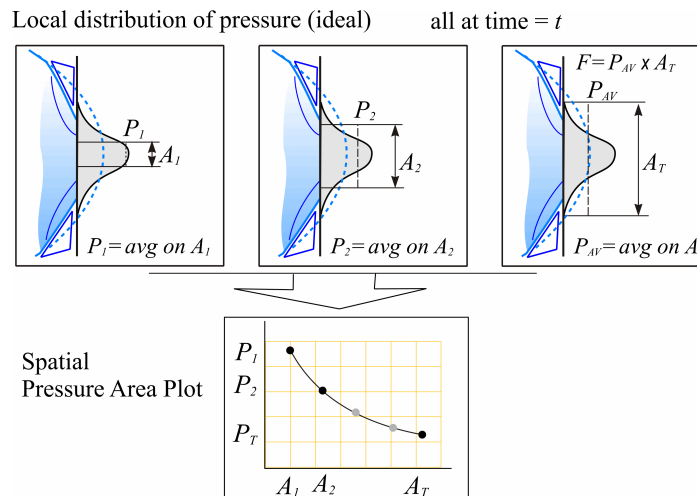


Figure 8.38 Sketch of ice pressure and the meaning of a spatial pressure-area plot.

Process Pressure Distribution

At any instant during an impact, there is a total area, and an average pressure. The product of these two values is the force. Figure 8.39 illustrates the process pressure-area plot, as would be derived from measured data using an array of pressure sensors.

Referring again to Figure 8.39 it is obvious that the measured average pressure on the measured total area is similar to the nominal pressure. In cases where there is no independent measure of both total force and nominal pressure (i.e. no independent measure of penetration distance and geometry), the values as would be estimated in Figure 8.39 are the only way to determine the nominal values.

Nominal pressure-area values are required to extrapolate design forces. This is the case for iceberg-structure collision and many ship-ice collision loads. To date, no field data has both complete coverage with pressure panels, and independent measurement of force and nominal contact. Such a data set would allow force to be determined by two independent measurements. All the extensive data from ships only contain pressure panel measurements. Consequently, there are only 'interior' measurements of the process pressure-area relationship though it would be far preferable to have an exterior measurement for this purpose. It is hoped that future ice load data collection programs

will be able to gather the indentation and ice edge geometry that is required to make exterior process pressure-area measurements.

Figure 8.39 illustrates another point about the process pressure-area relationship. Unlike the spatial pressure-area relationship, there is no a-priori reason for the pressure to fall with increasing area. Factors such as increasing confinement could well lead to increasing average pressures as the interaction proceeds. Most authors have suggested declining trends [Sanderson, 1988], yet some have suggested rising trends [Kheysin et.al. 1973, Ghoneim 1984].

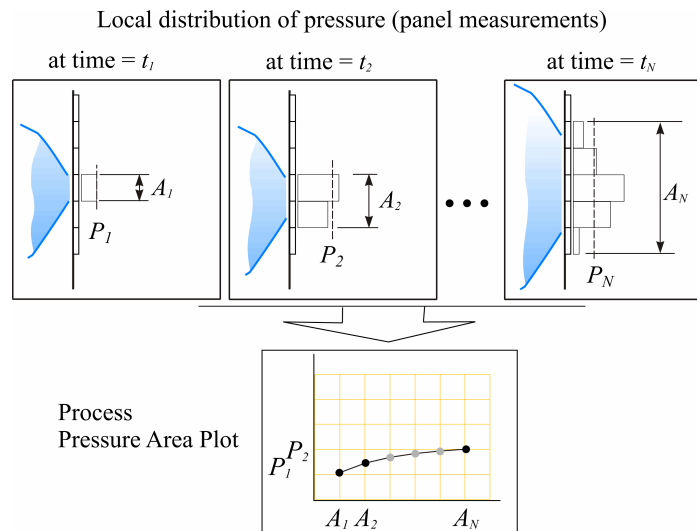


Figure 8.39 Sketch of measured ice pressure data and process pressure-area plots.

Link between Process and Spatial Distributions

The spatial and process pressure area plots are derived from the same data. The process values are just the average pressures over all the active (non-zero) sensors. Figure 8.40 shows both types of data on the same plot. This again illustrates how the spatial pressure area curve can be falling, even as the process curve is rising. Note that the connection between the two types also suggests that higher local pressures will tend to occur with greater total areas and total contact forces. Figure 8.40 is only a concept, not actual data. This concept will be explored through a look at some actual data. First, the Polar Sea data will be re-visited. When the data was first reported in 1984, the idea of separating process and spatial data was not thought of.

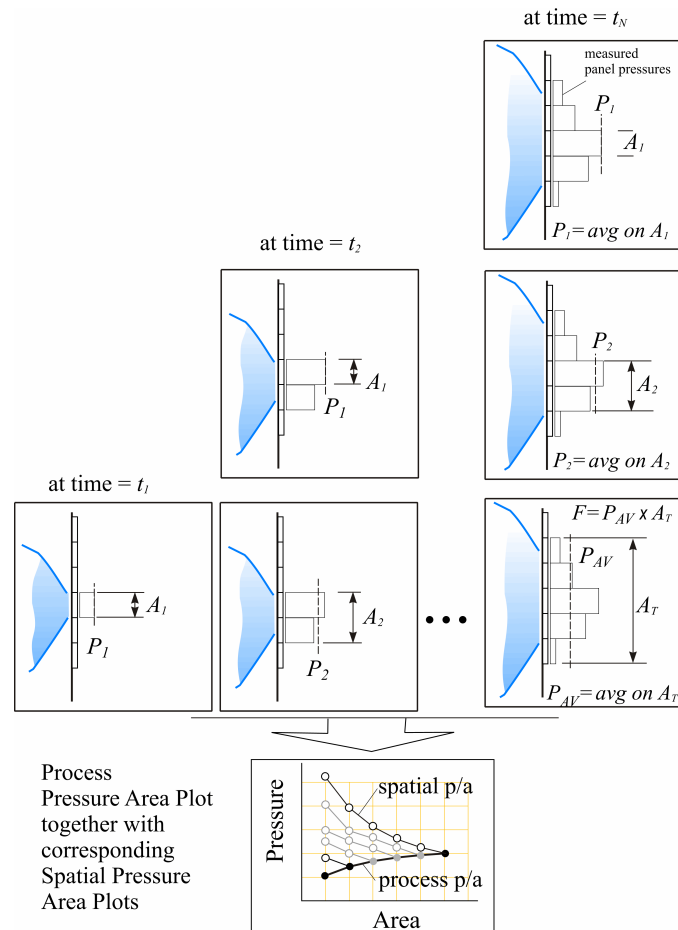


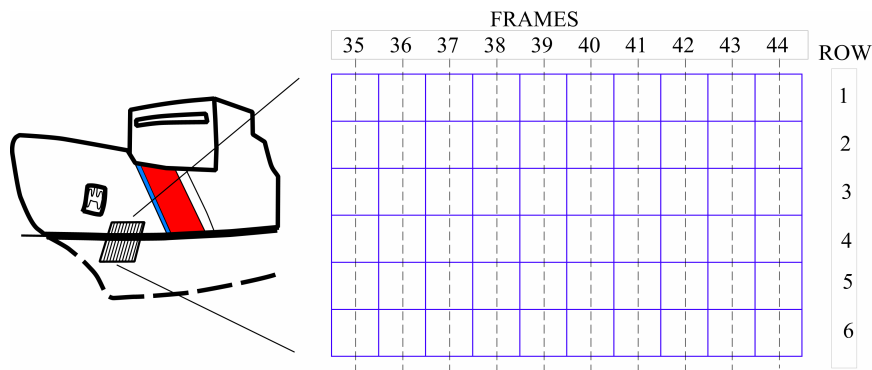
Figure 8.40 Combined spatial and process pressure-area data.

8.8 USCGC Polar Sea Data

Description of the Pressure Measurements

Figure 8.41 shows a sketch of the instrumented portion of the bow of the USCGC Polar Sea [Daley et.al. 1984]. An array of strain gauges was placed on 10 structural frames in the bow of the ship. The location was chosen to give the highest chance of large collisions. Each of ten frames was instrumented with 8 strain rosettes. The primary measurement was compressive strain normal to the shell. The gauges were placed in such a way to give continuous coverage within the panel, and yet be as insensitive as possible to pressures outside the local region. Cross-over effects were removed by the use of a matrix of influence factors derived by finite element analysis. The measurement system was validated by means of a physical calibration.

The panel layout is shown in Figure 8.41. Each sub-panel was 0.152 m^2 , and the total panel covered 9.1 m^2 . The strain gauges were sampled 32 times per second. Each event began when a threshold level of ice pressure was read. Once triggered, the event was sampled for the same amount of time. The event lasted from one second before the trigger to approx. 4 seconds after the trigger. The first trials in the Beaufort Sea in 1982 had a record length of 200 samples (6.25 sec.), while all subsequent trials (e.g. Chukchi Sea 1983) had a record length of 158 samples (4.94 sec). Very few ice load events lasted more than one record.



Layout of the instrumented panel on the bow of the USCGC Polar Sea.
Each sub-panel is centered on a frame.

Figure 8.41 Ice load panel layout on the Polar Sea

Polar Sea Data Reduction

The Polar Sea data, after conversion, is a set of panel pressures. The data was analyzed initially in a number of ways. The force on the panel was found by summing the sub-panel forces (product of pressure and area). Thus, a force time history of the collision could be plotted. Peak force and peak pressures were tabulated for each event. Similar values were found for each row and frame (to be used to assess loads on transverse and longitudinal frames). For each of the events, a spatial pressure-area plot was calculated

for two cases; the time of peak force, and the time of peak pressure. Figure 8.42 shows how the spatial pressure-area plots are calculated.

For this report the data from the Beaufort Sea trials of 1982 and the Chukchi Sea trials of 1983 were re-analyzed. These trials contain mainly collisions with large multi-year ice floes. For a large selection of events, the pressure records were re-analyzed to give spatial pressure-area data for every time step. The highest force events were included. With the spatial pressure-area data at every time step, it was then possible to extract the process pressure-area data, which required the total area and average pressures. The process pressure-area data were divided into two parts. The first part was during rising force, which was presumably while ice penetration occurred. The second part was while the force declined, when presumably the penetration was over and rebound and slide-off occurred. To use the data as a basis for extrapolation to larger collisions, it is reasonable to separate these two types of data. This data is only plotted for that part of the event when the main activity (the main impact) occurred. This further helps to clarify the processes that occur during collision from the general ‘noise’ that occurs before and after.

Spatial Pressure/Area Calculation

Panel Pressures in MPa

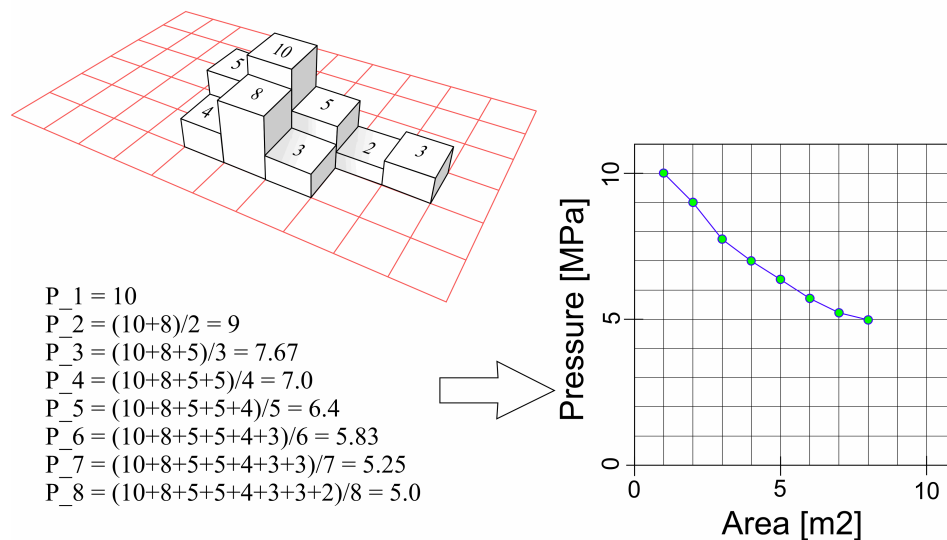


Figure 8.42 Illustrative example of the spatial pressure-area calculation with Polar Sea data.

Polar Sea Data Re-Analysis

The Polar Sea data has been re-analyzed to extract both spatial and process pressure-area curves. In Figure 8.43 the top plot is a set of spatial pressure-area curves during ice penetration phase of the impact, along with the process pressure area curve for that event. As can be seen, the peak pressures (closest to the pressure axis) rise as the whole curve rises, and as the total area rises. The process pressure-area curve is found by joining the ends of the spatial pressure-area curves. The process pressure-area curve rises in both pressure and area. The total force at each step is found from the product of the values of the process curve (pressure x area). The rebound part of the impact is not included as it

serves little purpose here. The four smaller plots below show the various relationships between average pressure, total area, total force and peak pressure. It is apparent that all four of these quantities rise together.

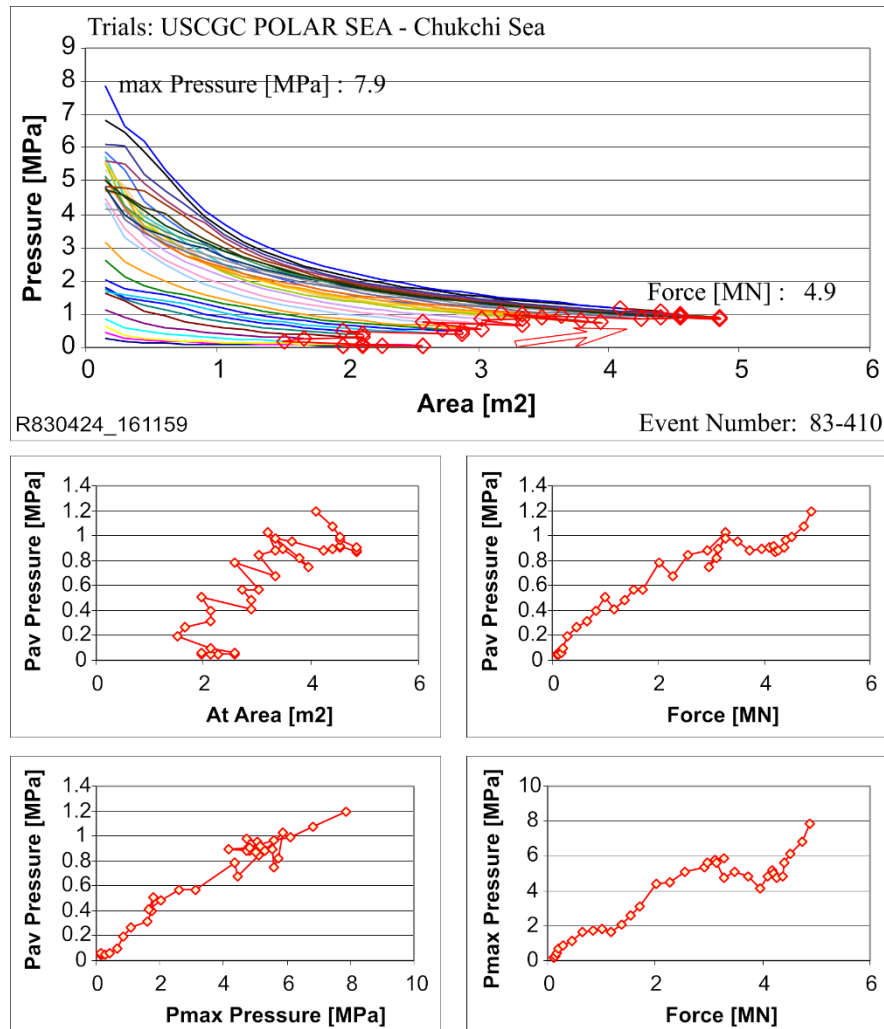


Figure 8.43 Re-analyzed data from event #410. (the highest force event in the 1983 trials).

The plots in Figure 8.44 show the relationships among average pressure, total area, force and peak pressure for the five largest events during both the 1982 and the 1983 trials. All events show similar trends, the most important being that average pressure rises as area and force increase. Similarly, the peak pressure rises as well. Although they follow similar trends, the two data sets do not match. The 1982 data shows higher average pressure. One can only speculate as to the cause of the difference. One cause could be that the two data sets were from different times of the year (Oct. in 1982 and April in 1983). The only odd aspect of this is that the weather was warmer in October and so, presumably, was the ice. Could it be that warmer ice caused higher average pressures? This idea runs counter to the usual trend with ice strength. However, given that the colder ice may have been more brittle (and 'dry' as crushed ice was extruded), it may make

sense that the warmer ice produced higher average pressures. This is a curious result and deserves further attention.

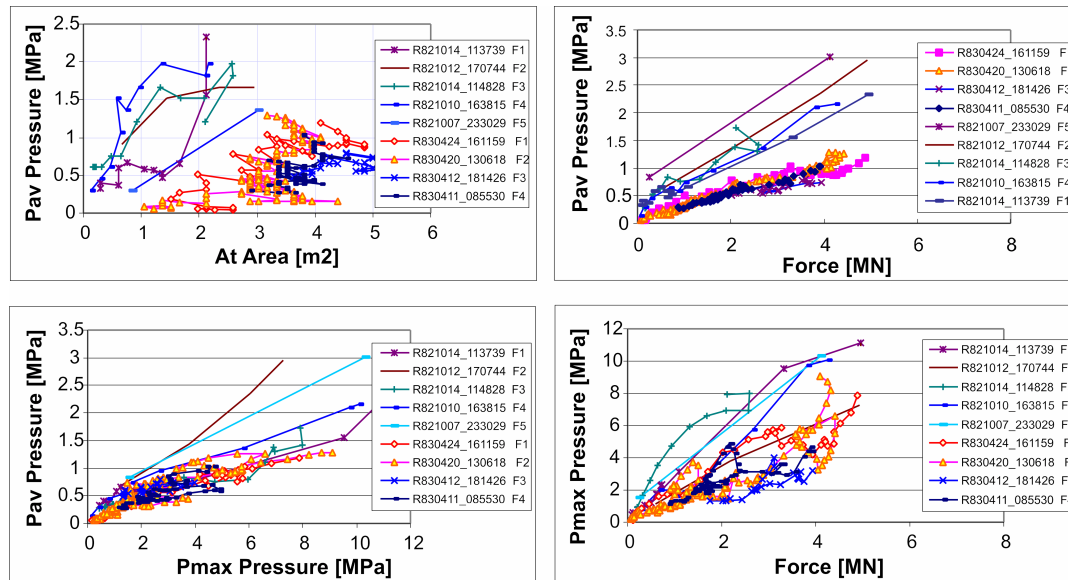


Figure 8.44 Comparison of pressure trend plots for 1982 and 1983 Polar Sea data.

Discussion of POLAR SEA Data

The Polar Sea data has shown some interesting and potentially important trends. When the data from several experiments is all plotted together (e.g. Figure 8.45), the plot appears to show an inverse relationship between pressure and area. This is because the plot is primarily showing the spatial pressure-area relationship. Further, when sets of data are grouped and plotted, an inverse pressure-area relationship is also often seen in the upper envelope of the data. Unfortunately, such a trend is only a reflection of the limited level of force in the various data sets. Pressure and area can never be truly independent variables, because pressure is really force per unit area. A line of constant force with increasing area will appear as an inverse relationship between pressure and area.

Most of the empirical evidence we have for pressure-area trends comes from impact tests of quite limited force. Either the ram has limited force capacity, or the vessel has limited energy/momentum. Consequently, any assemblage of events from a given set of similar experiments will almost certainly be constrained by a level of force. When plotted, such data will necessarily show an envelope with an inverse relationship between pressure and area. Such a trend may be misleading when one is attempting to extrapolate to situations involving larger loads. In effect, our limited experience with large forces is indicating that pressures (and forces) will stay small, but this may not be true. Figure 8.46 [Daley 2004] shows a plot of most available high-quality pressure area data. The cloud to the left of the plot tends to be from the kind of low aspect ratio impacts that are of interest here. An envelope line, often assumed to be highly conservative, is shown. This apparent trend may not be a true indication of the actual pressure in a high force large-scale impact.

The analyses presented above have shown a surprising trend. The average pressure rises as the force and contact area rise during the collision. This is to say that the process pressure-area curves rise, not fall. This is a very significant result. Figure 8.45 shows how some of the process pressure area curves from the Polar Sea compare to the general data. From this it would appear that ice pressure in high force collisions could be well above anything observed to date.

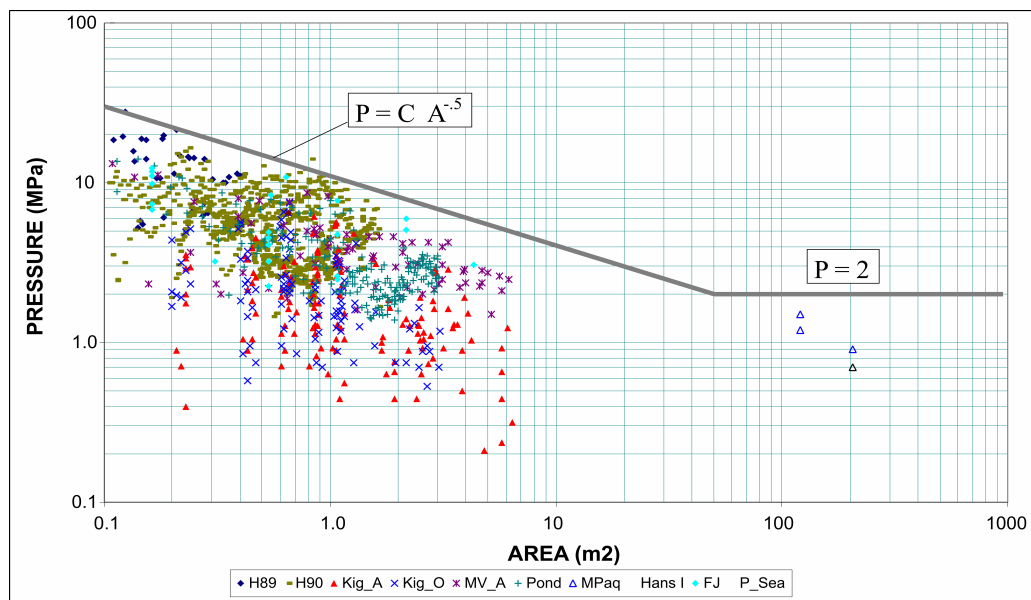


Figure 8.45 Assemblage of measured pressure area data.

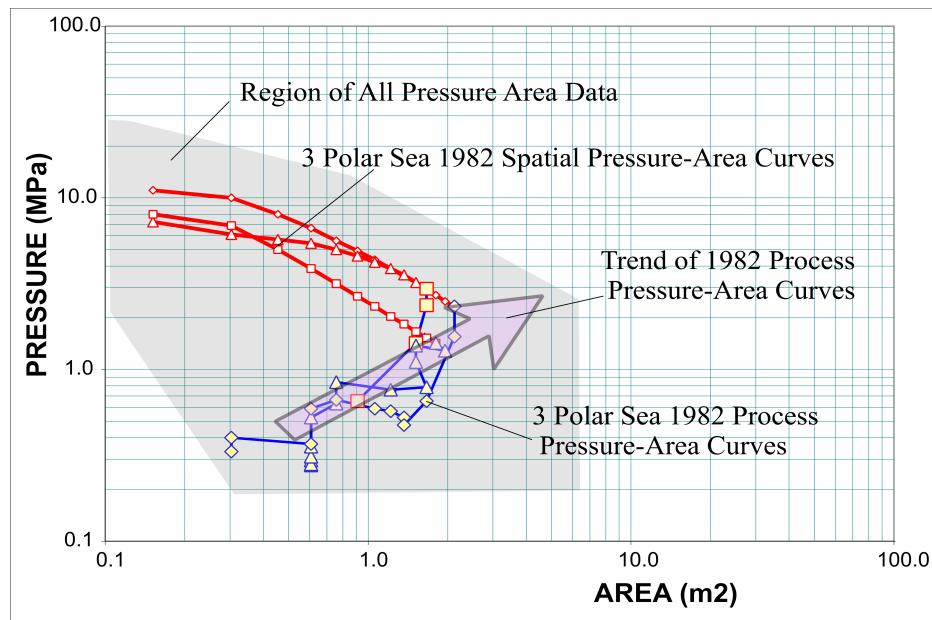


Figure 8.46 Assemblage of Pressure-area data with example spatial and process pressure-area curves from the 1982 Polar Sea trials.

Figure 8.47 illustrates what might happen if one were to extrapolate both the process and spatial pressure area curves up to a collision of 100MN. All pressures would rise, with local pressures being substantially higher than anything measured to date. Two alternative extrapolations are sketched. These are not predictions, but conjectures. If the process and spatial pressure-area curves are connected, then it becomes crucial to establish the precise nature of the link.

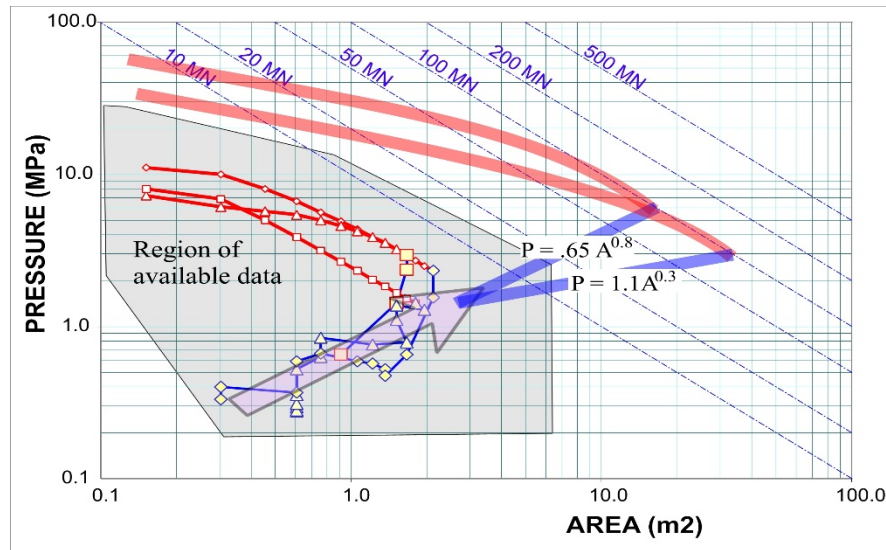


Figure 8.47 Polar Sea pressure-area data with extrapolated spatial and process pressure-area curves (conjecture).

8.9 Other Ice Pressure Data

There are other sources of ice pressure data. The Canadian icebreaker *Louis S. St Laurent*, along with the USCGC *Polar Sea*, made a polar transit in 1994. The ‘*Louis*’ was instrumented to measure ice pressures (Ritch et al. 1999). Figure 8.48 shows one set of time history measurements from the ‘*Louis*’. While this is not shown as a process or spatial pressure area plot, it is obvious that (for most of the record) the average pressure and the local peak pressure are rising together as the impact force increases. This is very much like the *Polar Sea* data. It would be interesting to further analyze the *Louis* data to examine this correlation. This shows the same kind of link among force, local and average pressure variables (i.e. a link between process and spatial pressures).

A very significant set of ice load data was collected in a series of field experiments, generally referred to as the medium scale indentation tests. (see Frederking et al. 1990). In a re-analysis of that data, (Daley 1994) the process pressure-area data was re-examined. These data were collected using a large hydraulic ram, indenting into a prepared ice edge. As such, this data is ideal for extracting process pressure-area data (as well as spatial pressure-area data). Figure 8.49 shows the process pressure-area curves from several ice indentation tests. The ice edge geometry and consequent confinement conditions varied among the tests. There are a number of points to note in the data. For many of the ten tests presented, the process pressure rose after the area exceeded about

0.4 m². Also it can be seen that the data is bounded by a line representing 12 MN (the experimental apparatus capacity). The 12MN boundary tends to look like a declining pressure with increasing area, but represents an experimental artifact rather than an ice property.

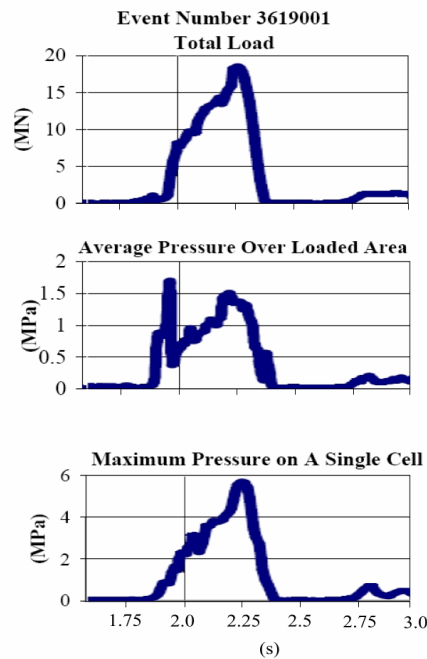


Figure 8.48 Measured pressure data from Louis S. St. Laurent. (Ritch et. al. 1999).

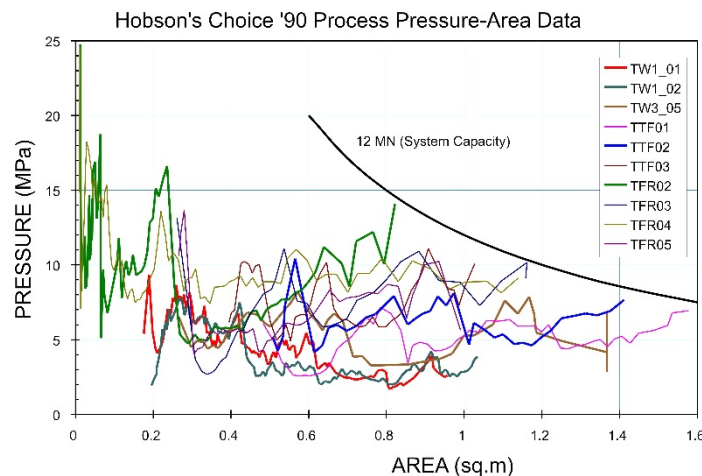


Figure 8.49 Measured process pressure-area data from Hobson's Choice (Daley 1994).

Figure 8.50 (redrawn from Croasdale et al. 2001) represents an analysis of another set of ice indentation tests done in iceberg ice. In this case a rising process pressure-area curve is proposed. The proposed model describes the contact process as being comprised of a

high-pressure region surrounding by a low-pressure region of constant width. As the total contact area and force increases, the average pressure rises because the central high-pressure region is a growing fraction of the total area. While the Croasdale model proposed rising average pressures, the model will necessarily be asymptotic to a line of constant pressure. Another difficulty with this model is that there is no clear link between spatial and process pressure-area models.

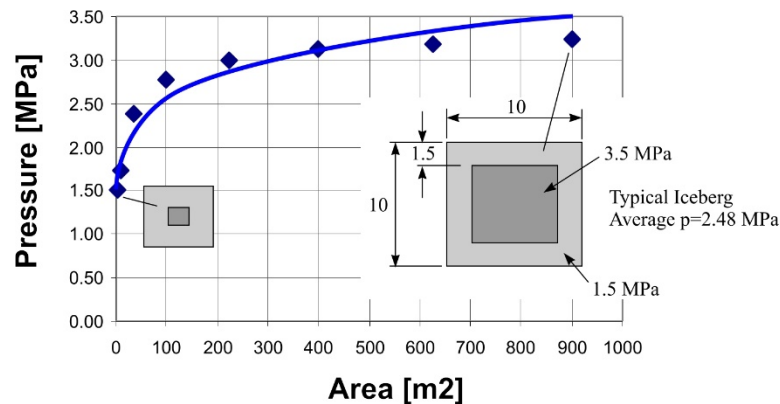


Figure 8.50 Measured/Proposed Global Pressure-Area model based on iceberg tests (Croasdale et.al., 2001).

Figure 8.51 combines Figure 8.45, 8.47 and 8.50, to get a comparative view. The Croasdale suggestion is somewhat like the lower extrapolated pressure area curve shown in Figure 8.47.

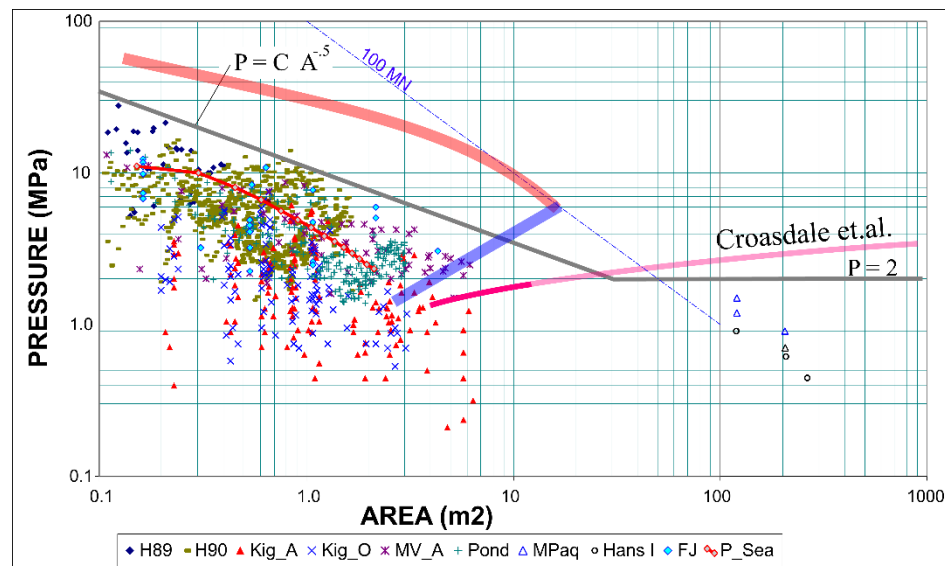
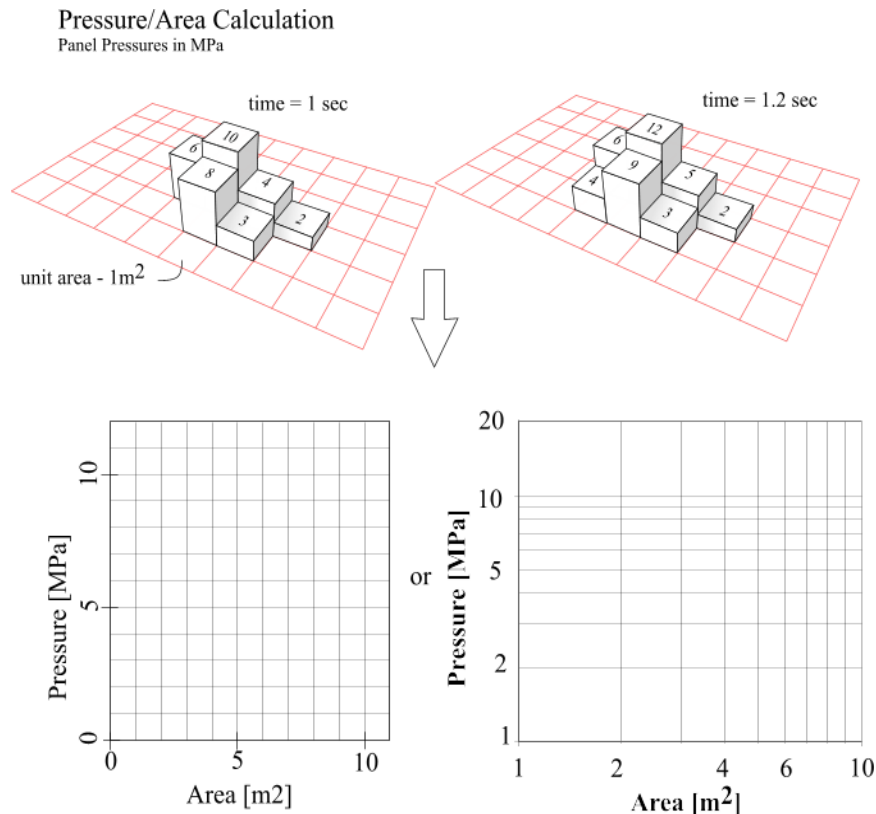


Figure 8.51 Measured/Proposed Global Pressure-Area model based on iceberg tests (multiple sources).

Chapter 8: Problems

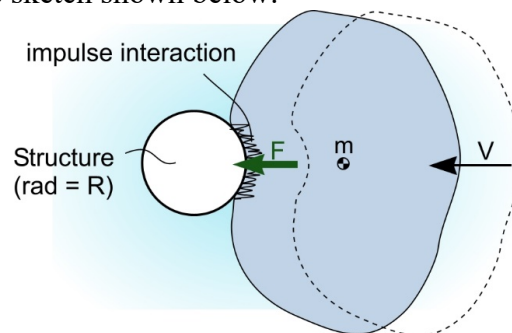
8.1 Explain the differences between ‘spatial’ and ‘process’ pressure-area models.

8.2 For the two measured sets of pressure given below, plot the spatial and process pressure-area curves. What is the equation for the process P/A curve?



8.3 Think of a fixed offshore structure, something like the Hibernia GBS, but sitting in the Beaufort Sea. Discuss how Croasdale’s limit load concepts can be used to help determine the design load.

8.4 The sketch below is associated with a certain type of ‘limit’. Describe the associated concept and label the sketch shown below.



8.5 Discuss Korzhavin's equation (explain its rational, assumptions, significance etc)

8.6 Pressure area

- a) A load panel consists of 42 sensors arranged in a grid of 7x6 sub-panel. Each panel is 0.2 x 0.2 m. Panels measure the average pressure in themselves in MPa. Data from two moments in time is shown below. Compute and plot the spatial and process pressure area curves.
- b) Discuss potential sources of error in this data. What could to improve this data?

At 0.1 sec							
				1			
				2	1		
At 0.3 sec max load							
				1	1		
			4	8	2	1	
				3			

8.7 Ice Indentation

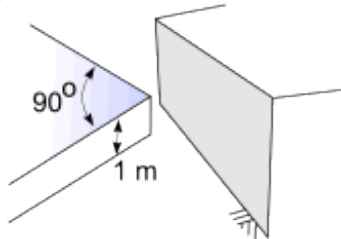
[20]

The sketch below shows a 90 deg ice edge, 1m thick, coming into contact with a solid wall. Assuming that the ice crushing can be described with a process pressure-area relation of;

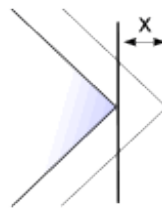
$$P_{av} = P_o A^{-0.1}, P_o = 2 \text{ MPa}$$

Find the contact Area, Force and crushing energy, all as functions of the penetration depth x .

oblique view



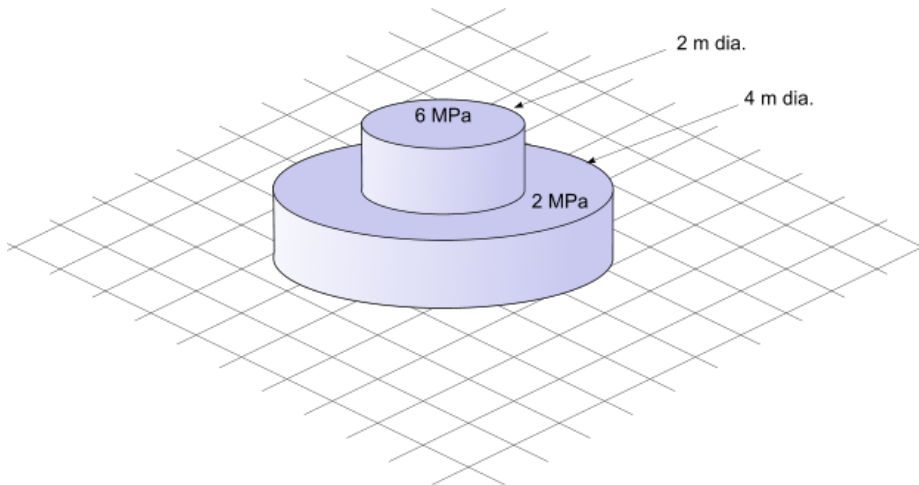
top view



8.8. Pressure Area

A load patch consists of a circular region of 6 MPa surrounded by a larger region of 2 MPa.

- Sketch the spatial pressure-area curve for this load.
- what would be the spatial pressure-area curve for a point load (over the area range of 0 – 10 m²)



8.9 Consider a large sheet of 1m level ice moving towards a wide sloping island.

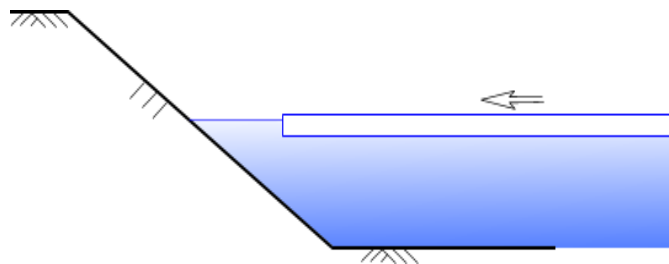
What will happen when the ice strikes the island and moves one meter?

What happens when the ice moves 20m?

What happens when the ice moves 1km?

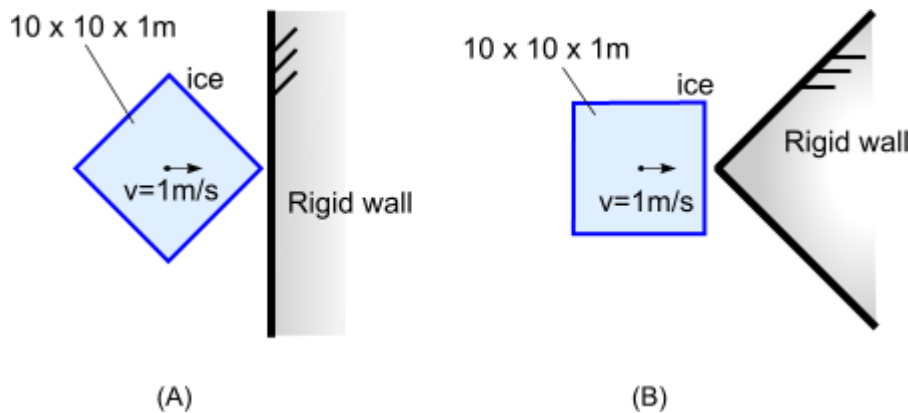
Use words and sketches to communicate your answer.

[20]



8.10 Consider the two cases of ice-structure impact (A and B). The geometry of the two cases is very similar. In both cases an ice indentation of 1m would result in a nominal contact shape that would be 2m wide and 1 m high.

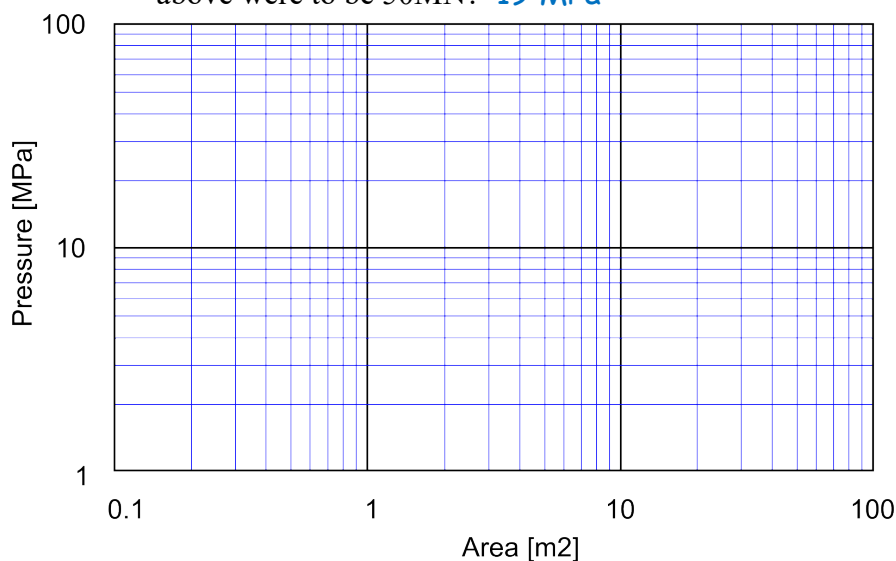
- Explain how you would solve these scenarios to get the max. collision force.
- Explain why the two scenarios would give the same result (e.g. what assumptions in the solution would cause the results to be the same?).
- Discuss why the real scenarios might have different results.



8.11 Pressure area Curves.

Consider a design problem involving icebergs and rigid offshore structures. Assuming that the collision process can be modeled with a “process” pressure-area curve of the form $P_p = 2 A^{-2}$, and that the local pressures are modeled with a “spatial” pressure-area curve of the form $P_s = C A^{-4}$. Assume that the two curves are connected, meaning that the (right hand) ends of both curves are at the same spot.

- Plot the process pressure-area curve,
- Plot the point (pressure and area) on the process pressure-area curve that corresponds to a force of 15MN at $P=2.8 \text{ MPa}$, $A= 5.36 \text{ m}^2$
- Find the value of C for a spatial pressure-area curve so that the right hand end of the spatial curve meets the process curve at the 15MN spot. $C = 5.48$
- What is the predicted local pressure (from the spatial pressure-area curve) at an area of 0.2m^2 ? 10.4 MPa
- What would the local pressure (as found in ‘d’ above) become if the force in ‘c’ above were to be 50MN? 19 MPa



9 Ship-ice interactions

9.1 Introduction

Ships are the primary vehicles used in ice-covered waters. There are other alternatives, for example: helicopters, hovercraft, wheeled and tracked vehicles, and other concepts including submarines and Archimedean Screw Tractors (ASTs), but ships have proven to be the most reliable and economical vehicles for dealing with floating ice. Some of the usual forms of icebreakers and the evolution of design ideas are illustrated in Figure 9.1 and Figure 9.2. It was understood early that icegoing ships needed to have more bow flare to push the ice down and away. The 'White' bow (named for Lt. White of the USCG, who developed a form intended to minimize ice resistance) is typical of many icebreakers built in the 1960s and 70s. The spoon bow form is easier to build (single curvature in the shell) and is intended for very heavy ice. The various landing craft forms are intended to cut a very clean channel for following ships. The '2nd Generation Beaufort' shape is typical of many current designs and combines benefits of the spoon and traditional form, and is good for heavy ice, and is also acceptable when operating in open water, as icebreakers must do for much of the time.

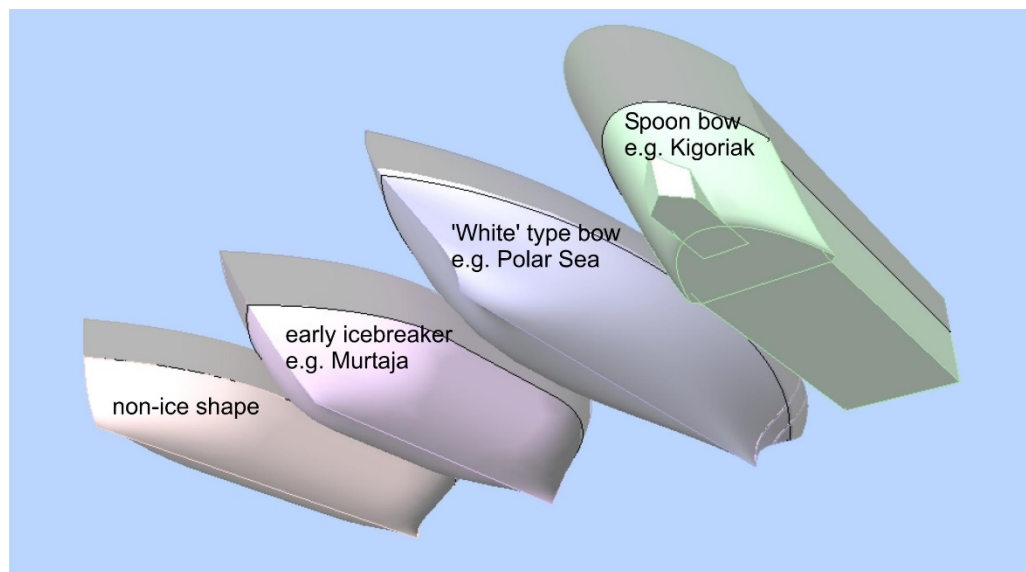


Figure 9.1 Evolution of icebreaking ship forms - 1.

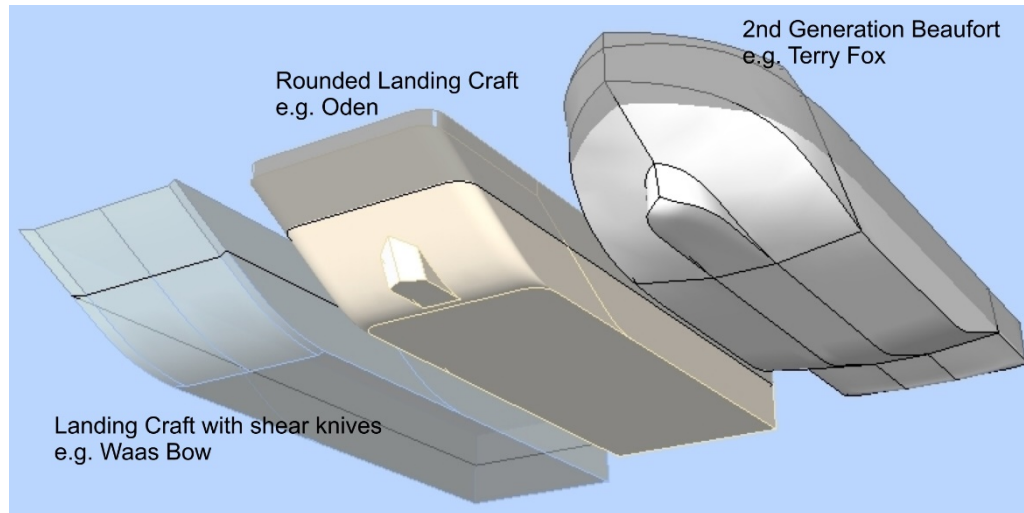


Figure 9.2 Evolution of icebreaking ship forms -2.

9.2 Vessel operations

Ice conditions vary widely. In some circumstances the ice is widely separated and the vessel is essentially operating in open water (see Figure 9.3). In such cases, detection of the ice is the key concern. Ships would prefer to travel at high speed, but will slow down to a speed that reflects the risk of ice collision. If there is contact with ice, the loads can be modeled as a simple collision, with just two bodies involved. This type of collision is modeled using Popov assumptions.

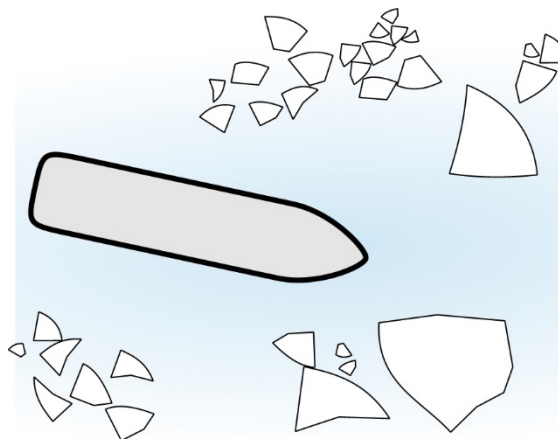


Figure 9.3 A ship in open pack ice (1/10).

As the ice gets more concentrated, the ship must contact multiple ice floes simultaneously (Figure 9.4). When a single floe is contacted and pushed, it pushes on neighboring ice. Modeling resistance in this situation is complicated by the many parameters (floe shape, size, distribution, thickness).

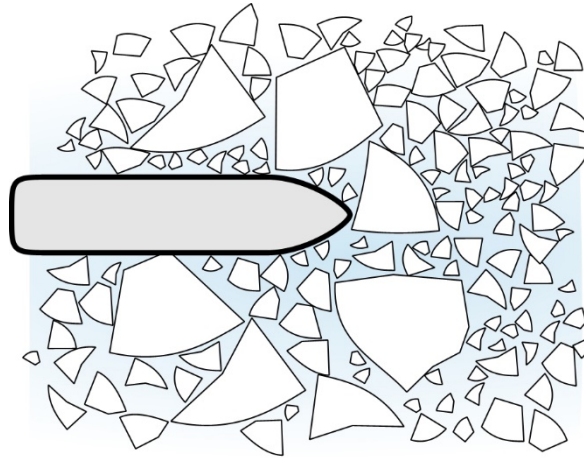


Figure 9.4 Ship in 7/10 pack ice.

Once the ice becomes solid, the ship must break a track through the solid ice. Icebreaking ships are shaped to push down on the ice, breaking off slabs of ice and then submerging them below the hull to allow passage. Much of the ice thus submerged surfaces behind the ship leading to a following channel full of pieces of broken ice.

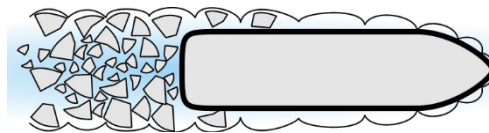


Figure 9.5 Ship breaking level ice.

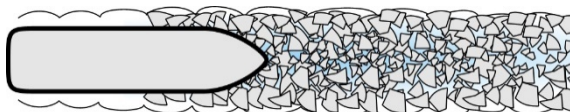


Figure 9.6 Ship in a broken channel.

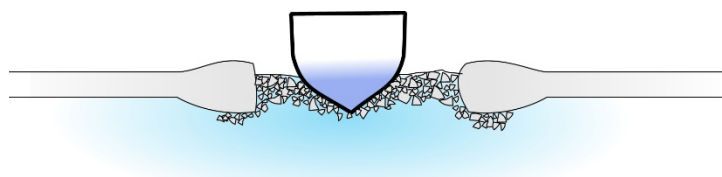


Figure 9.7 Cross-section of a ship in a broken channel.

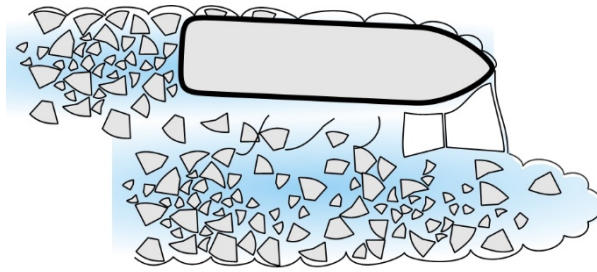


Figure 9.8 Ship widening a track.

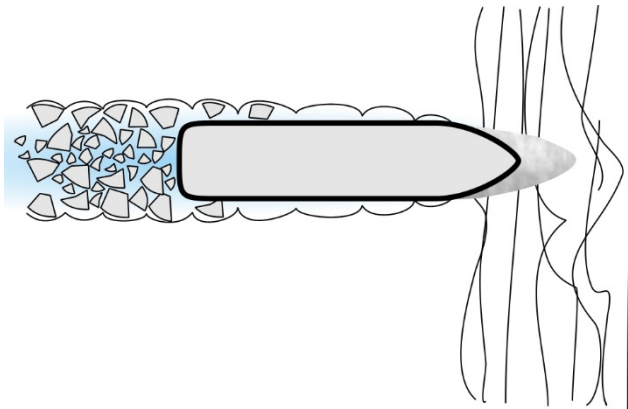


Figure 9.9 Ship ramming a ridge.

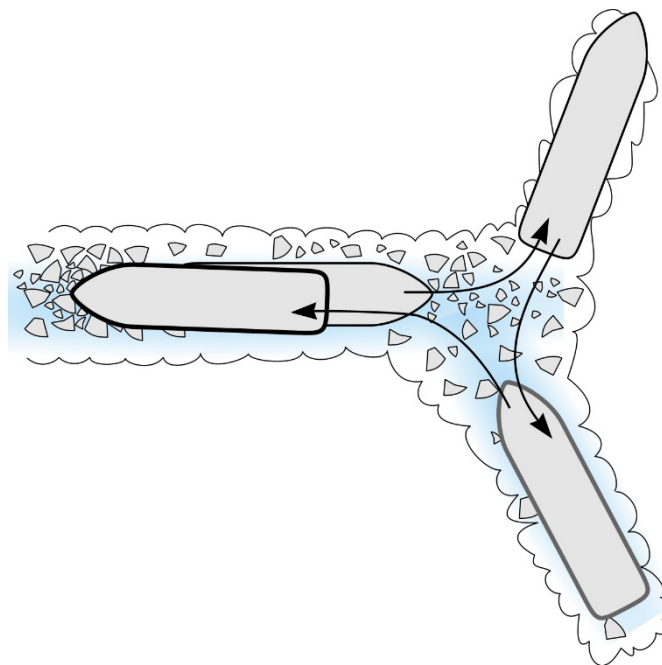


Figure 9.10 The Star or Captain's Maneuver.

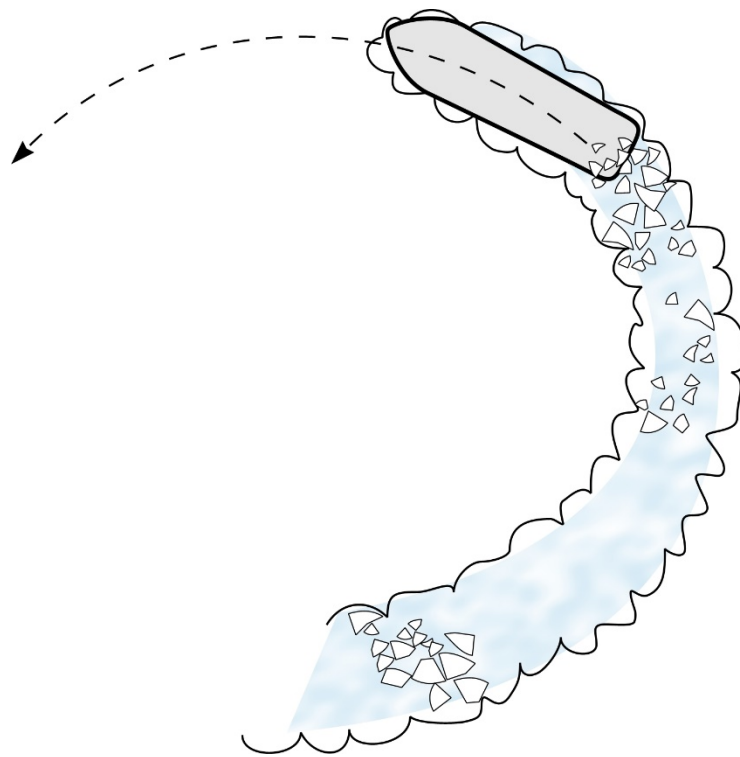


Figure 9.11 A turning circle in ice.

9.3 Ship Icebreaking process

Ships break ice by forcing the ice downwards to break in flexure. In operational conditions the ship has the power to break ice steadily and continuously. As the ice gets thicker the power required increases and the ship tends to slow. At some point the ice force exceeds the available thrust and the ship is brought to a stop. If further progress is needed to ship must change to a mode of operation called “backing and ramming”

Figure 9.12 illustrates the various aspects of ship contact with level ice. The ice edge is forced down as the sloping bow moves forward. The water just below the ice edge is pressed quickly from above and must accelerate out of the way. This results in higher water pressures, which lead to some spray escaping upwards. The previously broken ice slides down the hull. Figure 9.13 shows the forces that act on both the ice edge and submerged blocks. These forces must overcome the flexural strength of the ice, the buoyancy forces required to submerge the blocks and the friction along the hull. The ice edge, which is initially very sharp, is crushed while the force builds. This process results in a rising force while the ice edge flexes, and then a big drop in load when the flexural failure occurs. The average force (averaged in time and over the ship) is called resistance, and is the force that must be balanced by the propellers if the ship is to maintain a steady speed.

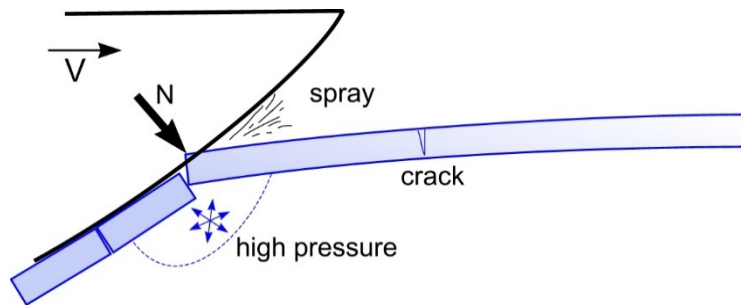


Figure 9.12 Aspects of Level Icebreaking.

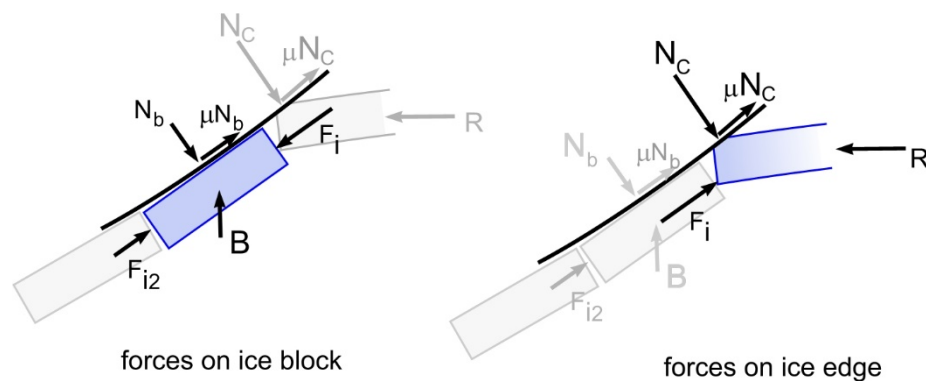


Figure 9.13 Level Icebreaking Contact Forces.

Figure 9.14 illustrates the process of icebreaking as a series of cusps. In thicker ice the cusps are larger and thus less frequent. In thin ice the cusps are numerous and very frequent. Figure 9.15 illustrates why the icebreaking resistance tends to be velocity dependent. Although the ice strength is not especially strain rate dependent, the dynamics of the ice edge failure result in significant accelerations of the ice edge. This in turn raises the pressure of water under the ice (tending to support the ice) and shortens the moment arm (the point of max. moment) so that a higher force is required to break the ice in flexure. Together these effects lead to higher forces at higher ship speeds.

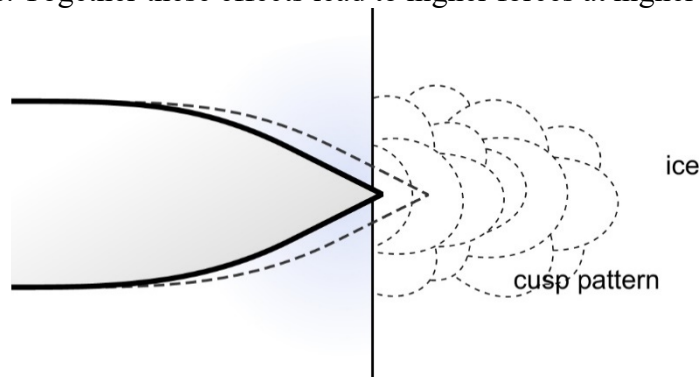


Figure 9.14 Level Icebreaking Cusp Patterns.

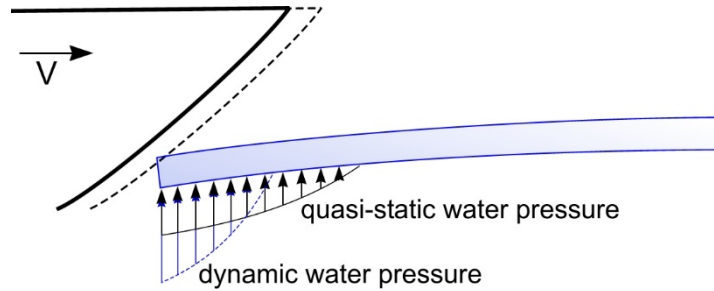


Figure 9.15 Speed Influences the Level Icebreaking Process.

A ship in level ice feels two kinds of forces. It feels the resistance of the water and the forces of the ice. The thrust available from the propeller is greatest when the ship is stopped. This is called the bollard condition. As the ship speeds up, the thrust decreases. The ship will naturally tend towards the speed where the thrust balances the forces from the water and ice (Figure 9.16 and Figure 9.17).

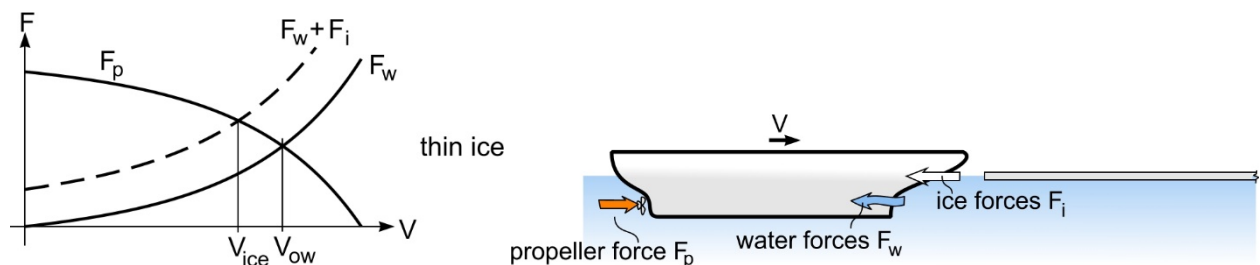


Figure 9.16 Speed Influences the Level Icebreaking Process – thinner ice.

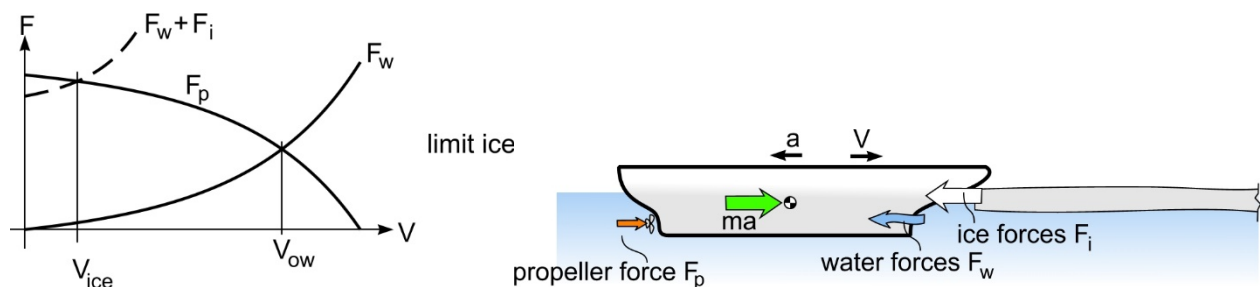


Figure 9.17 Speed Influences the Level Icebreaking Process – limiting ice.

Ships cannot operate effectively at very low speeds. When the speed in ice gets very low, the ship may lose the ability to steer. Rudders only work when there is a reasonable water flow over them. This is because they are lifting surfaces like wings.

When a ship is unable to proceed steadily in a given ice condition, it backs down its own track, reverses direction and rams the old ice edge. This gives the ship the ability to

generate higher forces because the thrust is augmented by the inertial forces. When a ship is engaged in backing and ramming the ramming cycles can be plotted as follows.

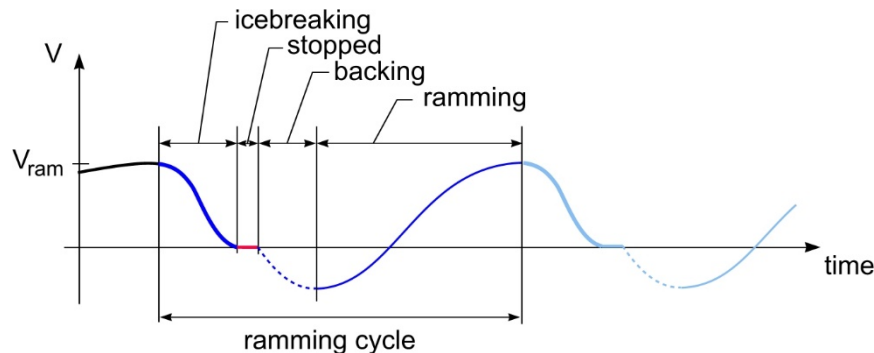


Figure 9.18 Speed vs Time in a Ramming Cycle.

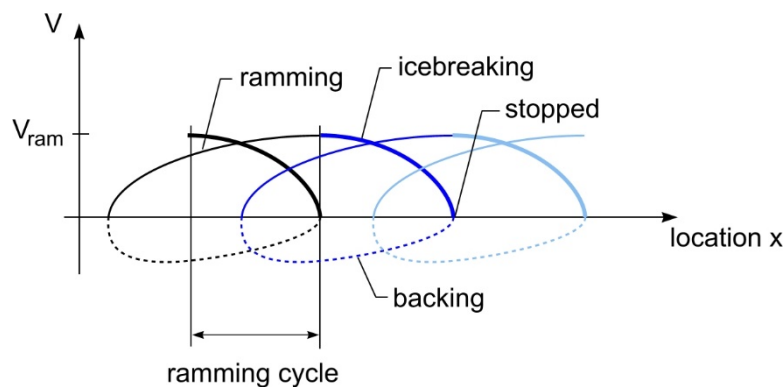


Figure 9.19 Speed vs Location in a Ramming Cycle.

9.4 Ship Icebreaking Resistance – General Discussion

The forces experienced by a ship transiting level continuous ice can be divided into four fundamental categories. The first is force associated with deforming, crushing, bending and fracturing the ice to break pieces off the main ice sheet. These forces all depend on the mechanical strength of the ice material up to the point that pieces of ice break off. These forces are more or less complex functions of the ice elasticity, plasticity and fracture or failure strength, either in crushing, flexure or shear.

The second type of force is associated with moving the newly separated broken pieces of ice to enable the ship to progress. These mechanisms involve submerging and accelerating the ice pieces out of the way of the ship, usually by pushing them down and to the side (although some unsuccessful designs have tried to push ice up). The fact that they are pushed down means they are fully submerged in the fluid and thus subject to hydrodynamic forces in addition to buoyancy and inertia.

The third type is force associated with the hydrodynamic drag of the ship as it progresses. These forces involve viscous skin friction, form drag and wave making resistance. These

forces are present even for ships that are not in ice, but the presence of the ice tends to modify the hydrodynamic forces. For instance, a surrounding ice sheet will suppress waves generated by the ship. Also, as part of the icebreaking process the flow around the hull has large pieces of solid ice moving in it. In addition, the design of modern icebreaking hulls frequently sacrifice hydrodynamic resistance, in increased wave making resistance and increased form drag, for better icebreaking performance or improved propeller protection.

The final category is force arising from friction. Friction is a factor that influences all the other forces and, when snow is present on the ice cover, provides an independent snow-friction force that can be substantial. Friction is an influencing factor for the breaking forces, the clearing forces and the hydrodynamic forces. In each case, a rough high-friction hull will experience a higher average force in each category than a smooth low friction hull. The issue is compounded by the fact that ice is particularly abrasive to coatings and most vessels suffer an increase in frictional roughness with service life.

Most of the researchers who have analyzed icebreaking as a process and attempted to develop either, numerical models, analytical expressions or experimental procedures to predict icebreaking resistance have used the above categorization of forces, or some subset of it. Thus, we tend to think of the icebreaking process as a series of independent mechanisms that can be predicted individually and then summed to give a total value. The idea of independence of mechanisms is not entirely true but may, for many cases, be a practical compromise. Additionally, each researcher (or institution) has developed their own ideas of what mechanisms or processes are the more important ones and to date there has not been much convergence of ideas towards a common understanding. This is partially because the problem is complex, and partially because the work has tended to be done by competitive commercial or semi-commercial organizations. The sections following describe some example numerical models and a later chapter discusses model testing and experimentation for ice structure (or ship) interaction processes. Both topics should be read in the context of the discussion above.

9.5 Resistance and powering – Lindqvist's model

Gustav Lindqvist (1989) presented a semi-empirical numerical model of icebreaking that is representative of the standard methods to predict ice resistance without resorting to model tests. It is an analytical model that builds on previous approaches by Enkvist and Kasteljan et al. There are other approaches, including purely empirical (Keinonen) and numerical (Valanto), both of which have their advantages and disadvantages. The Lindqvist model is useful, as a design tool to estimate resistance and powering (and transit times) at the design stage and to help understand model scale and full-scale test results. Resistance in ice is still not well understood, and most specialists recommend the use of model and full-scale data, as well as analytical methods to help estimate the true capabilities of a ship. With model scale data being expensive and imperfect, and with full-scale data being very expensive and uncontrolled, there is still a use for resistance models such as Lindqvist's.

Lindqvist's resistance equation is comprised of three components with two modifiers. The three components are R_C – the crushing resistance (at the stem), R_B – the bending (flexural) resistance over the whole bow, and R_S – the submergence term, which includes the force to submerge the ice and slide it along the hull. There are two velocity terms, which modify the three resistance terms, as follows;

$$R_{ice} = (R_C + R_B) \left(1 + 1.4 \frac{v}{\sqrt{g \cdot H_{ice}}} \right) + R_S \cdot \left(1 + 9.4 \frac{v}{\sqrt{g \cdot L}} \right) \quad (9.1)$$

Where g is the gravitational constant and v is the ship velocity. Other terms are illustrated in Figure 9.20.

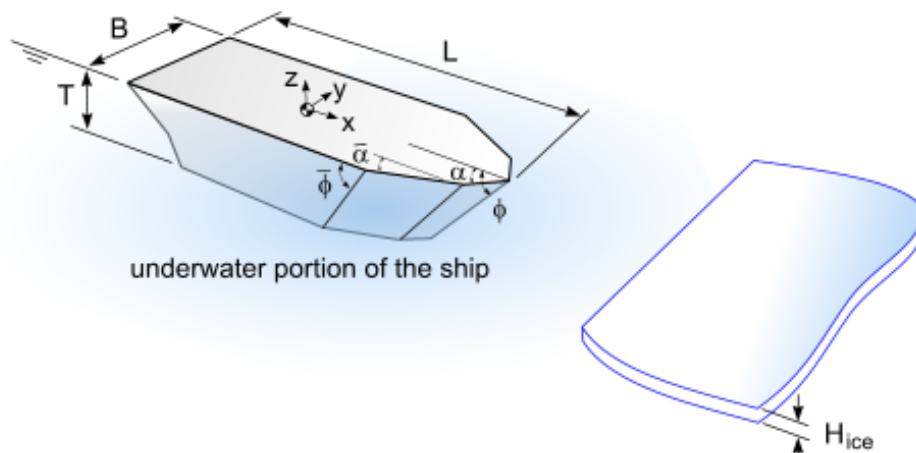


Figure 9.20 Lindqvist's hull form with angles and dimensions.

Ice Crushing Term R_C

Lindqvist notes that the stem of ice going ships tends to crush continuously into ice. Clearly this will only occur on bows with sharp stems, and not on blunt forms (i.e. Spoon or landing craft forms have no distinct point at the stem). So this term is applicable to sharp hull forms. Lindqvist does say that his solution for this force is only based on an intelligent guess and not on a thorough explanation of the mechanics. In fact his solution relies on the flexural capacity of the ice. He starts by estimating the vertical force needed to fail an ice edge in flexure:

$$F_v = 0.5 \cdot \sigma_b \cdot H_{ice}^2 \quad (9.2)$$

where σ_b is the flexural strength of ice.

He then assumes that this force is generated (continuously) on each side of the stem and resolves the x (along ship) component, which is the resistance that the ship will feel;

$$R_C = F_v \frac{\tan\phi + \mu \cdot \frac{\cos\phi}{\cos\psi}}{1 - \mu \cdot \frac{\sin\phi}{\cos\psi}} \quad (9.3)$$

Where μ is the friction factor, ϕ is the stem angle, α is the waterline angle at the stem (See Figure 11.20) and ψ is the true vertical angle of shell plate. (note: ψ is the complement of the true frame angle β' , shown in Fig. 9.29, $\psi = 90^\circ - \beta'$);

$$\psi = \arctan\left(\frac{\tan\phi}{\sin\alpha}\right) \quad (9.4)$$

These equations are dimensionally consistent, so any units will work.

Ice Breaking Term R_B

The breaking term is meant to express the time and space averaged force required to break the ice in flexure. Linqvist notes that in order to create the flexural force, the ice edge must be crushed. This crushing does involve shearing (spalling) of the ice edge, and so uses energy, and lengthens the time during which the force builds. If no local crushing occurred, the load would build quickly and drop, producing a lower average (see Figure 9.21).

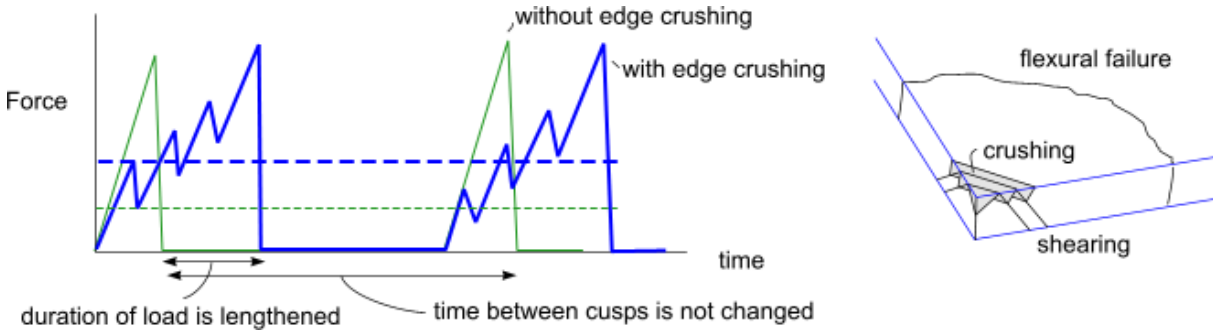


Figure 9.21 Cusp forces as influenced by edge crushing.

The breaking resistance term (see appendix in Linqvist 1989 for derivation) is as follows;

$$R_B = k \cdot B \cdot \left(\frac{H_{ice}^3}{l_c^2}\right) \left(\tan\bar{\psi} + \mu \frac{\cos\bar{\phi}}{\sin\bar{\alpha} \cdot \cos\bar{\psi}}\right) \left(1 + \frac{1}{\cos\bar{\psi}}\right) \quad (9.5)$$

Where k is a constant, B is the beam of the ship, the angles are the average angles over the bow sides as shown in Figure 9.20 and l_c is the characteristic length of the ice sheet;

$$l_c = \sqrt[4]{\frac{E \cdot H_{ice}^3}{\rho_w g 12(1 - \nu^2)}} \quad (9.6)$$

Linqvist makes the following assumptions to simplify the equation. Poisons ratio is 0.3. The elastic modulus is 2 GPa. He assumes the cusp length is 1/3 of the characteristic length and the shear strength is equal to the flexural strength. With these he suggests a breaking resistance formula of;

$$R_B = .003 \cdot \sigma_b \cdot B \cdot \left(\frac{H_{ice}^{1.5}}{\sqrt{m}} \right) \left(\tan \bar{\psi} + \mu \frac{\cos \bar{\phi}}{\sin \bar{\alpha} \cdot \cos \bar{\psi}} \right) \left(1 + \frac{1}{\cos \bar{\psi}} \right) \quad (9.7)$$

The root-m term returns the equation to constant units although $m = 1$. The 0.003 term is thus dimensionless.

Ice Submergence Term R_S

Ice can completely envelop the underwater portion of the hull during ice breaking in level ice. The submergence term accounts for the forces required to sink the ice, and to overcome the friction of the ice sliding along the hull. The normal force is governed by the buoyancy of the blocks. Figure 9.22 illustrates the coverage of a hull by submerged blocks. Linqvist assumed that the bow is completely covered, with the rest of the hull covered to 70% of its length. This is reasonable for smaller vessels, though may be too high for large ships. This is also shape dependent, as some vessels have features that are meant to clear ice to the sides and leave a clear track.

The submergence resistance term (see appendix in Linqvist 1989 for derivation) is derived from energy consideration and is as follows;

$$R_S = \delta \rho \cdot g \cdot H_{ice} \cdot \left(\frac{B \cdot T \cdot (B + T)}{B + 2T} + \mu \cdot (A_u + \cos \bar{\phi} \cdot \cos \bar{\psi} \cdot A_f) \right) \quad (9.8)$$

Where $\delta \rho$ is the density difference between ice and water (the cause of buoyancy) A_u is the area of the flat of bottom and A_f is the area of the bow. With approximations for the areas involved, Linqvist proposed the alternate formula;

$$\begin{aligned} R_S &= \delta \rho \cdot g \cdot H_{ice} \\ &\cdot B \left(\frac{T \cdot (B + T)}{B + 2T} + \mu \cdot \left(\begin{aligned} &0.7 \cdot L - \frac{T}{\tan \bar{\phi}} - 0.25 \cdot \frac{B}{\tan \bar{\alpha}} \\ &+ T \cdot \cos \bar{\phi} \cdot \cos \bar{\psi} \cdot \sqrt{\frac{1}{\sin^2 \bar{\phi}} + \frac{1}{\tan^2 \bar{\alpha}}} \end{aligned} \right) \right) \end{aligned} \quad (9.9)$$

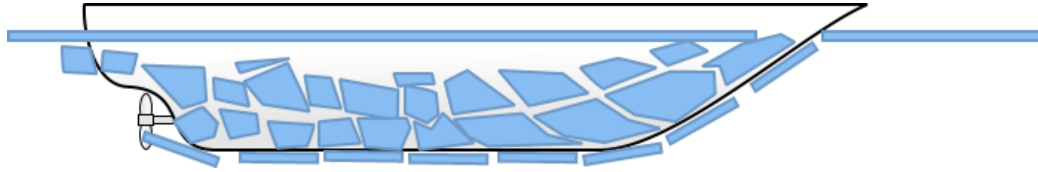


Figure 9.22 Ice Submergence during level ice breaking.

The total resistance is equation (9.1) in which the parts are as defined above. Table 9.1 illustrates the values produced by Linqvist's model for three different vessels, and can be useful when checking the equations. Linqvist's model is relatively straightforward and is a useful starting point for many designs.

Table 9.1 Example Calculations for Linqvist's Model

Lindqvist's Resistance Model

Description	Name	units	Jelppari	Otso	Silma
ship length	L	m	15	90	48
beam (wl)	B	m	5.1	23.4	8
draft	T	m	2.9	7.4	3.8
ice buoyant density	δ_r	t/m ³	0.104	0.104	0.104
ice thickness	H _{ice}	m	0.15	0.65	0.35
ice flexural strength	σ_b	kPa	190	330	475
shear angle at stem	ϕ	deg	26	22	32
waterline angle at stem	α	deg	31	30	15
plane angle at stem	ψ	deg	43.4	38.9	67.5
shear angle (average)	$\bar{\phi}$	deg	28.0	22.0	28.0
waterline angle (average)	$\bar{\alpha}$	deg	25.0	25.0	13.0
plane angle (average)	$\bar{\psi}$	deg	51.5	43.7	67.1
friction factor	μ	-	0.16	0.1	0.1
Vertical Force at stem	F _v	kN	2.1	69.7	29.1
Crushing resistance	R _c	kN	1.6	38.3	28.6
Breaking resistance	R _b	kN	0.8	36.4	28.4
Submergence resistance	R _s	kN	2.6	168.8	15.1
Total ice resistance (vel=0)	R _{ice_0}	kN	5.0	243.6	72.1
Ship velocity	v	m/s	2.0	2.0	2.0
Total ice resistance (vel=v)	R _{ice_v}	kN	14.5	433.3	171.2

9.6 Interactions with pack ice

Pack ice is a common ice feature in sub-arctic areas such as the east coast of Canada, offshore Greenland and in the Russian pacific coast regions. Vessel and structural interactions with pack ice form a subset of ice interaction scenarios where the dynamics of the collision are more important in the analysis of loads than is the case for interactions with infinite or semi-infinite ice sheets.

Origins of pack ice

The term Pack Ice describes sheet sea ice that has been broken up into random-sized discrete ice pieces. These ice pieces are able to move on the sea surface under wind or current action. Because the ice pieces are free to move, pack ice is strongly influenced by wind and is able to drift substantial distances from the area in which it was formed. A good example of pack ice is the ice that appears off the east coast of Canada in the spring. This ice forms in the lower Davis Strait and off the Labrador coast and then drifts south to cover the coast of the island of Newfoundland.

Descriptions of pack ice



Figure 9.23 Small vessel caught in pressured pack ice (Sky News Photo)

Pack ice is described primarily in terms of thickness and ice concentration. Concentration is effectively a measure of the percentage of sea surface covered by ice, usually expressed in tenths. Thus 10/10 coverage means that the entire surface is covered and 5/10 concentration means that, on average, 50% of the water surface is occupied by ice pieces.

Another important feature of pack ice is that at full (10/10) coverage the ice can be “pressured”. This means that the pack ice has been pushed up against land by wind or current forces and that there is a level of lateral pressure in the pack ice, which acts to force the pieces together. Figure 12.2 shows a small vessel caught in pressured pack ice. This pressure effect is probably where the term pack ice came from as the ice is packed together by the environmental forces. If the lateral pressure is high enough, ridging and rafting can take place within the pack ice.

The strength of pack ice is sometimes quantified but is usually highly irregular. Relatively large floes (ice pieces) may be subject to large-scale fracture and

disintegration into smaller pieces during an ice interaction event. In that case the flexural strength of the ice would be of interest but in most cases we are interested in the local crushing strength of the floes as this is the main mechanism that comes into play as the individual pieces of ice act against a ship or structure or as they bump into each other.

Ship resistance in pack ice – effect of ice concentration

Ship interactions with pack ice can be considered as similar to the ice clearing part of the total level ice icebreaking resistance. If the pack ice pieces are small enough, we can assume that little or no ice fracturing takes place and the force on the ship or the structure is entirely due to the requirement to move the ice pieces out of the way. In analyzing the problem we can then use a formulation similar to that developed for the ice-clearing component of the total icebreaking resistance. On this basis, the equations below define a Froude Number based, non-dimensional system for ice clearing as developed previously. In extrapolating to pack ice, we assume that only the ice-clearing component from the original formulation is relevant. This assumption may break down somewhat at 10/10 concentration or with large floes where energy will be consumed in fracturing or crushing ice.

As with the analysis of the icebreaking problem, before we look at the ice-induced loads, we calculate and extract a viscous drag component to remove the fluid movement effect. For analysis of ship transit in pack ice this is an obvious step but for fixed or moored offshore structures it may not be such an obvious step. For fixed structures, we would subtract the viscous drag for model test data where the structure was moved through the water and ice medium. There would be no need to add the viscous drag back into the total force predicted for full scale, as the structure is not moving relative to the water in that case.

Because pack ice interactions with ships (or offshore structures) can take place in instances where the ice concentration is less than 100%, we need to account for this reduction in mass in our analysis. As a first approximation, this reduction could be a linear function of ice concentration, but based on experience with ships moving through pack ice at both model and full scale, a higher exponent gives a better fit to observed data. It is generally accepted that ice concentrations below 6/10 do not induce significant loads on vessels. There is also a sharp increase in load as the concentration increases above 8/10. On this basis a cubic relationship between ice concentration and measured force has been found to best describe the effect of concentration reduction. This gives rise to the following formulation for the Pack Ice Force Coefficient (C_p);

$$C_p = \frac{F_p}{\frac{1}{2} \rho_i B h V_i^2 C_o^3} \quad (9.10)$$

Note that this is still a pure non-dimensional number because concentration C_o does not have units. In the case of the Pack Ice Froude Number (F_{n_p}) a linear function was found to be the most appropriate.

$$Fn_p = \frac{V}{\sqrt{ghC_o}} \quad (9.11)$$

Again, the Froude number remains dimensionless because C_o does not have units. As was the case previously for full icebreaking resistance we can develop a function that relates the Pack ice resistance coefficient to the Pack Ice Froude number.

$$C_p = f(Fn_p) \quad (9.12)$$

Where	F_p	is the average pack ice force
	C_o	is the ice concentration
	g	is the acceleration of gravity
	ρ_i	is the density of ice
	B	is the vessel Beam
	h	is the ice thickness
	V_i	is the pack ice drift velocity
	f	is an arbitrary function

This formulation is useful in conducting and analyzing model tests of ships in ice or offshore structures in pack ice, particularly at reduced concentrations. The form of the function f is derived from the test data and can be used to make full-scale predictions.

Local structural loads arising from pack ice interactions cannot be predicted from formulations such as this as this only provides the average global force associated with steady state movement in a pack ice field. In order to estimate local structural forces it is necessary to analyze individual collisions or a series of individual collisions to determine the load experienced at the interface between the structure and an individual floe. The Popov model presented earlier provides a reasonable analytical expression for assessing such loads.

The following plots give some data for pack ice loading from experiments conducted on a moored ship shape. This data is similar to that which would be derived for a ship transiting a pack ice field. The data illustrates trends with speed and ice concentration but is dependent on the vessel shape, the friction coefficient, and the pack ice piece size.

The model ice in this case was prepared at set thicknesses and then sawn or chopped into roughly rectangular pieces, which were initially left in-place to provide 10/10 (100%) coverage. Following this initial trial, the ice was reduced in concentration and redistributed in the tank to provide a lower concentration and the vessel towed through again. This process was repeated at a number of lower concentrations down to approximately 6/10. Surge direction resistance was resolved from the mooring line loads and the displaced position of the vessel.

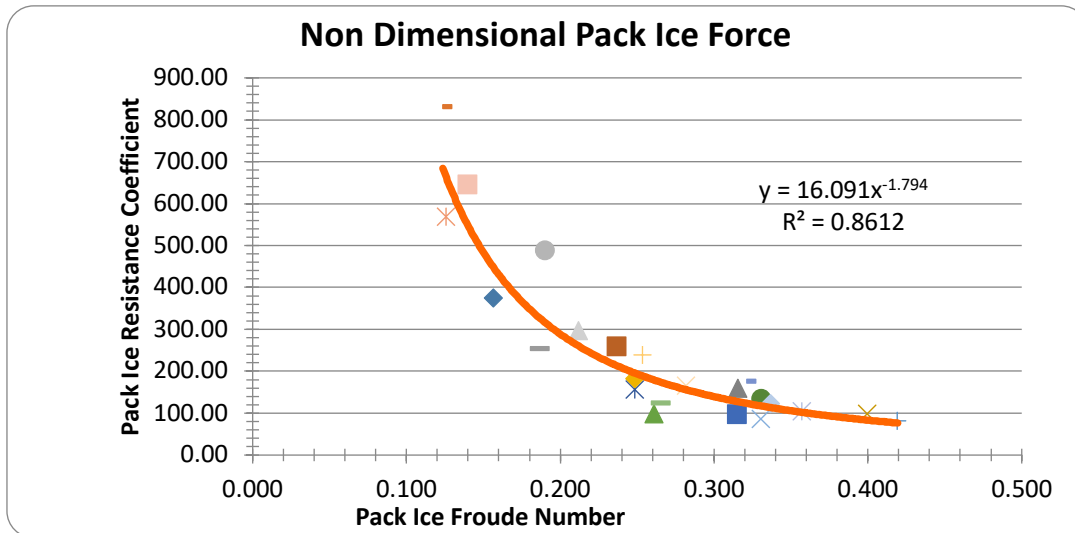


Figure 9.24 Non-Dimensional Pack Ice Force, IMD Generic Tanker

Data from pack ice tests is usually quite scattered. The main cause of the scatter is the shortness of test runs. The valid data in most ice tests is usually only 5 to 6 minutes long at full scale. This run length limits the confidence intervals on statistics such as mean load. In this case the non-dimensional numbers helps the analysis by normalizing all data to a common curve that reduces the confidence bands.

Figure 12.3 illustrates the application of the non-dimensional numbers and shows the mean line that can be derived from the data. This is the form of the function f mentioned earlier and this function allows us to extrapolate to full scale based on the Pack Ice Froude Number and the Pack Ice force coefficient. This is valid assuming that the vessel shape, ice friction coefficient and the scaled ice floe piece size remain the same as they were in the model test the data was measured in.

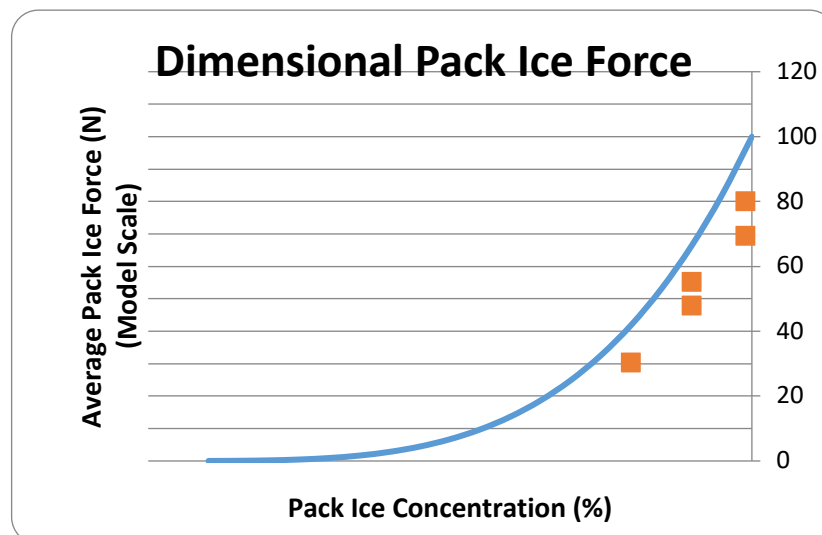


Figure 9.25 Pack Ice Force, IMD Generic Tanker

To give an example of predictive data that can be drawn from the non-dimensional function, Figure 9.25 illustrates the average pack ice force data for the same vessel and shows directly the form of the mean curve for a specific speed and ice thickness. The data points are those measured in the model test at the corresponding speed and ice thickness. These points are slightly below the mean predicted line, which indicates that the form of the function f is influenced by other points in the total data set. This could either mean that the non-dimensional formulation is not adequately explaining all the factors in the experiment or that there may have been some problem with that particular set of tests. However the trends in both the mean line and the data are consistent for the range of concentrations above 8/10 and this shows the relative lack of effect for low concentrations and the sharp increase in the average force at higher concentrations.

9.7 Ice Impact Loads

When setting the structural design load, a single heavy impact is normally considered. This is particularly true for Polar ships. A publication by Popov et.al. (1967) presented a general approach for calculating the forces resulting from a ship-ice collision. The Popov model is based on the notion that a general 3D impact between two bodies can be represented as an equivalent 1D (normal) collision between a single body and a rigid wall. To make the transformation there are two steps required. First, the effective mass and velocity must be determined. Then, with a model of the ice crushing behavior, the problem can be solved as an energy balance and the collision forces determined. In the original publication, the ice crushing was described using the theories of Kheysin (1961), where the ice pressures were partially dependent on the velocity of penetration. This rate sensitivity makes the solution of the equations more difficult. The Popov model was adjusted in Daley (1999), to include a pressure-area model to describe the ice crushing. This adjustment makes the ice force dependent only on the depth of ice crushing and makes algebraic solutions possible and relatively simple.

General Description of Ship-Ice Impact Calculations

When two objects collide, forces act in an equal and opposite way on both objects. There are various ways to characterize impact, with “elastic” vs “inelastic” being the most common. The differences between elastic and inelastic are important, but this is a relatively minor issue. In any collision, both bodies obey Newton’s laws throughout the event. The laws of conservation of momentum, conservation of energy and conservation of mass must be satisfied. The important characteristics of a collision involve how these laws of conservation are satisfied. In the case of ship-ice impact, the Popov approach made a number of important assumptions to permit the calculation of the impact force, including;

- The ship is a rigid body
- The ice is a rigid body except for the edge which is crushed
- The hydrodynamic added mass is assumed constant for each object and degree of freedom
- The friction is low and can be ignored
- The impact is assumed to be of so short duration that only the energy of impact changes the kinetic energy of the ship and ice
- All non-impact forces (propulsion, buoyancy, wind, current, etc) are assumed to be irrelevant. They do no ‘work’ during the collision.

As the collision occurs, a force arises that acts on both the ship and the ice. As shown in Figure 9.26 the line of action of the force is eccentric to the center of gravity and so tends to roll, pitch and yaw both the ship and the ice. The collision may seem to quite complicated, with the two bodies moving in a total of twelve degrees of freedom, in addition to the crushing behavior. Luckily, with the above assumptions, it is possible to greatly simplify the collision problem.

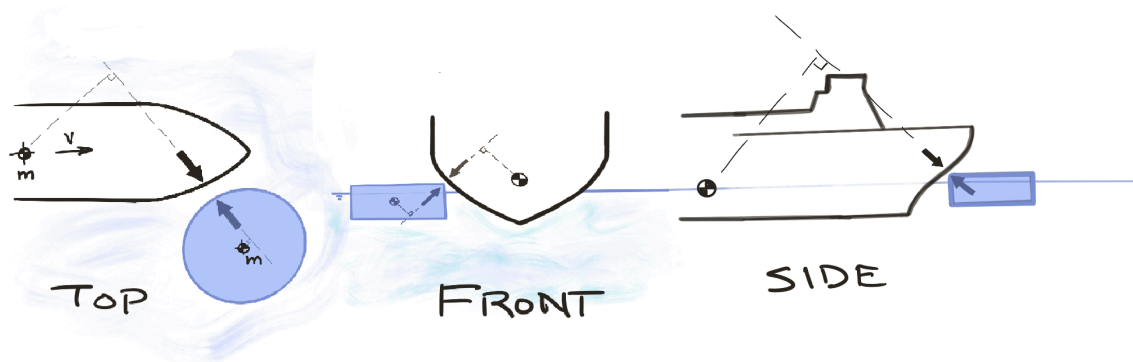


Figure 9.26 Collision in 3 views

Figure 9.27 sketches a ship-ice collision. From a global perspective there are two large bodies with 12 degrees of freedom. However, if we consider the local view around the region of impact, the ship appears as a rigid steel plate, and the ice appears as a shaped crushable edge. The gap between the two bodies has a closing speed in the normal direction (normal to the ship) and tangential velocities can be ignored. The key insight that Popov had, and that makes the problem easily solvable, is that, from a local point of view, the side of the ship and the side of the ice each have an ‘effective’ mass, and each of these ‘effective masses’ behaves like a simple mass.

Mass can be thought of as the constant that relates force with acceleration for a free body. If we apply a force to a free body it will produce an acceleration. The acceleration will be proportional to the force and inversely proportional to the mass ($F = m a$). If we focus on the local view, the ice applies a force to the ship and the ship accelerates at some rate. The point of contact has an effective mass that is equal to the force divided by the acceleration ($m = F/a$). So, the problem comes down to determining how much the contact point (on ship or ice) will accelerate when a force is applied.

The collision force is applied to the ship at a known location in a known direction. This force causes the ship to respond in all six degrees of freedom and similarly the ice. When the collision begins there is a velocity difference at the point of contact, the closing velocity in the normal direction. As the two bodies overlap, a force builds up. This force is applied to both bodies and accelerates both bodies, slowing the rate of overlap until the overlap reaches a maximum and the closing velocity goes to zero. If the force is only dependent on the magnitude of the overlap, the force becomes a maximum when the overlap is maximum. Not only can we view the local problem as a simple 2-body collision, but the problem can be further simplified to a single rigid body striking a rigidly held ‘spring’ that represent the ice crushing process. Twelve degrees of freedom become one.

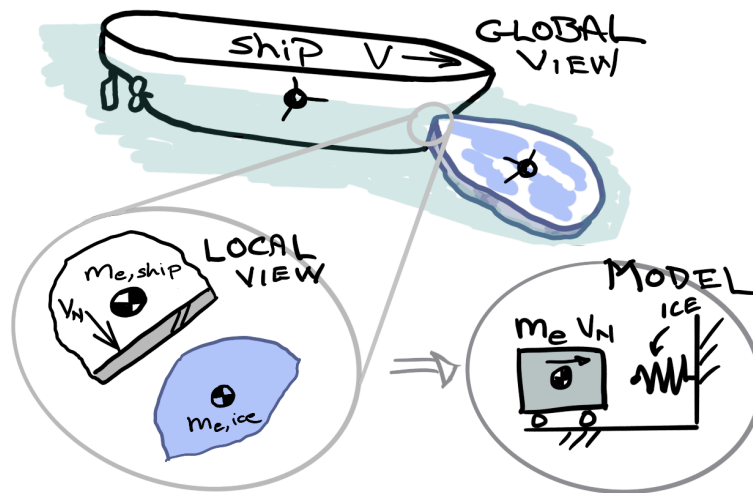


Figure 9.27 Collision for global and local view

Mass reduction coefficient.

This section describes the calculation of the mass reduction coefficient C_o . This approach was developed by Popov (1969). A collision taking place at point (x,y,z) (see Figure 9.28), will result in a normal force F_n . The point will accelerate, and a component of the acceleration will be along the normal vector, with a magnitude a_n . The collision can be modeled as if the point P were a single mass (1 degree of freedom system) with an equivalent mass M_e of;

$$M_e = \frac{F_n}{a_n} \quad (9.13)$$

The effective mass is a function of the inertial properties (mass, radii of gyration, hull angles and moment arms) of the ship. The effective mass is linearly proportional to the mass (displacement) of the vessel, and can be expressed as;

$$M_{e,ship} = \frac{M_{ship}}{C_o} \quad (9.14)$$

where C_o is the mass reduction coefficient. The components of the mass reduction equation are presented below. The full derivation can be found in Appendix B.

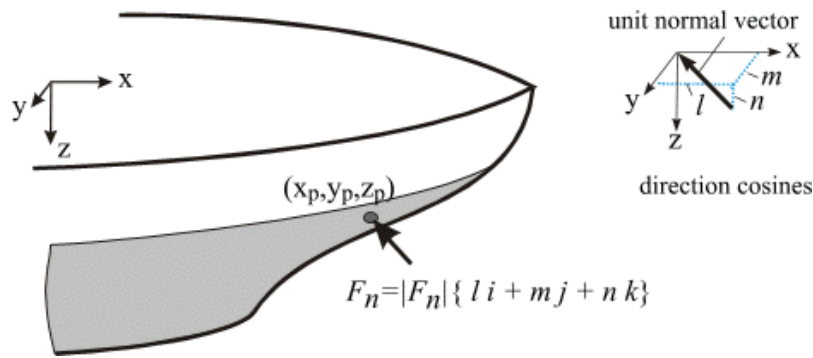


Figure 9.28 Collision point geometry

The inertial properties of the vessel are as follows;

Hull angles at point:

α = waterline angle

β = frame angle

β' = normal frame angle

γ = sheer angle

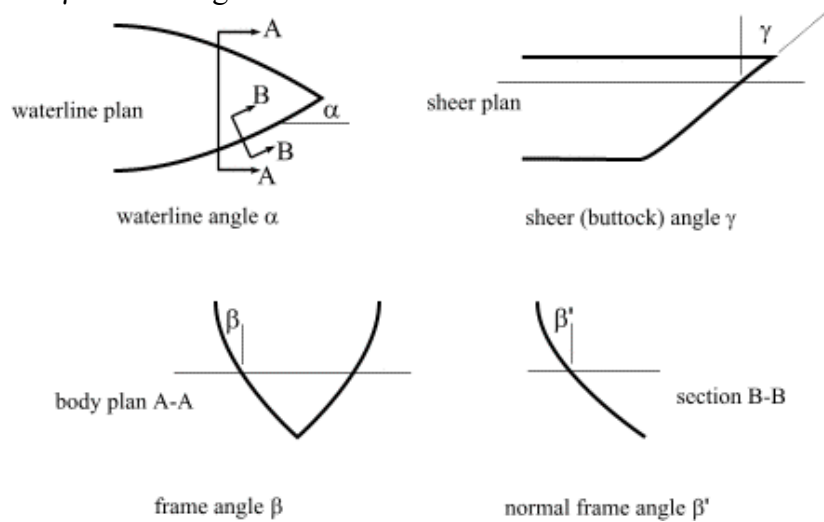


Figure 9.29 Hull angle definitions.

The various angles are related as follows,

$$\tan \beta = \tan \alpha \cdot \tan \gamma \quad (9.15)$$

$$\tan \beta' = \tan \beta \cdot \cos \alpha \quad (9.16)$$

Based on these angles, the direction cosines, l, m, n are

$$l = \sin \alpha \cdot \cos \beta' \quad (9.17)$$

$$m = \cos \alpha \cdot \cos \beta' \quad (9.18)$$

$$n = \sin \beta' \quad (9.19)$$

and the moment arms are

$$\lambda_1 = n \cdot y_p - m \cdot z_p \quad (9.20)$$

$$\mu_1 = l \cdot z_p - n \cdot x_p \quad (9.21)$$

$$\eta_1 = m \cdot x_p - l \cdot y_p \quad (9.22)$$

The added mass terms for the ship are as follows;

$$AM_x = 0 \quad (9.23)$$

$$AM_y = 2 \frac{T}{B} \quad (9.24)$$

$$AM_z = 2/3 (B C_{wp2}) / (T(C_b(1 + C_{wp}))) \quad (9.25)$$

$$AM_{rol} = 0.25 \quad (9.26)$$

$$AM_{pit} = B / ((T(3 - 2C_{wp})(3 - C_{wp})) \quad (9.27)$$

$$AM_{yaw} = 0.3 + 0.05 L/B \quad (9.28)$$

The mass radii of gyration (squared) are;

$$rx^2 = C_{wp} \frac{B^2}{11.4 C_m} + \frac{H^2}{12} \quad (9.29)$$

$$ry^2 = 0.07 C_{wp} L^2 \quad (9.30)$$

$$rz^2 = \frac{L^2}{16} \quad (9.31)$$

With the above quantities defined, the mass reduction coefficient C_o is

$$C_o = \frac{l^2}{1 + AM_x} + \frac{m^2}{1 + AM_y} + \frac{n^2}{1 + AM_z} + \frac{\lambda_1^2}{rx^2(1 + AM_{rol})} + \frac{\mu_1^2}{ry^2(1 + AM_{pit})} + \frac{\eta_1^2}{rz^2(1 + AM_{yaw})} \quad (9.32)$$

Contact with General Wedge (Normal to hull)

The next step is to describe the contact process and the development of force with increasing ice indentation. A specific case of contact will be used for illustration, though the method is generally applicable for a variety of contact situations. Figure 9.31 shows a ship-ice collision (this is the IACS Polar Rules design scenario for hull local strength design. The ship contacts the ice on the bow shoulders. The ice is assumed to be angular, with vertical sides. The ship is locally flat and inclined. Figure 9.31 shows the geometry of a general wedge-shaped edge indentation (normal to hull). From this geometry we can determine the contact area and ice force as a function of the ice crushing depth (penetration depth) ζ_n .

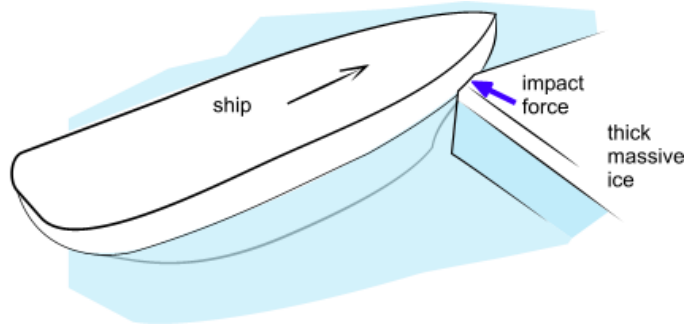


Figure 9.30 Shoulder (Oblique) Impact Scenario.

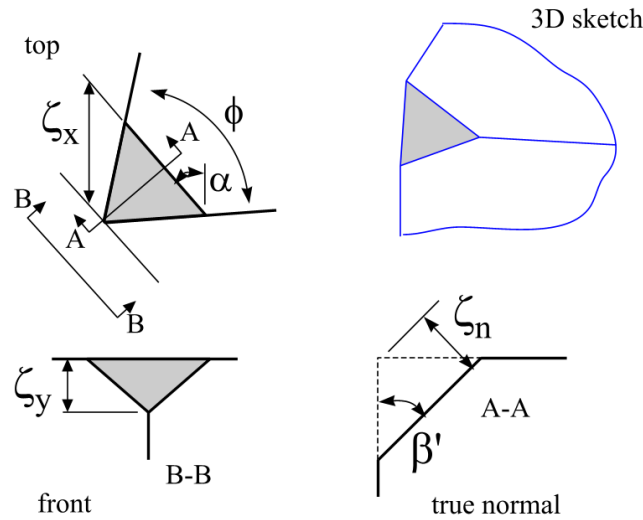


Figure 9.31 General Wedge-shaped Edge (normal to hull).

For the wedge case shown above the projected areas, vertical, horizontal and normal are;

$$A_v = \zeta_n^2 \cdot \frac{\tan\left(\frac{\phi}{2}\right)}{\cos^2 \beta'} \quad (9.33)$$

$$A_h = \zeta_n^2 \cdot \frac{\tan\left(\frac{\phi}{2}\right)}{\sin \beta' \cos \beta'} \quad (9.34)$$

$$A_n = \zeta_n^2 \cdot \frac{\tan\left(\frac{\phi}{2}\right)}{\sin \beta' \cos^2 \beta'} \quad (9.35)$$

The pressure-area approach is used again.

$$P_{av} = P_o A_n^{ex} \quad (9.36)$$

$$F_n = P_{av} A_n \quad (9.37)$$

Substituting (9.35) into (9.37) we arrive at:

$$F_n = p_o A_n^{1+ex} = p_o \left(\frac{\tan \frac{\phi}{2}}{\sin \beta' \cos^2 \beta'} \right)^{1+ex} \zeta_n^{2+2ex} \quad (9.38)$$

Note: this can be expressed in a general form as:

$$F_n = p_o \cdot fa \cdot \zeta_n^{fx-1} \quad (9.39)$$

where

$$fx = 3 + 2 ex \quad (9.40)$$

$$fa = \left(\frac{\tan \frac{\phi}{2}}{\sin \beta' \cos^2 \beta'} \right)^{1+ex} \quad (9.41)$$

The ice Indentation energy

$$IE = \int F_n d\zeta \quad (9.42)$$

Which becomes;

$$IE = \frac{p_o}{fx} \cdot fa \cdot \zeta_n^{fx} \quad (9.43)$$

The above geometry parameters are used in the collision calculations for wedge shaped ice edge cases. Appendix C provides a table of additional ice geometry cases.

Popov Force Calculation

The Popov collision scenarios can be analyzed by equating the normal kinetic energy with the ice crushing energy.

$$KE_e = IE \quad (9.44)$$

where the kinetic energy is;

$$KE_e = \frac{M_e}{2} \cdot V_n^2 \quad (9.45)$$

Which for the case of the ship moving straight forward, and the ice static and of infinite mass (or at least 10x larger than the ship), becomes;

$$KE_e = \frac{M_{ship}}{2 C_o} \cdot V_{ship}^2 l^2 \quad (9.46)$$

which, using equation (9.43) and (9.44) we can write;

$$KE_e = \frac{p_o}{f_x} \cdot f a \cdot \zeta_n^{f_x} \quad (9.47)$$

Solving for the normal indentation:

$$\zeta_n = \left(\frac{KE_e \cdot f_x}{p_o \cdot f a} \right)^{\frac{1}{f_x}} \quad (9.48)$$

The normal force can be found by substituting eqn. (9.48) into (9.39) to give

$$F_n = p_o \cdot f a \cdot \left(\frac{KE_e \cdot f_x}{p_o \cdot f a} \right)^{\frac{f_x-1}{f_x}} \quad (9.49)$$

The values from (9.46) and (9.41) can be substituted into eqn. (9.49), together with (9.40) to get impact force equations for each case. The effective kinetic energy depends on the nature of the collision. For simple direct collisions the effective kinetic energy is the total kinetic energy. For ship-ice collisions (see Figure 9.30), the effective mass and velocity properties at the point of impact are determined as follows (see equations (9.17) for the l and (9.32) for C_o terms);

$$V_n = V_{ship} \cdot l \quad (9.50)$$

where: V_n is the normal velocity at the point of impact
 V_{ship} is the x-direction velocity (all others are zero)
 l is the direction cosine in x

$$M_e = \frac{M_{ship}}{C_o} \quad (9.51)$$

where: M_e is effective mass at the point of impact
 M_{ship} is the ship's mass (displacement)
 C_o is the mass reduction factor

By combining the above equations, a single closed-form expression for the collision force is found;

$$F_n = p_o \cdot \left(\frac{\tan \frac{\phi}{2}}{\sin \beta' \cos^2 \beta'} \right)^{1+ex} \cdot \left(\frac{\frac{M_{ship}}{2 C_o} \cdot V_{ship}^2 l^2 \cdot (3 + 2 ex)}{p_o \cdot \left(\frac{\tan \frac{\phi}{2}}{\sin \beta' \cos^2 \beta'} \right)^{1+ex}} \right)^{\frac{2+2 ex}{3+2 ex}}$$

Even this equation has terms such as C_o and l that depend on basic ship parameters, so it is quite lengthy. Nevertheless, this is a closed-form algebraic equation for ice force in one category of ship-ice impact. This equation is easily implemented in a spreadsheet and can be used to assess a variety of ice load issues. (9.52)

Example Popov Force Calculation Values

For the shoulder collision shown in Figure 9.32, with inputs as listed in Table 9.2, Table 9.3 shows the calculation results using the Popov approach and pressure-area equations. The inputs include all the ship and ice parameters needed. The output table includes some intermediate results as well as the impact force. This can be used to check calculations.

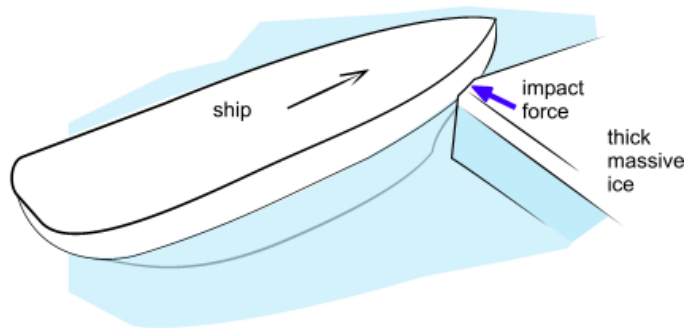


Figure 9.32 Head-on (Symmetrical) and Shoulder (Oblique) Impacts.

Table 9.2 Example Popov Shoulder Collision Calculations (Input)

Input Values			
Ship Main Parameters			
Ship Name	SN	M.V.Popov	text
Length	Loa	95.0	m
Beam	B	15.55	m
Draft	T	6.22	m
Height	H	8.09	m
Block Coef.	CB	0.78	nd
Waterplane Coef	Cwp	0.88	nd
Midship Coefficient	Cm	0.9	nd
Mass	M	7351	tonnes
Ship Speed	Vs	3.0	m/s
Hull Angles and coordinates			
Alpha	α	30	deg
Beta	β	40.00	deg
Beta prime	β'	36.01	deg
gamma	γ	55.5	deg
x coordinate	x	42.8	m
y coordinate	y	3.9	m
z coordinate	z	0	m
Ice Crushing Terms			
Ice strength term	Po	3	Mpa
Ice exponent (process PA)	ex	0.2	nd
Wedge angle	ϕ	135	deg
form factor 1	fx	3.40	nd
form factor 2	fa	9.06	nd

Table 9.3 Example Popov Shoulder Collision Calculations (Output)

Calculated Values			
Popov Terms			
x dirn cosine	l	0.4045	nd
y dirn cosine	m	0.7006	nd
z dirn cosine	n	0.5879	nd
roll moment arm	λl	2.2860	m
pitch moment arm	μl	-25.1311	m
yaw moment arm	ηl	28.3769	m
Surge Added Mass	Amx	0.0000	nd
Sway Added Mass	Amy	0.8000	nd
Heave Added Mass	Amz	0.8802	nd
Roll Added Mass	Amrol	0.2500	nd
Pitch Added Mass	Ampit	0.9510	nd
Yaw Added Mass	Amyaw	0.6054	nd
roll gyrad(squared)	rx2	26.2037	m2
pitch gyrad(squared)	ry2	555.94	m2
yaw gyrad(squared)	rz2	564.06	m2
Mass Reduction Coef.	Co	2.2512	nd
Effective mass	Me	3265229	kg
Normal Speed	Ve	1.213	m/s
Kinetic Energy	KEe	2403925	kg-m2/s2
Impulse	Ie	3962163	kg-m/s
Results			
pen(n)	ζn	0.702	m
Normal Force	Fn	11.64	MN

Chapter 9: Problems

9.1 Resistance in ice (Linqvist)

For a ship of the following dimensions, the owner wishes to be able to break 0.5m of ice at 4 m/s (8 knots). Assume characteristic length of ice is 15x thickness (in this case 7.5m).

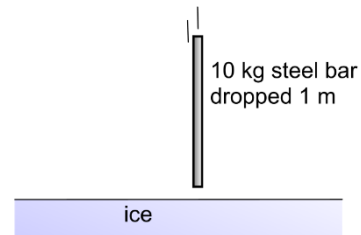
- Ship length L: 100 m
- Ship Breadth B: 20 m
- Ships Draft T: 6 m
- Ship's stem vertical angle $\emptyset$: 45 deg
- Ship's stem waterline angle α : 45 deg
- Ship's bow average waterline angle $\bar{\alpha}$: 30 deg

- a) Describe Linqvist's assumptions and approach.
- b) Compute the breaking component of resistance:
- c) How would you go about verifying that value?

9.2 Ice impact

Consider the case of impact where a round steel bar, dropped from a height of 1m (1m from base of bar to ice surface – also the distance that the center of gravity drops prior to impact), strikes a sheet of ice. The bar weights 10 kg has a diameter of 0.025 m. The bar penetrates 4cm into the ice.

The area of a circle is $\pi/4 \text{ dia}^2$.



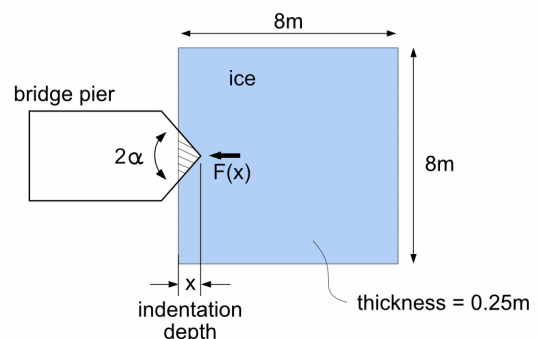
- a) Can you estimate the ice crushing strength? State your assumptions and describe your reasoning.
- b) What would you expect to happen if you dropped the bar from a height of 2m?

9.3 For the ship described below calculate the level ice resistance force (Lindqvist).

- $V = 3 \text{ m/s}$
- $L = 100\text{m}$, $B=20\text{m}$, $T=5\text{m}$, Block Coefficient $C_B = 0.8$ (recall : $\text{mass}=\rho L B T C_B$)
- use $\rho = 1025 \text{ kg/m}^3$, $\alpha = 25^\circ$, $\phi = 30^\circ$, $H_{ice} = 1\text{m}$

9.4 An ice floe with dimensions 8m x 8m by 25

cm (fresh water ice) hits a bridge pier as pictured below, at 1 m/s. The pier is vertical, with $2\alpha = 90\text{deg}$. The ice pressure (process pressure) can be described with $P=2xA^{-.5} \text{ MPa}$. What is the impact force on the bridge pier? Once this is done, compare the answer to Korzhavin's equation (with $\sigma_c = 5 \text{ MPa}$).



9.5 For the ship shown below calculate the collision force on the bow, assuming Popov mechanics, and a pressure-area curve of $P=1 A^{-1}$.

Assume:

$$V = 3 \text{ m/s}$$

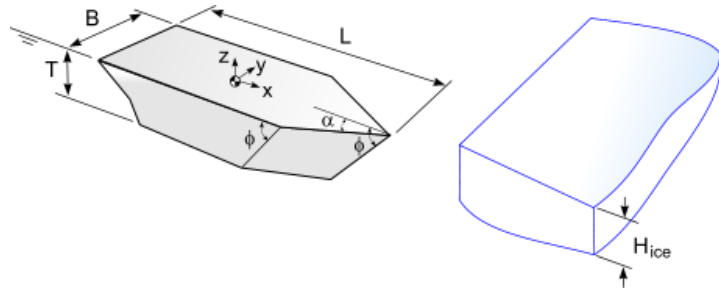
$$L = 100\text{m}, B=20\text{m}, T=5\text{m}, \text{Block Coefficient } C_B = 0.8 \text{ (recall : mass}=\rho L B T C_B\text{)}$$

use $\rho = 1000 \text{ kg/m}^3$ (for simplicity)

$$\alpha = 25^\circ, \phi = 30^\circ$$

impact coordinates: $x = 45\text{m}, y = 5\text{m}, z = 0\text{m}$

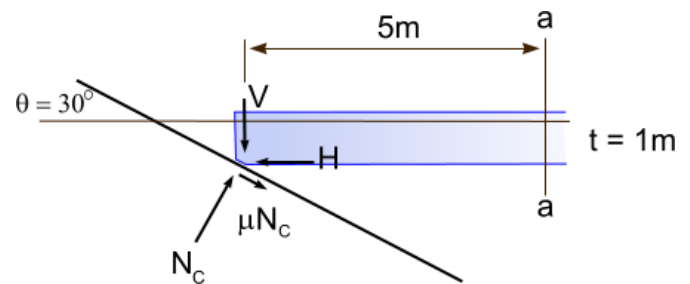
for ice, assume wedge angle is 90° (very thick)



9.6. Consider a case of sea ice

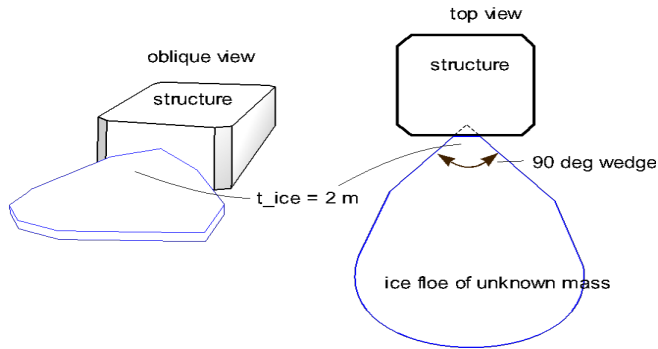
striking a sloping structure. The ice is 1m thick. The slope of the structure is 30 degrees. The ice-structure friction factor is 0.1. The ice will crack at the section 'a-a' when the tensile stress reaches 1 MPa. The goal is to find the normal force N_c just when the ice breaks. You can ignore shear stresses, and assume that the horizontal force H acts along the bottom edge of the ice. Determine V and H for a 1m wide strip of ice (ie 1m into the page).

- What is the ratio $V:H$?
- Draw the pattern of axial stress in the ice at a-a.
- Find V , H and N_c when the max axial stress at a-a is 1MPa



9.7 Consider the case of ice-structure impact where an ice floe strikes a fixed (and essentially rigid offshore structure). The people on the structure observe the ice coming straight towards them. From a film record looking straight down at the ice contact event, they estimate the impact velocity at 1 m/s, the ice edge angle of 90 degrees, and the ice thickness (at the edge) to be 2m thick. They also estimated that the ice crushed (ie penetrated) 2m into the structure prior to stopping. They want to estimate the mass of the ice.

- assuming ice crushing pressure of 1 MPa estimate the mass of the ice.
- Assuming ice crushing pressure of $P = C_o A^{ex}$, where $C_o = 1 \text{ MPa}$ and $ex = -0.5$, estimate the mass of the ice



9.8. Read the news story below.

Husky Energy says one of their oil platforms had a close call with an iceberg off the coast of Newfoundland.

By: Staff The Canadian Press Published on Thu Mar 30 2017

ST. JOHN'S, N.L. — A floating oil platform off Newfoundland has had a near-miss with an iceberg the size of a small office building.

Husky Energy said a "medium size" iceberg came within 180 metres of the SeaRose FPSO at about 5:30 a.m. Wednesday.

"We had an iceberg pass close by our production facility," Husky's Colleen McConnell said Thursday.

"We've been monitoring this particular piece of ice for awhile. It changed direction at about two in the morning, and we obviously had to respond quickly."

The Canada-Newfoundland and Labrador Offshore Petroleum Board described the iceberg as 40 metres wide, 60 metres long and standing eight metres above the waterline.

The massive, 270-metre SeaRose is Husky's lone oil-producing asset in the area. Built in 2004, the red-hulled, ship-like vessel can also store up to 940,000 barrels.

The board says Husky de-pressurized production wells and flushed flowlines with treated seawater, while the crew mustered in preparation for a potential disconnect.

But the iceberg passed without incident and was more than 500 metres away by 6 a.m.

The board says it is discussing the near-miss with Husky.

Icebergs are monitored constantly in the area, about 350 kilometres east of St. John's in the Jeanne d'Arc Basin, McConnell said.

She said Husky uses satellite monitoring and dedicated surveillance flights to monitor for icebergs in what has been a busy season for them.

"There have been a number of icebergs in the area, we've been monitoring and managing those," she said. "Certainly, we've had a very busy number of days."

The company has several vessels in the area able to undertake ice-management measures, including towing and water cannons, she said.

McConnell wouldn't speculate on whether the SeaRose was in danger of being hit, or what might have happened if it had been.

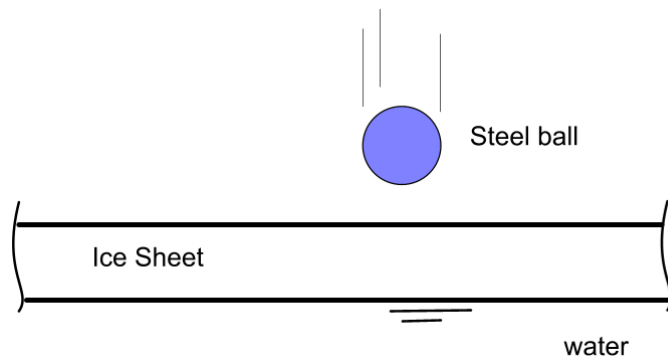
The SeaRose took similar measures in 2015 during another near-miss. It has never had to disconnect, she said.

She said Husky decided Wednesday to move its nearby drilling rig, the Henry Goodrich, into an ice-free area. It had already suspended operations on Sunday because of ice and weather conditions.

- Discuss how you would go about estimating the size of the impact that might have occurred but didn't in the case described above.
- What information would you need? What would be a reasonable range of values for the needed information?
- Can you provide an estimate of the possible impact force, with an estimate of its accuracy?

9.9 Consider the case of impact where a steel ball, dropped from an airplane strikes a sheet of ice at 130 m/s. The ice is 1m thick. The ball has a diameter of 0.2m. Steel has a density of 7850 kg/m³.

The volume of a sphere is $\frac{4}{3} \pi r^3$. What will happen? State your assumptions and describe your reasoning as you compute the likely behavior of the steel ball.

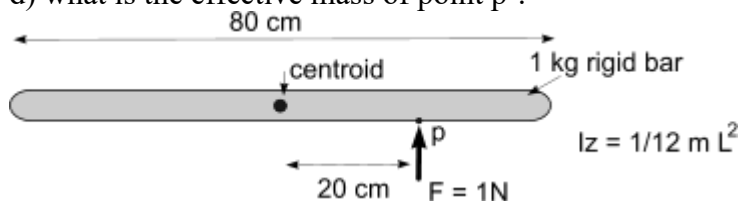


9.10 Effective Mass

[20]

A force of 1 N is applied to the side of an 80cm bar as shown, causing the bar to accelerate.

- what is the vertical acceleration at the centroid?
- what is the angular acceleration of the bar?
- what is the vertical acceleration at point p (where the force is) ?
- what is the effective mass of point p ?



10 Ice Model Testing

10.1 General Discussion

A frequent method of estimating ice forces on ships and offshore structures has been to conduct physical experiments or model tests. This is a common approach to physical situations that are complex and insufficiently understood to allow for analytical solutions or full numerical models. This is still very much the case for engineered structures in marine ice environments. In addition, there is a well-established history of model testing in the design of ships and offshore structures.

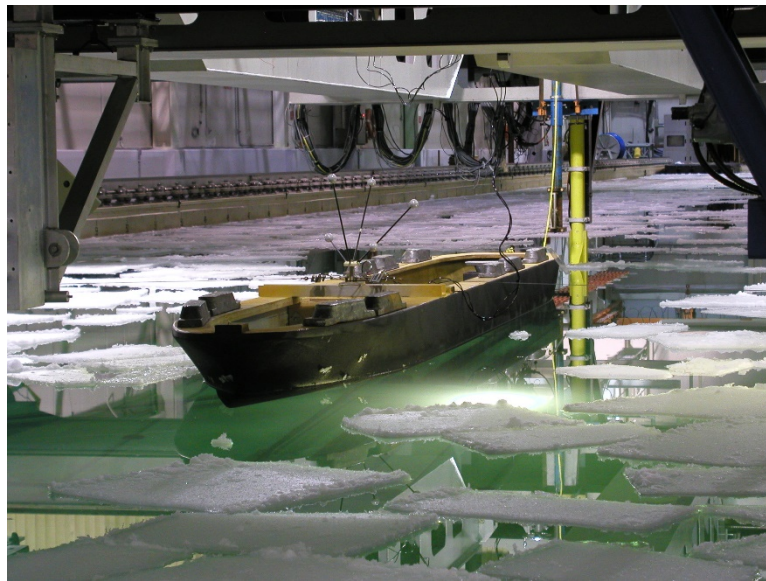


Figure 10.1 Model Test in the NRC-IOT Ice tank

However, model testing in ice is more complicated than situations where we only have to worry about the fluid. The challenge with modeling ships or structures in ice is that we now have a mixed fluid-solid medium and many different physical mechanisms simultaneously contribute to the applied average environmental force. These include all the mechanisms or components identified in Part 9. It is impractical to correctly model and scale all these mechanisms at the same time, particularly those associated with the solid ice. The issue is compounded by the fact that no agreement has emerged in the professional community as to which mechanisms dominate. Furthermore there are many ways in which conditions in a model tank differ from the full scale. By necessity, model-testing conditions are simplified representations of real life (Figure 13.1). Indeed, tests carried out in a tank are not so much models of the real situation as reference cases for comparison between forms.

In an ideal scale model experiment the geometry, the physical properties and the kinematics of the full scale situation are all properly reduced so that the forces and motions measured at scale are all correctly proportioned to those that will be experienced

in real life. In reality, even for purely fluid cases, it has proven impossible to achieve proper scaling of all properties so that some compromise and calculated adjustment is always required. The following sections identify some of these issues.

10.2 Icebreaking Mechanisms – Components

It is traditional to divide the problem of icebreaking into discrete mechanical mechanisms. This idea is evident in most of the literature on ship icebreaking analysis and prediction and can be extended to interactions with offshore structures. What differs between researchers is the details of the mechanisms that each identifies as important. To summarize, it is generally agreed that the resistance of a ship can be broken down into three basic mechanisms, those being: **1. breaking or fracturing the ice**, **2. moving the broken ice** after it has been reduced to discrete pieces and **3. hydrodynamic drag** associated with the vessel movement. The tendency in the literature has been to identify these basic mechanisms or variations on the basic theme and then develop an empirical or semi empirical expression for each component mechanism. The total resistance is then the sum of the components. The Lindqvist model presented in Section 9.5 is a good example of one such model. The following discussion of scaling mechanisms in the context of model testing and experimentation is an extension of this idea where the scaling system and the model testing procedures are developed to treat each individual mechanism as a separate measurement and analysis problem. The individual mechanisms are measured, scaled and then summed to yield a prediction for the full-scale situation.

10.3 Requirements of Similarity

Similitude or Similarity is a concept used in testing engineering models that has its origins primarily in work testing fluid flow conditions with scale models. Thus the science of similitude and dimensional analysis originates in the Hydraulic, Naval Architecture, Aeronautic, and Offshore Structure fields in roughly that order of development. In order to provide scalable measurements, a model must have similitude with the real full-scale application. Similitude is achieved if the model and the full scale exhibit **geometric similarity**, **kinematic similarity** and **dynamic similarity**. Similarity and similitude are used interchangeably in this context. The term dynamic similitude is often used to cover all requirements because it implies that geometric and kinematic similitude have already been met, and in the end it is the dynamics of the situation that we are usually most interested in.

Similitude for ice presents a number of challenges, although in theory we should be able to develop similitude requirements for ice and then just apply them. The problems arise for the following reasons:

- Ice is a solid and we are trying to fracture it as part of the scaled process.
- Our testing medium is a mixed solid-fluid (ice in or on water) environment so we have to consider interaction within the medium.
- Ice in nature and in model tests is neither homogeneous nor stationary. Thus the material properties vary in space and in time.
- Ice as a material exhibits strength properties that are difficult to quantify and thus

difficult to scale.

To deal with each of these issues in turn, engineering analysis is usually aimed at keeping a material from fracturing but in this case we are trying to get the ice to fracture. Thus we are loading the ice material beyond linear elastic behavior and into regions of plastic deformation, and/or fracture and ultimately disintegration. None of these mechanisms are particularly well understood, even for well-behaved conventional engineering materials such as say steel or concrete.

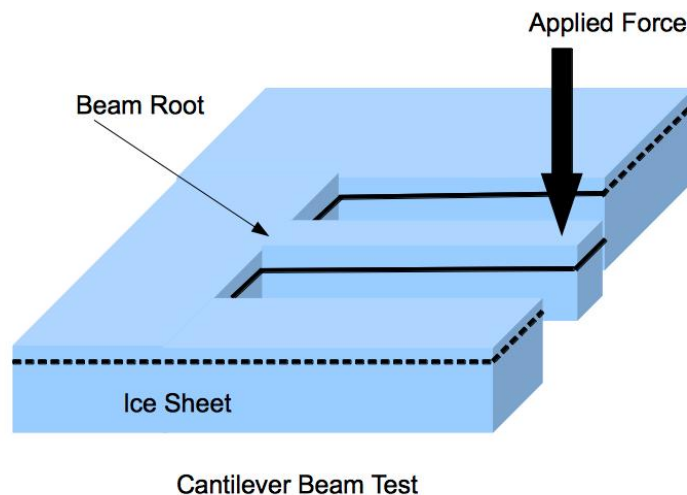


Figure 10.2 Flexural Strength Cantilever Beam test

Thus we tend to use simple measures of ice ultimate strength. The best example of this is Ice Flexural Strength, which is a commonly used gauge of ice strength for both full scale and model scale trials. Flexural strength is derived by loading a cantilever beam sample cut out of an ice sheet until the cantilever fails in tension and breaks away from the sheet (see Figure 13.2). Thus it is a kind of measure of tensile strength. The sample is loaded in a downward direction because that is the way a ship would load the ice. If we loaded the beam in an upward direction the result would be different because the ice is not generally homogeneous through the depth of an ice sheet.

The second issue is that of a mixed fluid-solid medium, which gives us a test material that is not uniform in properties such as air or water would be in conventional fluid tests. We need to separately consider scaling for the fluid water and for the solid ice and we need to keep in mind that there will be interactions between the two. This problem is somewhat mitigated by the fact that the forces associated with breaking the ice are relatively much higher than the fluid forces by themselves. However, at higher interaction speeds, the action of clearing broken ice out of the way leads to similar magnitude forces and is significantly influenced by the interaction between the fluid flow and the motions of the broken ice pieces.

The third issue of material property variations in space and time essentially means that we have to carefully define just what it is we are scaling. Because an ice sheet sits on top

of water it cannot be held at one thickness or strength value either in nature or in an experimental facility. Ice is always either growing or melting and either strengthening or weakening. It cannot be held in equilibrium. In nature there are also many natural irregularities such as spatial variations in thickness, ridging, rafting and large cracks. In fact most icebreaking ships progress by searching out areas of weakness to improve progress and save fuel. Thus we have to carefully decide what our full-scale reference condition is going to be and then we have to carefully measure the actual scaled conditions in an experiment.

The fourth issue is that of the atypical mechanical properties of ice, which have been explained previously in these notes. All these features make it more difficult to scale ice material and mechanical properties using either; ice, chemically modified ices, mechanically modified ices or alternative materials such as paraffin.

In answer to all these issues it is standard procedure to try to scale all the ice mechanical and material properties with an emphasis on those that dominate the flexural failure scenario. This is done to satisfy force similitude considerations for conventional ship-type icebreaking, while maintaining Froude velocity scaling. Experiments that involve other modes of failure or other types of structure may demand that the scaling emphasis be placed on other properties. Timco (in IAHR 1984) gives a good review of ice modeling and its associated problems.

Geometric similarity

Geometric similarity exists between model and prototype if the ratio of all corresponding dimensions in the model and prototype are equal. The ratio is commonly called the scale factor:

$$\frac{L_P}{L_M} = \lambda \quad (10.1)$$

where: L_P is any dimension of the full-scale prototype,
 L_M is any corresponding dimension of the model,
 λ is the scale factor.

This implies that measures of area scale by λ^2 and measures of volume scale by λ^3 . Angles do not have units and thus remain the same at model or full scale. Geometric similarity implies that all dimensions in a model are scaled by the same factor. For Ice this means that we should also scale the dimensions that matter. By general agreement the ice thickness is the most important dimension and the ice grain size is frequently considered as another scaled dimension.

Kinematic similarity

Kinematic similarity is the similarity of time and position. It exists between model and prototype when corresponding fluid velocities and velocity gradients are in the same ratios at corresponding locations. This requires that the paths of moving particles are

geometrically similar and this has the consequence that fluid flow streamline patterns are the same at model scale as they would be at full scale.

Dynamic similarity

Dynamic similarity exists between geometrically and kinematically similar systems if the ratios of all forces in the model and prototype are the same. These ratios are usually determined by so called dimensionless numbers, which set the ratios of different types of forces.

10.4 Dimensionless Numbers

A dimensionless number describes a ratio of quantities, such as forces, that are relevant to the physical system. The number is dimensionless because it is a ratio of two quantities with the same dimensions. Thus the dimensionless number does not change if one alters the units of measurement. Nor does it change with the scale of measurement and thus a dimensionless number is essentially a scaling rule or statement of dynamic similarity – if the ratio of relevant forces is the same at two different scales then forces measured at one scale correspond to those that will be experienced at another scale. Dimensionless numbers are widely applied in the field of fluid and aeronautical engineering.

Dimensionless numbers can be derived using a number of techniques of Dimensional Analysis (See Sharpe, Hydraulic Modeling 1982). According to the Buckingham- π theorem of dimensional analysis, the functional dependence between n variables relevant to a given problem, can be reduced by the number (k) of independent dimensions (for example length, mass and time) occurring in those variables to give a set of $p = n - k$ independent, dimensionless numbers. For the purposes of an experiment, corresponding systems, which share the same value dimensionless numbers, are equivalent. In fluid mechanics the important dimensionless numbers are usually ratios of forces.

Froude Number (Fn) is a ratio of gravitational force to inertial force.

$$Fn = \frac{V}{\sqrt{gL}} \quad (10.2)$$

where V is velocity,

g is gravitational acceleration

L is a relevant length dimension

This ratio is commonly used in testing ships and offshore structures where wave effects are the dominant force mechanism because waves arise from gravitational effects at the free surface between water and air.

Reynolds Number (Re) is a ratio of viscous force to inertial force

$$Re = \frac{VL}{\nu} \quad (10.3)$$

where ν is the kinematic viscosity of the fluid

This ratio is commonly used in fluid testing where there is no free surface consideration for example aircraft or submarines where the vehicle is fully immersed in the fluid. In these cases viscosity and fluid effects arising from viscosity dominate the forces.

Drag Coefficient (Cd) is a ratio of drag force to inertial force

$$Cd = \frac{F_D}{\frac{1}{2}\rho V^2 A} \quad (10.4)$$

where F_D is the measured drag force
 ρ is the fluid density
 A is a relevant area dimension

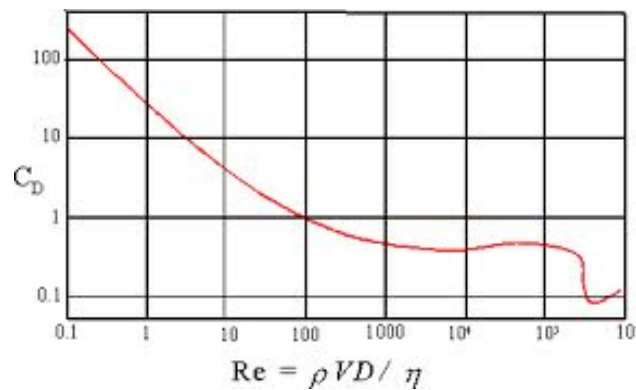


Figure 10.3 Non-dimensional drag coefficient for a smooth cylinder

It is a known problem that for model tests of ships, both the Froude number and the Reynolds number should be satisfied at the same time but that this cannot be achieved if we use water as the fluid medium in both cases. Thus we select the more important mechanism – the wave making resistance – and scale by the Froude number. A calculated correction is made to account for the mis-scaling of the Reynolds number. Tests of offshore structures are also generally conducted using Froude number based scaling on the assumption that the wave-induced forces dominate the viscous forces.

In modeling ice forces we deal with a fluid plus an additional solid material, which requires its own similarity ratios or non-dimensional numbers. Although different researchers use different systems, based on their assessment of what is important, one formulation is to use (see Colbourne & Lever SNAME JSR 1992) the following system:

Ice Froude number – a ratio of gravitational forces to inertial forces for a unit width of ice

$$Fni = \frac{V}{\sqrt{gh}} \quad (10.5)$$

where h is the ice thickness

Ice Strength number – a ratio of ice strength force to the inertial force for a unit width of ice

$$Sn = \frac{V}{\sqrt{\frac{\sigma}{\rho_i}}} \quad (10.6)$$

where ρ_i is the ice density

σ is the ice strength (in flexure – not really a material property)

This parameter was later modified to include a second non-dimensional ratio, the ice thickness to ship beam as this was found to improve data correlation in many cases.

$$Sn = \frac{V}{\sqrt{\frac{\sigma B}{\rho_i h}}} \quad (10.7)$$

where B is the width of the ship or structure breaking the ice

This last addition of additional parameters to a dimensionless number illustrates that dimensional numbers can be compounded by multiplying two pure non dimensional numbers to yield a third number which is still non-dimensional but includes additional effects in the scaling rule.

Ice force coefficient – a ratio of the measured ice induced force to the inertia of a unit block of ice.

$$Ci = \frac{F_i}{\frac{1}{2} \rho_i V^2 B h} \quad (10.8)$$

where F_i is the force arising from the icebreaking.

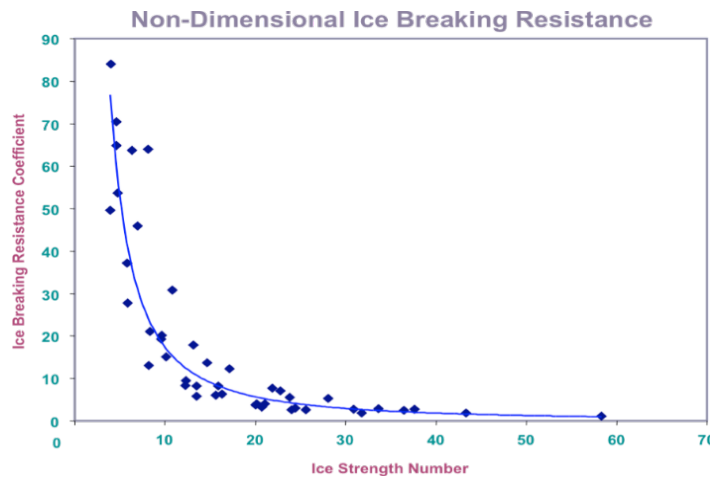


Figure 10.4 Non-dimensional icebreaking resistance

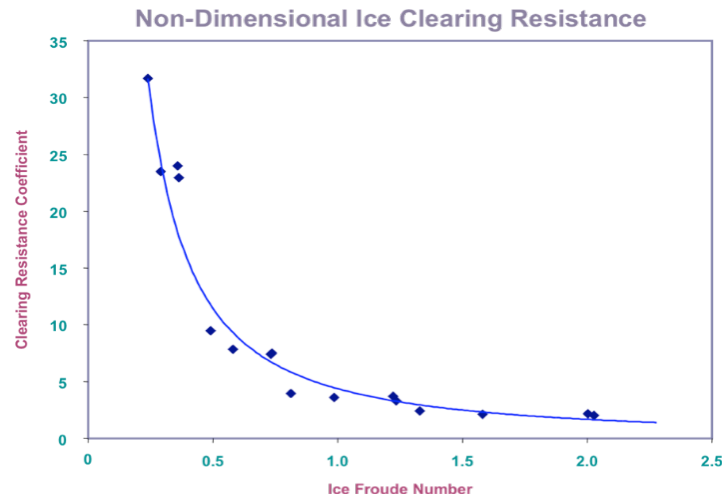


Figure 10.5 Non-dimensional ice clearing resistance

Figure 10.4 and Figure 10.5 show plots of measured icebreaking coefficients against the relevant non-dimensional number. The data points are from a typical icebreaking ship test.

10.5 Model Ice Formulations

In providing a scale model experiment involving a sheet of ice, the ideal situation would be to scale down both the dimensions (thickness and grain size) and the elastic and ultimate strength properties of the ice while maintaining the density and the frictional coefficient as per the dimensionless numbers above. These requirements arise from dimensional and similitude analysis of the problem. However, the model ice that achieves all things has not yet been invented. Scaling thickness is relatively simple, but scaling the strength properties and maintaining appropriate fracturing, crushing and bending characteristics has proven difficult. Most ice tank facilities use frozen water, although some have experimented with mixtures of paraffin and plastics.

Frozen water model ice formulations fall into two basic categories, seeded ice and sprayed ice. Seeded ice is initiated from a layer of small ice crystals sprayed onto the tank water surface and then allowed to grow naturally to the desired thickness based on heat transfer from the tank water to the room air. Sprayed ice is made by continuously spraying ice particles onto the water surface with the air temperature below freezing until the desired sheet thickness is built up from layers of sprayed ice. In both cases strength reduction in model ice is achieved by introducing dopants and controlling grain size. Dopants have included salt, carbamide (urea) and combinations of glycol, detergent and sugar (Timco IAHR 1984). All these formulations exhibit controllable flexural strength in the range of 15 kPa to 100 kPa, with the lower strengths achieved by tempering (warming) the ice sheet. Thus, both forms of model ice are chemically modified and sprayed ice is also mechanically modified. Seeded ice is non-homogeneous and non-isotropic in the way that sea ice is but sprayed ice is essentially homogeneous.

Elastic modulus is in most cases disproportionately low, and for saline and urea formulations, and fracture toughness is too high. It is generally believed that these factors lead to relatively higher energy consumption in scale model icebreaking tests. In providing a sheet of ice for tank testing, the most desirable feature is consistent mechanical properties. Given the nature of ice and scaling requirements for very low strengths, it is difficult to maintain consistent mechanical properties. There is also spatial variation in sheet thickness and mechanical strength over the area of the ice surface. Both properties continually change in time and cannot be arrested in order to conduct a test.

Thus, even in the best of scale model experiments there is a variation in results stemming from variation in ice properties. Furthermore, testing the ice sheet for flexural strength is destructive to the ice and very time consuming. Consequently, it is impractical to measure strength at a large number of locations in an ice sheet at either model scale or even less so at full scale, although thickness can be determined at any number of locations immediately after a test. Also related to ice strength for testing and scaling purposes is the degree of variability in the cantilever beam tests used to assess the flexural strength. Measured strength has been shown to be dependent on sample size, geometry and loading rate [Frederking and Hausler 1978]. Thus, the strength measured at model scale may not correspond directly to that measured in the field.

Another potential concern in a towing tank is the effect of in- plane confinement of ice by the tank walls. The effect of confinement on resistance is not yet clear, but it does not appear to have a great effect on measured resistance. Nevertheless, tests are normally conducted a minimum of 2-3 beam widths from the tank walls to minimize confinement effects.

It is widely reported in the literature on full-scale icebreaking that radial cracks in the ice emanate from the bow area during icebreaking. This radial cracking is not observed in model testing, and generally the ice fails along circumferential lines with limited secondary radial cracking (See Figure 10.9). The net result is still a cusped pattern of broken pieces in the channel similar to that reported for full-scale icebreaking. It is believed that the absence of primary radial cracks is due to a degree of cohesiveness in the model ice, which does not exist at full scale. Whether or not the lack of initial radial cracks in the model case causes an increase in the scaled ice resistance is as yet unproven.

Friction between ice and model surfaces is a problem for which adequate standards have not been established. Frictional coefficients are measured by moving ice samples over a model surface or similarly prepared friction plate. Normal load is varied and tangential force measured. Trends in results have been observed due to sample orientation and this has been attributed to water drainage leading to increased lubrication for some orientations. Trends have also been observed with sliding velocity, normal pressure, and ice temperature. This leaves a great deal of information to reconcile before frictional coefficients can be established. Although frictional coefficients are routinely measured as part of ice testing procedure, they are of limited value except for rough relative comparison between models. At present it is not possible to scale frictional results with

any accuracy. Friction has been shown to be a significant factor in the measured loads on slowly moving ship shapes (Woolgar and Colbourne 2010) at model scale.

Synthetic model ice formulations based on paraffin or other wax like materials have been developed but have been found to improperly model frictional characteristics. These are not widely used.

To date, a model ice formulation that fully satisfies proper scaling of all mechanical properties of natural ice has not been developed. Scale effects in crushing strength and frictional coefficient may require that these properties be adjusted by some factor other than the theoretical scale factor to give an adequate testing medium.

A number of tanks use an ice formulation called EG/AD/S Ice developed at NRCC and formed from a dilute aqueous solution of Ethylene Glycol, Aliphatic Detergent and Sugar in the ratios .40/.03/.04% by weight. Mechanical properties are described in detail in the reference (Timco 1984).

10.6 Ice Testing Techniques

Scale

Most ice tank tests and experiments are conducted at scales between 1:10 and 1:40. This range of scales is dictated by the ability to control the model ice thickness and strength. Minimum sheet thickness is approximately 12 mm with a preference for 20mm and minimum ice strength is 15kPa. Below these levels the ice is either too thin or too soft for practical handling. At a nominal scale of 1:20 this gives a minimum full scale ice thickness of 240-400 mm and a minimum full scale ice strength of 300kPa. These are quite reasonable lower bounds for icebreaking vessels.

Model Propulsion

While propelling a model through ice of limited dimensions, restraint must be placed on some model motions. Common practice is to tow from a point near the centre of gravity. This leads to a model that is not directionally stable and thus requires Yaw restraint. Yaw control on a full-scale vessel is provided by rudder, which is a force-exerting device, but model yaw restraint is a rigid connection applying a fixed displacement. Under fixed restraint, the model is less able to deflect due to asymmetric loads at the bow. This gives higher forces at the bow, probably leading to increased resistance. Consequently, it is expected that the use of rigid yaw restraint results in higher tow forces than would be experienced with a soft restraint.

Restraint in heave, pitch and roll are not normally provided so these motions do not present problems.

A similar condition to the yaw restraint arises in towing. Usually a model is towed at constant speed through the ice. This is contrary to full scale, where propulsion is supplied by a propeller – a force-generating device. Alternately the model can be propelled with a

scaled propulsion system. This is frequently used but suffers from some drawbacks, particularly the difficulty in reaching steady state, given the nature of a propeller drive system and variation in ice failure for even a uniform sheet. The problem is compounded when ice is ingested by the propeller causing fluctuations in measured torque and thrust. Constant speed towing offers greater economy in use of tank time and ice, and improved control of test conditions. The cost is in the realism of the test.

Ice Preparation

The following sections refer to techniques employed by NRC-IOT but are similar to those used in most tanks that use seeded ice. Prior to starting an ice sheet, tank water is cooled by circulating it through water chillers. Cooling efficiency is reduced below 1 deg. C so subsequent cooling is achieved by reducing tank room air temperature below zero and circulating tank water by means of an air bubbler system. Water temperature is monitored by thermocouples mounted in the tank walls and thermistor strings deployed in the tank.

NRC uses seeded ice in which a fine layer of ice crystals is deposited on the water surface to provide a starting layer of ice. Ice seeding is carried out with water temperatures between +0.3 and -0.1 deg. C and an air temperature of -20 deg. C. Remains of previous ice sheets are removed. At the time of seeding, refrigeration fans are switched off to reduce air circulation. The tank is wet seeded by using compressed air and spray nozzles to blow a fine mist of warm water into the air above the water surface. This creates a fog of ice crystals over the length of the tank that fall to the water surface. The seeding process provides an even layer of fine ice crystals on the water surface from which the sheet is nucleated.



Figure 10.6 Cross section of seeded EG/AD/S model ice

At the end of seeding, the refrigeration system is restarted and the freeze cycle commenced. Ice is grown at a temperature of -20 deg. C. During freezing, ice growth averages 2.5 mm/hr. Following completion of the freeze cycle, a warm up and tempering cycle is entered. Over a four hour warm up period, the room temperature is raised to +1

deg. C. The room is held at the 1 deg. C tempering temperature for some time. Tempering serves to weaken the ice to the desired test strength. Because ice growth continues during warm up and tempering, final ice thickness is greater than at the end of freezing. Thus ice thickness must be calculated considering growth rates during the three stages of preparation (freeze, warm up and tempering) and the cycle adjusted for different tempering times.

Different ice strengths are achieved by varying tempering time. As tempering time increases, ice strength decreases. The rate of decrease depends on ice thickness, but the trend for all is a negative exponential curve in time. The strength of an ice sheet cannot be maintained at any given value, so testing must be performed quickly when the strength is at the desired point.

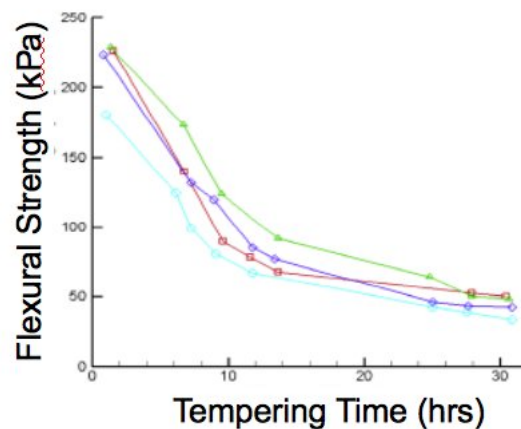


Figure 10.7 Typical model ice strength tempering curves

Ice Properties

Model ice physical and mechanical properties obviously play an important role in testing ships and structures. Model ice formulations differ substantially from the full-scale material and exhibit different mechanical and physical properties. The mechanical properties of the model ice are modified to satisfy certain scaling requirements that are judged to be of primary importance. However, other properties may not be suitably scaled, so a given ice formulation may not be ideal in all respects.

Ice Thickness

Based on ice thickness surveys over the tank area, average deviation in a 40 mm thick tank-grown ice sheet is typically 1 mm or 2.5 % as recorded along the model track. In most practical tests and experiments it is quite easy to survey the ice thickness along the model track after the test is completed and variations in thickness can be accounted for in analyzing results.

Flexural Strength and Fracture Toughness

Flexural strength of EG/AD/S ice can be practically adjusted in the range of 100 kPa to 15 kPa by varying tempering time. At lower strengths the ice starts to lose structural integrity and higher strengths are difficult to achieve unless tank temperature is held below 0 deg. C during testing. Strength is measured by in situ cantilever beam test, using a beam with a thickness-width-length ratio of 1:2:5. Failure load is applied manually using spring balances at moderate loading rates. Reported strength values are typically the mean value of four samples tested at a single location. There is some variation in flexural strength over the tank area. It is not possible to measure this variation completely, due to the time required to perform strength tests and the fact that they are destructive to the ice. Thus spatial variations in ice strength are not so easily accounted for as variations in ice thickness.

Fracture toughness in model and full-scale ice is widely discussed but infrequently measured. A claim of the original EG/AD/S formulation was much lower fracture toughness than previous formulations. However, fracture toughness is somewhat implicitly accounted for in the flexural strength test. Flexural strength testing determines a load to induce fracture without requirement to know flaw distributions. It is not a test of a fundamental material property but an indication of the gross ultimate mechanical strength of a given sample. If it is reasonable to assume that fracture properties will interact in the same way throughout an entire ice sheet, then flexural strength is a reasonable proxy for the effective strength of the ice sheet. However, because flexural strength is not a measure of any single material property, it is reasonable to assume that there will be variations due to scale or changes in geometry. Both these things have been observed in the literature on ice strength testing ([Frederking and Hausler 1978]). Therefore the principal use of flexural strength is as a relative indication of ice strength, much as resistance in level ice is a relative indication of icebreaking performance.

Compressive Strength

Compressive strength of the model ice is recorded by a uniaxial unconfined compression test performed in the in-plane direction on samples cut from the ice sheet. Compressive strength is not judged to be of primary importance in the flexural type failure, and thus it is not usually considered in analysis of ship icebreaking data. However for tests of certain types of structures such as bridge piers or other wall sided structures, the compressive strength may be more important than (or at least as important as) the flexural strength. In these cases a test procedure should be developed to put greater emphasis on measuring the compressive strength and incorporating this measure in the analysis and prediction of full-scale loads.

Elastic Modulus

Elastic modulus can be measured using a static deflection method such as that described in Hirayama (CRREL 1983). This involves recording sheet deflection at the point of application of a static concentrated load. The ice sheet is assumed to be an infinite elastic plate on an elastic foundation. Modulus measurement is usually performed once per ice sheet and used to indicate the E/σ ratio for the sheet. Because the measurement is rate

dependent, it is unlikely that it is a good measure of the effective dynamic elastic modulus at model speeds. At higher speeds, it is expected that the apparent elastic modulus would increase although the extent of this increase is unknown.

Density

Ice density measurements are typically taken once per ice sheet and have been found to correlate well with ice thickness and flexural strength. Effectively this means that the ice becomes denser as it tempers. Ice formulations have been developed at NRC to incorporate air bubbles into the ice sheet during freezing. These voids have a double advantage in that they reduce the density and they improve the fracture properties of the model ice. Density figures for each sheet are determined by cutting a sample from the sheet, measuring the volume and calculating density by measuring the force required to maintain submersion. The volume is calculated by manually measuring the sample dimensions. Values of ice density for the EG/AD/S ice, (without air bubbles) usually fall within the range of 925 to 950 kg/m³. Inclusion of the air bubbles allows the model ice density to be reduced to a more appropriate 900 to 910 kg/m³.

Pre-Sawn Ice Tests

Because we have chosen to divide the icebreaking process into mechanisms of at least icebreaking and ice clearing for the purposes of analysis we should also try and perform experimental measurements that try and measure these two mechanisms, either directly or indirectly. The method that has been developed to achieve this separate measurement of mechanisms or components is the pre-sawn ice test. In this case a model is run through a regular sheet of ice at various speeds and the pattern of icebreaking is observed (most easily in the bow print at the end of a test (Figure 10.9). A second test is then set up where the ice is sawn into a pattern that tries to mimic the pattern of cracks without disturbing the pieces from their positions (Figure 10.8).

The premise is that the second test will have removed any strength effect from the ice and thus the measurement will consist only of the ice clearing and the hydrodynamic resistance while the first test will have measured the ice breaking, the ice clearing and the hydrodynamic resistance. This technique was first introduced in Finland (Enkvist, POAC 1983) and then refined at NRC (Colbourne & Lever SNAME JSR 1992).

Some practitioners also like to add a fourth component, which is the resistance, associated with buoyancy in the ice. This involves a very slow speed test in pre-sawn ice that measures the static load associated with buoyancy.

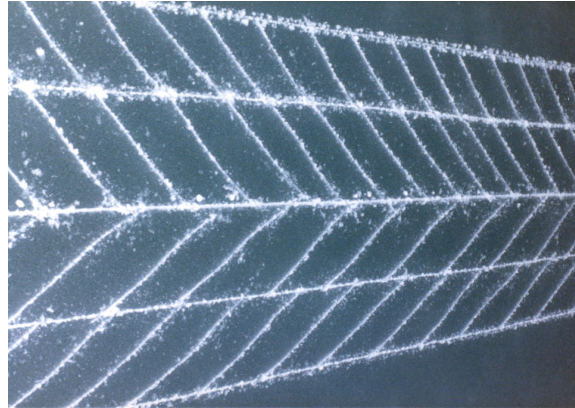


Figure 10.8 Pre-sawn pattern cut in model ice prior to testing



Figure 10.9 Bow-print showing the broken ice pattern for a ship model

Ice cutting is usually accomplished manually using hand-saws. Longitudinal cuts are made by holding the saws in the correct position on the service carriage, with tips in the ice, and running the service carriage down the length of the tank. Cross cuts in the chevron pattern are made by hand sawing as the service carriage moves slowly down the tank in the direction of model travel. Angle of cut can be maintained by towing a large adjustable protractor behind the carriage so that individuals making the cuts have a reference.

10.7 Data Analysis and Full Scale Predictions

A real icebreaking vessel or a stationary offshore structure rarely finds itself in a uniform sheet of level, continuous, flawless ice. However, a uniform sheet of level, continuous, flawless ice is a repeatable and definable condition that provides a good baseline for testing and comparison. Although it can be criticized as unrealistic in terms of actual full-scale conditions, it is preferable to stick with a well defined and controlled condition for research or evaluation purposes. This simplification is analogous to that made by testing for open water resistance in perfectly calm tank conditions.

Model testing in ice presents issues of data reliability that do not arise to as great a degree in other branches of testing. In fluid and aerodynamic fields, the small-scale behavior of the test medium is better understood on an empirical if not a purely theoretical basis. This is not the case for icebreaking. There is a degree of large-scale randomness in ice failure, coupled with variation in mechanical properties over the duration and area of a test. If distributions of these variables are normal, then a resistance value recorded during a test would not be truly repeatable but given sufficient samples at the same conditions, a distribution would be obtained of which the mean could properly be called the mean resistance for the given conditions.

A practical problem in gathering sufficient data for statistical validity is the high cost and time associated with ice testing. For a given sheet of ice it is rare to get more than four or five data points in a day. For thicker sheets the yield is lower, sometimes less than six points per week. Thus, it is a luxurious test program where runs are repeated purely to establish an average resistance for a given set of conditions. Undoubtedly better uniformity in material properties would reduce error, but this would not eliminate the randomness in material failure.

A method of presenting and analyzing data from icebreaking model tests is presented below based on the components and non-dimensional numbers presented earlier. This method requires that pre-sawn tests be conducted in addition to regular level ice tests. It is desirable that as many data points as possible be collected to improve confidence in the curves derived from the data. The primary advantage of this method over previous methods is that all data, regardless of ice strength, ice thickness or model velocity, applies to the same non-dimensional curve. This makes the most efficient use possible of results from all tests. The parameters are non-dimensional and based on ice properties and vessel dimensions that are easily and routinely measured at all ice model tanks, and in many full scale trials.

The steps are:

- 1) Measure model resistance in level ice (R_L) and pre-sawn ice (R_P) at a range of velocity, thickness and strength suitable to cover the required range of Thickness Froude and Ice Strength Numbers:

$$\text{Measure } R_L(\sigma, h, \rho, V) \text{ and } R_P(h, \rho, V)$$

- 2) Calculate viscous drag for the model using an appropriate method (in this case the ITTC method) and subtract it from the pre-sawn resistance to yield an ice clearing resistance:

$$R_C(h, \rho, V) = R_P(h, \rho, V) - R_f(V) \quad (10.9)$$

- 3) Plot $R_C/(1/2 \rho B h V^2)$ vs. $\frac{V}{\sqrt{g h}}$ (Thickness Froude Number) and perform a regression analysis to determine the two constants k_C and a in the equation:

$$\frac{R_C}{\frac{1}{2}\rho_i V^2 B h} = k_C \left[\frac{V}{\sqrt{g h}} \right]^{-a} \quad (10.10)$$

4) Using the clearing regression equation above calculate R_C for each R_L and subtract it and the viscous resistance from each R_L to yield the ice breaking resistance:

$$R_B(\sigma, h, \rho, V) = R_L(\sigma, h, \rho, V) - R_C(h, \rho, V) - R_f(V) \quad (10.11)$$

5) Plot $R_B/(1/2 \rho B h V^2)$ vs. $V/(\sigma B/\rho h)^{1/2}$ (Ice Strength Number) and perform a regression analysis to yield two constants k_B and b in the equation:

$$\frac{R_B}{\frac{1}{2}\rho_i V^2 B h} = k_B \left[\frac{V}{\sqrt{\sigma B/\rho h}} \right]^{-b} \quad (10.12)$$

6) Using appropriate vessel and ice data, calculate model or full-scale resistances based on the two regression equations and a suitable method for calculating viscous drag (skin friction):

$$R_T = R_B + R_C + R_F \quad (10.13)$$

This method provides a means of making full-scale predictions or comparing between models. It eliminates the need to accurately hit target ice conditions in order to compare or scale. The results of this analysis are non-dimensional coefficients for each of the two major mechanisms in the icebreaking process (ice breaking and ice clearing), which are form and friction factor dependent. The drawback of the method is that the friction factor cannot be explicitly separated, and its effect can only be determined by conducting repeat tests at a number of friction factors. Some more recent work has been done to incorporate friction, but this is not yet complete.

Functional singularities at $F_n = 0$ and $S_n = 0$ indicate that the expressions are unable to predict zero speed values of the breaking or clearing components. If the equations are rearranged to solve for R_B or R_C directly, then a zero value for velocity predicts a zero value for either resistance component, unless the exponents, a or b , are greater than 2, in which case the resistance is infinite. Neither approach provides a satisfactory solution for predicting zero speed resistances that are, in fact, both non-zero and finite.

This singularity at zero speed is not seen as a major drawback for two reasons. Zero speed resistance is of little practical value because vessels generally have to achieve minimum speeds, well removed from zero, to maintain progress in ice. Secondly, there is undoubtedly a discontinuity in the resistance curve at zero speed because of differences in static and dynamic friction coefficients and possibly due to differences in ice failure mechanisms at speeds low enough to introduce creep deformation. Thus, any dynamic resistance formulation is unlikely to give a proper prediction of the zero speed resistance values.

The following sections discuss some of the tank procedures typically used to gather the values used in the above equations and the effect of measuring methods on data quality.

In analyzing data from even a simple ice model test, only model speed is controlled sufficiently to ensure consistency from run to run. All other independent variables show some variation from target values. Thus, one is faced with a non-dimensional presentation as a matter of necessity. Even a good non-dimensional presentation will be subject to some random variation.

Raw data collected at the towing carriage consists of model resistance and speed. Model resistance is usually presented as a digital format time series. Quoted resistance is an arithmetic mean of all samples within the time interval of a steady state run, usually over the last 20 to 25 seconds (or at least one model length of travel) of each constant speed interval. Readings of model speed are digitized at the same rate and averaged over the same interval.

Recording information on ice properties is problematic because no aspect of the ice remains static in time. Although there are many properties of an ice sheet that can be measured, the two that are consistently used in ship-ice model and full-scale trials are ice flexural strength and ice thickness.

Flexural strength is monitored by cantilever beam tests as the ice sheet tempers and once before and after each model test. Recorded data are curve fitted to a negative exponential curve in time and this curve used to interpolate ice strength at test time. Strength is usually measured in the middle section of the tank and represents an approximate average for the entire sheet. Local variations in strength are not accounted for.

Ice thickness data are collected immediately after each test. Average thicknesses are computed for each test interval in a sheet. Elastic modulus is not used in analysis of data from ship model test programs, although the information is collected for each sheet to assess the E/σ ratio.

Ice density is recorded for each sheet and extrapolated to test time for each speed interval. This was achieved by deriving a regression equation in strength and thickness based on the readings for all ice sheets in a series. This equation was used to calculate density based on the average thickness and strength for each test interval.

10.8 Data Quality

Some methods used in gathering data for ship ice model tests are necessarily simple and allow considerable room for error. Because final analysis of model resistance requires combinations of measurements, all subject to some degree of error, it is worthwhile to consider the quality and degree of error in each of the variables recorded and used in analysis.

Measured resistance is judged to be of good quality at higher load levels. Background electronic noise in the load cell and data acquisition system has a peak amplitude equivalent to about 5 N of load. This noise is high frequency and does not affect average

resistances. Mechanical stickiness, hysteresis and drift are typically below 3-5 N in calibrations. Thus, a typical measured resistance should have an absolute error of no more than ± 5 newtons.

Model speed, provided by the towing carriage, is accurate to one part in one thousand. Consequently, model speed is judged to be the parameter least subject to variation.

Ice properties are more variable than parameters associated with the model. Ice thickness variation is usually within 5% of the mean value for a sheet. Locally measured thickness in a test interval is usually less variable (on the order of $\pm 3\%$ of the mean thickness in the interval) because values are taken over a smaller area. These are the values used in data reduction.

Flexural strength measurements frequently exhibit 10 to 15% variation even within a narrow test region. Variation across the tank width is of similar magnitude but lengthwise variation is higher. A lengthwise profile of ice strength would typically show a standard deviation of $\pm 10\%$ of the mean. Although quoted average strength is derived from a number of samples, usually eight, and fitted to a smooth curve in time, there can be considerable variation from the mean within an ice sheet.

Elastic modulus measurements are judged to be of good quality with up to ten measurements taken for each reported value. This is however a time consuming test and highly rate dependent. Elastic modulus and E/σ ratio are known to change with tempering time and this change is not routinely monitored making it difficult to predict the modulus at test time. Because E/σ is only used to characterize the ice sheet, this is not a major drawback.

Ice density is also only measured only once per test but is generally well correlated with thickness and strength. The range of variation at maximum is only 3.5% and within the regression for density at test time the error is estimated to be less than 2% even though the measurement error is greater. The results of the foregoing discussion are summarized below (Table 13.1).

Table 10.1 Typical Experimental Errors

PARAMETER	Maximum Expected Error
Measured Resistance	5N or 2-5%
Model Speed	0.1%
Ice Thickness	3%*
Ice Flexural Strength	15%
Ice Density	3%
* within a single speed interval	

Flexural strength is usually the largest single source of variability in the collected data. Because the strength of the ice influences the total resistance measurement, this variable can be expected to show a random variation of about 15%. Pre-sawn resistance is not subject to ice strength and thus should be less variable. This has been confirmed in the

data (see Figure 10.4 and Figure 10.5). Therefore, the derived clearing resistance shows less variability than the total resistance or the derived breaking resistance.

10.9 Consideration of Hydrodynamic Effects

To measure open water or hydrodynamic resistance for ship models, tests are typically conducted in clear water or in the broken channel after clearing out all ice pieces. These tests provide data on the open water resistance of the hull and give an indication of the effect of ice cover on the hydrodynamic resistance when operating in a channel. Resistance in a channel is typically slightly higher than resistance in clear water.

It has been common practice in analysis of icebreaking data to simply separate hydrodynamic resistance by subtracting open water resistance as measured in a clear tank from the total resistance measured in ice. This neglects effects that may arise from the ice sheet on the water surface or coupling between water flow around the bow and ice pieces that are cleared aside.

The higher resistance measured in a channel is thought to be due to the greater capacity of the covered free surface to absorb wave energy, particularly at short wavelengths. Thus, it is more difficult for the model to move water aside because of presence of the ice cover. It is expected that this effect would become more pronounced at higher speeds where larger waves are generated. However, it is not common for icebreakers to operate at these speeds, and thus the increase in resistance due to ice cover is not large in absolute terms.

Evidence of coupling between hydrodynamic flow and ice flow arises when the clear water resistance is subtracted from the pre-sawn resistance. In theory, the difference between these two should be resistance associated with clearing broken ice pieces. Increasing velocity should result in an increase in inertial forces required to push ice aside. However, as speed increases, the difference between pre-sawn resistance and clear water resistance has been observed to level off or decrease. This is attributed to coupling between the flow of water over the hull and the movement of ice pieces as they pass around the model.

Based on these data and experience with previous pre-sawing tests, it is concluded that there is coupling between the flow of water and the flow of broken ice pieces around the vessel, which masks the resistance, associated with clearing ice. Thus we do not subtract the wave-making component of clear water resistance from the pre-sawn resistance. Subtracting viscous resistance on the other hand is viewed as a legitimate step in light of the different scaling requirements. Thus the so-called Ice clearing resistance is derived by calculating viscous skin friction resistance and subtracting it from the pre-sawn resistance. The resultant ice clearing resistance is the sum of wave-making and form drag components of hydrodynamic resistance combined with resistance of moving broken ice around the model hull.

10.10 Differences between Ships and Offshore Structures

Most of the previous discussion applies mainly to the conduct of experiments or model tests of ships in ice, where the ship is making steady progress through the ice at some reasonable speed. When we speak of offshore structures, we are considering a system that is trying to stay in one place. The structure can be either fixed or floating which in the main determines how much movement the structure is designed to exhibit under environmental loading. Ice loads are usually the highest environmental load that a structure is going to see and thus the ice load most often drives the design.

In the simplest cases, an offshore structure has at least two important differences from a ship in the conduct of scale model ice measurements:

- The structure is stationary, and the ice is moving,
- The relative velocity between ice and structure is low.

These features require some thought in the conduct of experiments or scale model tests. In ice model basins it is not practical to move the ice sheet in a way the reasonably mimics nature. Any mechanical pushing of an ice sheet tends to break or buckle it and if we are dealing with broken pack ice, pushing it just tends to bunch all the ice together. Thus we most often invert the situation and even for a stationary structure, we move the



Figure 10.10 Confederation Bridge showing icebreaking cones at the waterline

structure through the ice. If it is a fixed structure it is towed on a very rigid attachment and if it is a moored floating structure then the towing attachment consists of relatively low-rate springs that mimic the compliance of the full-scale mooring. In this latter case it is necessary to measure both the loads and the relative motions of the structure during the interaction with ice.

The relatively slow velocity of natural ice movements leads to much slower test speeds when evaluating offshore structures. This has implications for the ice material properties because the strength is known to be rate dependent, particularly in model ice. In addition, it is common for fixed structures to be fitted with upward-breaking cones at the ice interaction zone (see the Confederation Bridge Figure Below) and this requires that the ice flexural strength be quantified in the upward direction.

Towing system dynamics are also relevant to the nature of measured loads for both ships and offshore structures but probably more importantly for offshore structures. With fixed speed towing, the towing post and model form a mass-spring combination that will vibrate when excited. Forces exerted on the model by ice are cyclic and of considerably higher magnitude than those in an open water test. It is desirable to avoid resonance, but this may not always be possible in modeling real mooring systems. In ship towing the

natural frequency of the tow post-model combination is much higher than the range of fundamental frequencies arising from the ship model-ice interaction.

The towing arrangement can be stiff with a high natural frequency or soft with a low natural frequency. A soft system is most often used to model full-scale moored systems such as FPSOs. Rigid systems are used for ship towing and for fixed offshore structures but the system stiffness has an effect on recorded results. Given the nature of icebreaking, even at model scale, vibrational noise is generated and filtered by the towing system. This filtered noise is recorded as fluctuation in force at or near the natural frequency of the towing system. Indeed, most high peaks observed in resistance traces are due to vibration in the towing system and not model-ice interaction events. Account must be made for this in data analysis.

Chapter 10: Problems

11 Ice regulations and standards

11.1 Ice class rules for ships

There are generally two broad classes of ice rules for ships that reflect the type of ice conditions. There are Polar classes, intended for ships operating in the relatively heavy sea ice of the polar regions (Arctic and Antarctic) and there are sub-polar or general ice classes intended for ships operating in winter ice in sub-polar regions including the Baltic Sea, Canada's East Coast and Great Lakes, Russian far east, China's Bohai Bay, and a few other seas with first year ice.

Baltic Ice Class Rules

General ice classes are found in most classifications society's rules, though the most widely used and supported rules are those of the Finnish-Swedish Maritime Administration, which develops and maintains rules for the Baltic. There are six ice classes in the system. Each class is defined according to the type of ice going operations that the ship can safely engage in (in the Baltic). The Finnish-Swedish Maritime Administration maintains a fleet of icebreakers, which assist shipping, if the ships comply with the regulations. This is the primary incentive for ships to ice class and is essentially an economic incentive. Ships with insufficient ice class will be charged higher fairway dues and will not be assisted in getting in and out of ports in the Baltic (see Figure 11.1 for class descriptions) .

1. **ice class IA Super**; ships with such structure, engine output and other properties that they are normally capable of navigating in **difficult ice conditions without the assistance of icebreakers**;
2. **ice class IA**; ships with such structure, engine output and other properties that they are capable of navigating in **difficult ice conditions, with the assistance of icebreakers** when necessary;
3. **ice class IB**; ships with such structure, engine output and other properties that they are capable of navigating in **moderate ice conditions**, with the assistance of icebreakers when necessary;
4. **ice class IC**; ships with such structure, engine output and other properties that they are capable of navigating in **light ice conditions**, with the assistance of icebreakers when necessary;
5. **ice class II**; ships that have a steel hull and that are structurally fit for navigation in the open sea and that, despite not being strengthened for navigation in ice, are capable of navigating in **very light ice conditions** with their own propulsion machinery;
6. **ice class III**; ships that **do not belong to the ice classes** referred to in paragraphs 1-5.

Figure 11.1 Ice Classes in the Finnish Maritime Administration (FMA) Ice Class Rules

The Baltic Ice Class Rules require strengthening of a belt around the ship as shown in Figure 11.2. The strengthening is exactly specified in the rules. For example, Figure 11.3 shows the requirement for the shell plate thickness. There are rules for framing and powering as well. The strengthening and powering requirements are functions of the ship size and layout.

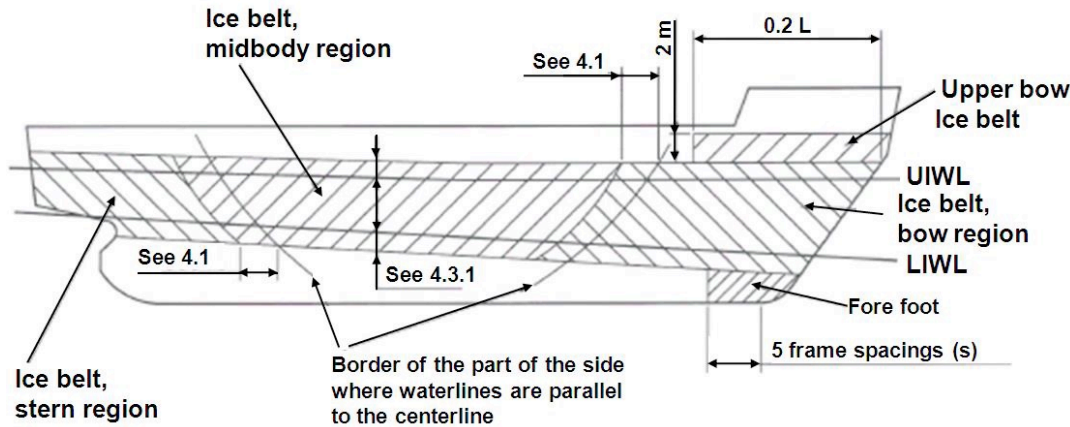


Figure 11.2 Ice Belt Regions in the Finnish Maritime Administration (FMA) Ice Class Rules

4.3.2 Plate thickness in the ice belt

For transverse framing the thickness of the shell plating shall be determined by the formula:

$$t = 667 s \sqrt{\frac{f_1 \cdot p_{PL}}{\sigma_y}} + t_c [\text{mm}]$$

Figure 11.3 Extract from the FMA Rules (Baltic Ice Rules)

The Baltic Rules are part of a comprehensive transportation network and as such are intended serve economic as well as safety goals. The rules are continually reviewed and are slowly changing, but there is a substantial investment in the present system. This tends to make changes difficult. The philosophy behind the rules is somewhat old, but the system has been very successful and as such is difficult to criticize.

Some key aspects of the Baltic rules that are noteworthy from a load and strength perspective are as follows:

The Baltic rules define the load as a line load at the waterline, with a specified height (dependent on class) and pressure (dependent on class, ship size and power). The pressure definition contains a term related to the square root of the product of displacement and power. While one can imagine that these terms affect the pressure, there is only some empirical suggest this influence, and even that is not especially compelling. There is no ice mechanics based load formulation underlying the rules.

The rules define strength in terms of yield. Some newer rules systems make use of plastic strength requirements. There can be significant variations in the ratio of elastic to plastic strength so some update in this direction is warranted and may occur soon.

The rules are relatively straight forward, so that determining the required plate thickness or frame modulus is readily calculated with a simple spreadsheet.

The Finnish Maritime Administration maintains a web site where ice rules and other ice information can be obtained. The general site is at

https://www.trafi.fi/en/maritime/ice_classes_of_ships

The specific location where the latest ice class rules can be downloaded is currently:

https://www.trafi.fi/filebank/a/1510737568/021da3a49321139231df027d50ff5b13/28389-TRAFI_494_131_03_04_01_00_2016_EN_Jaaluokkamaarays_2017.pdf

Polar Class Rules

The International Association of Classification Societies (IACS) has recently issued a set of Unified Requirements for Polar Ship construction. These are intended to replace the member societies' current Rules and to provide alternatives to national systems such as the Canadian Arctic Shipping Pollution Prevention Regulations (ASPPR) and standards.

The definitions for the 7 polar classes are given in Table 11.1 The key aspect is that polar classes are designed for at least some ability to deal with multi-year ice, which distinguishes polar sea ice from the sub-polar regions.

Figure 11.4 and shows the hull areas to be ice strengthened. The entire exterior (wetted) hull must be strengthened, as ice may contact any part. This is a key feature distinguishing the Baltic and Polar rules. Other distinguishing features include:

- The Polar rules use plastic limit states for determining required shell structure
- The Polar rules base the load on a defined collision scenario, with a load and response formulation that is analytically derivable.
- The load formulations do depend on assumed speeds but are insensitive to installed power.
- The Polar rules contain requirements for hull girder strength, as ramming heavy ice can hazard the hull girder.
- The steps required to check or design a Polar rules ship are a bit more lengthy compared to the Baltic rules, though a spreadsheet can readily be written to accomplish the task.

Table 11.1 Polar Classes

POLAR CLASS	GENERAL DESCRIPTION
PC 1	Year-round operation in all Polar Waters
PC 2	Year-round operation in moderate multi-year ice conditions
PC 3	Year-round operation in second- year ice with old ice inclusions
PC 4	Year-round operation in thick first-year ice which may contain old ice inclusions
PC 5	Year-round operation in medium first-year ice with old ice inclusions
PC 6	Summer/autumn operation in medium first-year ice with old ice inclusions
PC 7	Summer/autumn operation in thin first-year ice with old ice inclusions

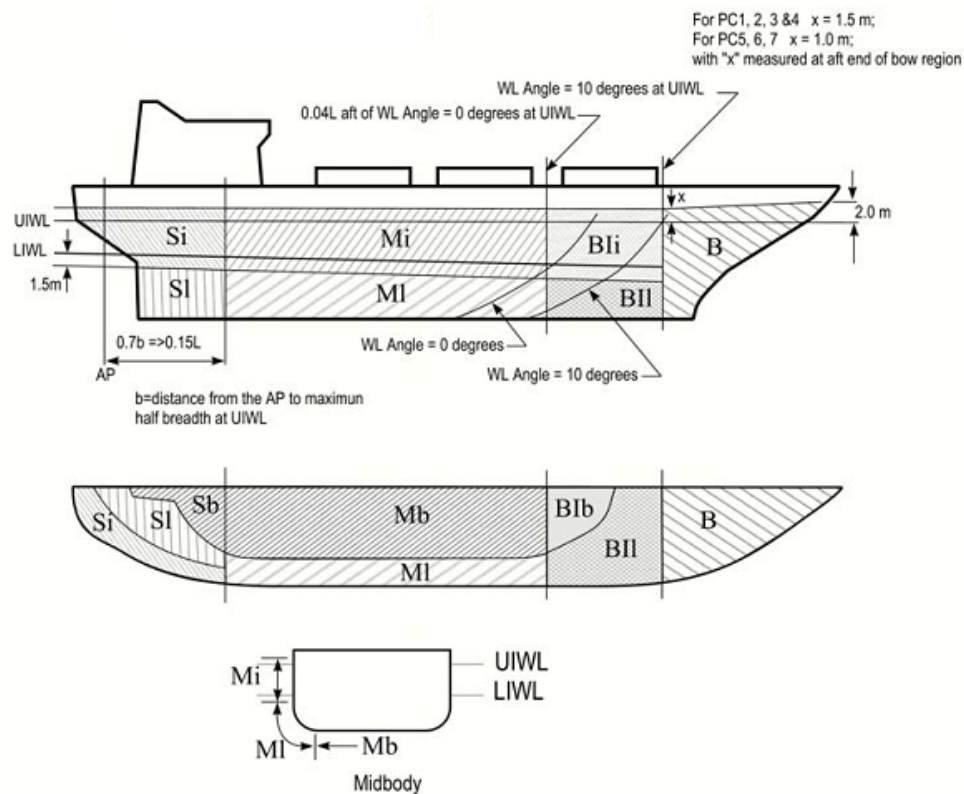


Figure 11.4 Hull Areas in the IACS Polar Class Rules

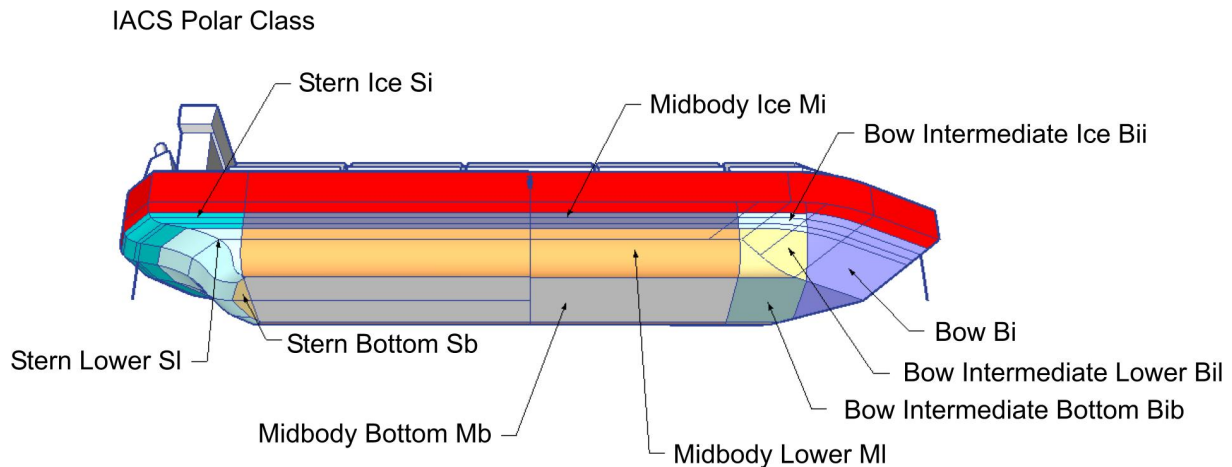


Figure 11.5 Hull Areas in the IACS Polar Class Rules (3D)

Like the Baltic rules, and ship rules in general, there are specific dimensional requirements for the various components in the ship. For example Figure 11.6 shows the requirements for the shear area of transverse frames. This differs considerably from the common practice in the offshore.

I2.6.2 The actual net effective shear area of the frame, A_w , as defined in I2.5.7, is to comply with the following condition: $A_w \geq A_t$, where:

$$A_t = 100^2 * 0.5 * LL * s * (AF * PPF_t * P_{avg}) / (0.577 * \sigma_y) \text{ [cm}^2\text{]} \quad \text{[Equation 22]}$$

where LL = length of loaded portion of span
 = lesser of a and b [m]
 a = frame span as defined in I2.5.5 [m]
 b = height of design ice load patch according to Equation 12 or 14 [m]
 s = transverse frame spacing [m]
 AF = Hull Area Factor from Table 3
 PPF_t = Peak Pressure Factor from Table 2
 P_{avg} = average pressure within load patch according to Equation 15 [MPa]
 σ_y = minimum upper yield stress of the material [N/mm²]

Figure 11.6 Example text from the IACS Polar Class Rules

The International Association of Classification Societies maintains a web site at:

<http://www.iacs.org.uk>

The text of the Polar Rules can be found at:

http://www.iacs.org.uk/document/public/Publications/Unified_requirements/PDF/UR_I_pdf410.pdf

11.2 Ice codes for offshore structures

There are a variety of codes for offshore structures. The codes have many features in common, both with each other and with building codes for land structures. There are significant differences in approach in comparison to codes for ship structures. Each offshore structure is quite unique and intended for a specific site. As such, its specific structural philosophy is to be determined uniquely. This is reflected in the offshore codes, which only prescribe a methodology for arriving at structure, and do not give precise allowable structure. This is in contrast with ships, where the specific structure is mandated.

In Canada, the CSA (Canadian Standards Association) developed a code called S471: Code for the Design, Construction and Installation of Fixed Offshore Structures. The code contains a variety of general and topical provisions, including the establishment of an overall safety level and recommendations concerning the calculation of ice loads.

S471 defines two safety classes depending on severity.

- Safety Class 1 - failure would result in great risk to life or a high potential for environmental damage
- Safety Class 2 - failure would result in small risk to life and a low potential for environmental damage

CSA S471 contains the following target annual reliability levels:

- Ultimate limit state, Safety Class 1: $1/100,000$
- Ultimate limit state, Safety Class 2: $1/1000$
- Serviceability limit state: $1/10$

These are considered to be desirable values and are not necessarily met under all loading conditions. These values do not account for advantageous effects of structural redundancy, reserve capacity and ductility. Consequently, the reliability level in a structure designed in accordance with the code provisions may exceed these levels. On the other hand, the unique nature of offshore structures means that there is no long-term data on any particular approach, so there is no way of empirically validating the reliability. If offshore structures were to actually achieve safety levels of $1/100,000$ per annum, that would mean that even with 1000 fixed offshore structures world-wide, we would have to wait approx. 100 years (on average) between major disasters. The current record is not so comforting. Clearly the design reliability targets are notional targets rather than specifications.

In the case of ice loads in CSA S471, there is an appendix that guides the designer in considering the various issues. Figure 11.7 is an extract from the ice loads appendix, and introduces the strategy to be employed. The designer is given general guidance on what to do, though the specific load calculations require both extensive site-specific data, and expert knowledge in the methods used in ice engineering to calculate loads. The loads and process have not been 'codified' to allow a (non-ice expert) designer to determine the ice loads.

Unfortunately, even the experts don't agree on the ice loads. One group of experts compared the load values that they felt would be required by four different international codes. Table 11.2 illustrates the situation. The different codes result in ice loads (for a given scenario) varying by a factor of 6 to 10 times. Another study compared values that 20 experts would arrive at, for a single well-defined scenario, by whatever means they felt was best. Figure 11.8 shows the range of answers, varying by almost 3 times.

The underlying reason for such lack of agreement is related to our lack of understanding of the true nature and mechanics of ice loads. Some feel that the lack of such knowledge is one reason why a probabilistic approach is warranted. However, reliability calculations are quite sensitive to the load level. A 10% difference in load translates into a very large difference in probability. The imprecision in our load models, coupled with the imprecision in our ability to even anticipate the nature of all the risks that structures face, means that detailed mathematical risk calculations can be elaborate, but un-checkable exercises. Luckily, most specialists do understand this, and have begun to focus more on developing knowledge than on over-using the mathematical theory of probability. HAZID (Hazard Identification) studies are being used more and more. Such studies are largely qualitative, and help to identify the myriad of issues and potential weaknesses in a design.

E2.1 Overview of Strategy

A block diagram of the logic and a procedure to estimate ice design loads for offshore structures is provided in Figure E1. The different steps are as follows:

- (a) identifying the ice loading scenarios that apply for a specific location;
- (b) determining the ice loading models that should be considered; and
- (c) obtaining the ice information required to compute ice loads for specified annual probability levels.

Figure 11.7 Ice load estimation strategy in CSA S471.

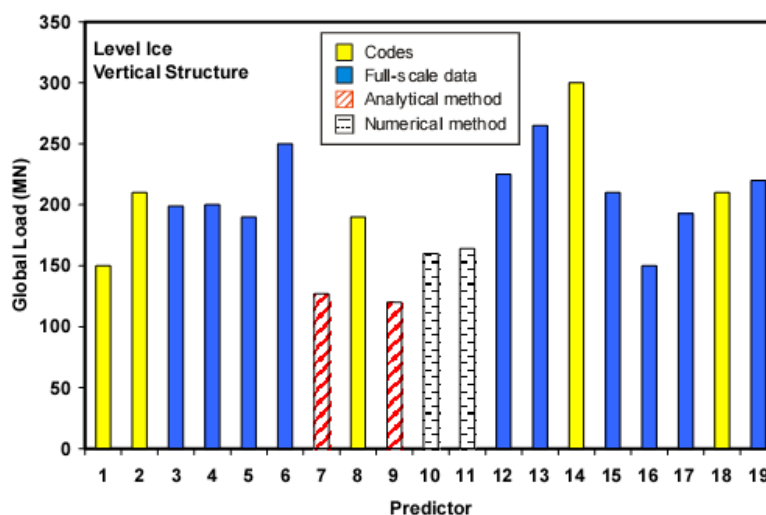


Figure 11.8 Comparison of Ice Load Predictions by 19 Specialists (Timco and Croasdale, 2006)

Table 11.2 Comparison of Ice Load Calculations (Sandwell, 1998)

Item	CSA	API LRFD	SNiP	VSN
Scenario 1 - Level Ice	• 100 MN • limit stress at upper bound of empirical large scale data	• 180 MN • limit stress at mean + 2 SD of ice pressure/area data	• 598 MN • formula (121) for monopod structures or • 159 MN formula (122) for wide structures • limit stress at Korzhavin stress with no size effect	• 172 MN • limit stress at Korzhavin stress with no size effect
Scenario 2 - FY Ridge	• 127 MN • limit stress at crushing of consolidated layer at upper bound of empirical large scale data • clearing of sail and keel rubble	• 239 MN • limit stress at crushing of consolidated layer at mean + 2 SD of ice pressure/area data • clearing of sail and keel rubble	• 896 to 1195 MN formula (121) for monopod structures or • 239 to 319 MN formula (122) for wide structures • application of a 'ridge coefficient' to the level ice load • no explicit consideration of consolidation or rubble in sail or keel	• 257 MN • application of a 'ridge coefficient' to the level ice load • no explicit consideration of consolidation or rubble in sail or keel
Scenario 3 - Partial Ice Coverage	• Scenario not covered • load same as Scenario 1	• Scenario not covered • load same as Scenario 1	• Scenario not covered • load same as Scenario 1	• Scenario not covered • load same as Scenario 1

from - Comparison of International Codes for Ice Loads on Offshore Structures
PERD Report 11-20, 1998

11.3 ISO Arctic Structures Standard

In 2010 a new standard for Arctic Structures design was published by ISO and this standard was adopted as a Canadian National Standard in 2011. ISO 19906-2010 specifies requirements and provides guidance for the design, construction, and installation of offshore structures in arctic and cold regions. For the purposes of the standard, the definition of arctic and cold regions is deemed to include both the Arctic and other cold regions that are subject to sea ice, iceberg and/or icing conditions. The objective of ISO 19906 is to ensure that arctic offshore structures provide an appropriate level of reliability with respect to personnel safety, environmental protection and asset integrity.

Development of ISO 19906 started in 2000 when several factors provided an impetus for the development of a new global standard for arctic offshore structures. ISO formed an international working group to develop a new standard as part of the ISO 19000 (Offshore Petroleum and Natural Gas) series, to harmonise regional and national standards and to include the latest knowledge.

Significant factors that lead to development of a new standard included:

1. Several codes and standards for structures in ice existed. Even the best of those did not provide the same methodology for the design of an in-ice offshore structure.
2. New and proposed activities in Arctic regions created an interest in establishing a common basis for the design of structures for exploration and production in these areas.
3. Experience with measured ice loading from offshore structures deployed in the Beaufort Sea during the 1980s and newer research projects, and measurement of ice loads in China, on the Confederation Bridge in Canada and in Japan, provided new insights into ice loads and ice behaviour which could be incorporated into the new standard.
4. Advances in analysis of measured data and in the calculation of ice loads on structures were thought to have improved the reliability of predictions of ice loads.
5. A number of ice capable structures designed for a given region had subsequently been redeployed in another. These changes in location would have been simplified by the worldwide adoption of a single International Standard.
6. Government regulators and industry would benefit from the introduction of a single internationally recognised standard focusing on structures design for ice environments.

The new standard is still in the early stages of use by the industry and it is expected that as usage increases that the standard will be further revised and updated as new working experience is gained.

Table 11.3 below gives the contents of the standard which goes a bit beyond most previous offshore structures standards for arctic regions in that it considers Ice Management and issues of Escape Evacuation and Rescue.

Table 11.3 Contents of ISO 19906 Standard

ISO 19906 Arctic Offshore Structures (2010)	
Contents	
Section #	Section Title
1	Scope
2	Normative References
3	Terms and Definitions
4	Symbols and Abbreviated Terms
5	General Requirements and Conditions
6	Physical Environmental Conditions
7	Reliability and Limit States Design
8	Actions and Action Effects
9	Foundation Design
10	Man-made Islands
11	Fixed Steel Structures
12	Fixed Concrete Structures
13	Floating Structures
14	Subsea Production Systems
15	Topsides
16	Other Ice Engineering Topics
17	Ice Management
18	Escape, Evacuation and Rescue

As an example of the way the ISO Standard is specified in terms of reliability, in broad terms the document defines ice resistance or strengthening requirements as follows:

If the ALIE event occurs, the facility can be damaged, but there should be no loss of life or significant pollution to the environment.

This type of specification reflects a general trend of specifying required system performance based on probabilities of occurrence rather than specific instruction about how a structure should be built.

Chapter 11: Problems

11.1 Consider a design problem involving the development of an oil production structure for the arctic. The intended location is in northern Baffin Bay, in 150meters of water. There is sea ice and icebergs to be contended with.

- a) What sort of structures and design options would you consider for this case?

- b) What are the jurisdictional and regulatory issues that you would consider to be important?
- c) Discuss the factors that you would think are most important to a risk assessment of the possibility of ice damage?
- d) What codes and standards would you use to help with the design?

12 Safe Operations of Ice Class Ships

Introduction

Ice Class ships are assigned a class based on how they are constructed (primarily hull and propulsion capabilities). There are many different ice classes that reflect the fact that ice conditions can vary widely. Table 11.1 in the previous chapter gives a general definition of the Polar Classes and nominal capability. Figure 11.1 provides a similar overview of the Baltic classes. In actual operations the ice conditions can be quite complex. Safe operations depend on an understanding of the specific ice conditions and how to safely proceed. Traditionally the safe operation of a ship in ice was completely left to the vessel captain. Different countries have developed icebreaker fleets and provide icebreaker assistance, depending on the national policies. Sweden and Finland maintain significant icebreaker fleets and help ice class vessels navigate to all Swedish and Finnish ports in winter. The icebreaker services are provided to ships that pay fairway dues and follow the requirements of the Finish-Swedish Ice Class Rules). Russia has a similar policy of requiring ships transiting the Northern Sea Route to charter Russian icebreakers to assist. Icebreakers not only provide direct icebreaking support, but also provide information and guidance based on extensive experience in ice.

Canada has an icebreaking fleet, but due to the size of Canadian waters, does not promise to support all ships in ice. Canada expects that ships will normally conduct independent operations in ice. Canadian government icebreakers are multi-purpose vessels, providing a combination of services including escort as needed, search and rescue, environmental response, navigations systems support, resupply to arctic communities and various forms of science support and data collection.

12.1 Zone/Date System

Starting in the 1970's, Canada introduced a method to control shipping in the arctic, and attempt to ensure safety. After a study of historical ice patterns, the Zone/Date System (Z/DS) was introduced. Figure 12.1 shows the 16 Zones identified. Generally Zones with higher numbers had easier ice conditions. Figure 12.2 shows the dates that ships of various classes were permitted access to the zones. The Classes listed refer to the old ASPPR Classes. In that system Type A was equivalent to the FSICR Class 1ASuper, Type B was equivalent to the FSICR Class 1A, Type C was equivalent to the FSICR Class 1B, Type D was equivalent to the FSICR Class 1C. Type E was essentially non-ice class. At the time many equivalent ice classes were developed by many Classification Societies. Figure 12.3 shows the correspondence between the Type classes.

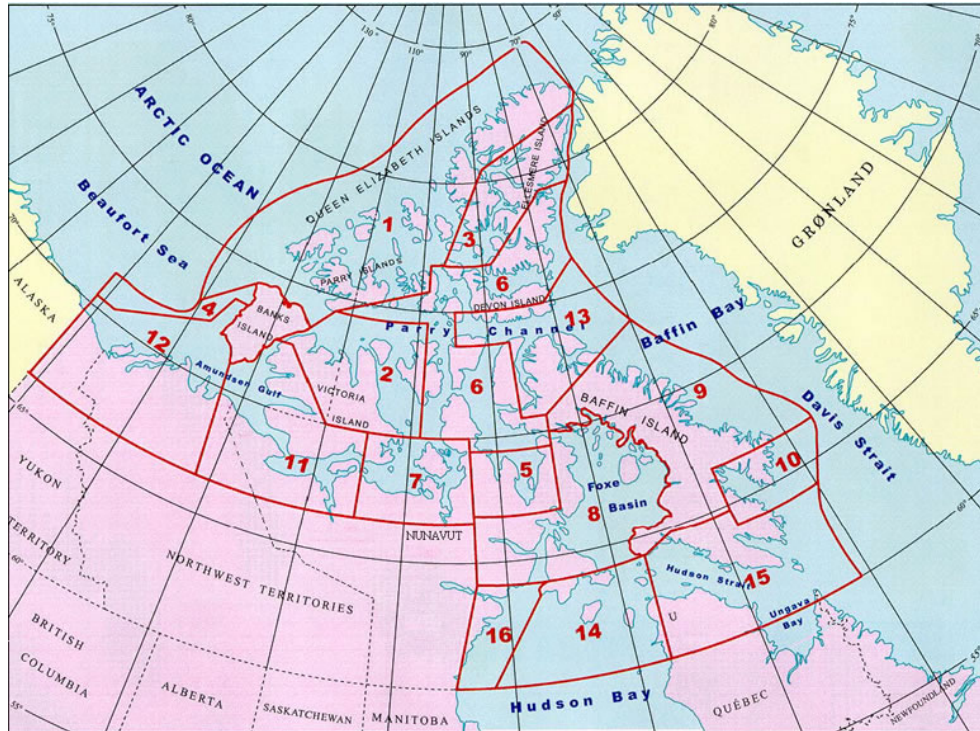


Figure 12.1 Zones in the Canadian Arctic Shipping Pollution Prevention Regulations

Item	Col. I Category	Col. II Zone 1	Col. III Zone 2	Col. IV Zone 3	Col. V Zone 4	Col. VI Zone 5	Col. VII Zone 6	Col. VIII Zone 7	Col. IX Zone 8	Col. X Zone 9	Col. XI Zone 10	Col. XII Zone 11	Col. XIII Zone 12	Col. XIV Zone 13	Col. XV Zone 14	Col. XVI Zone 15	Col. XVII Zone 16
1.	Arctic Class 10	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year
2.	Arctic Class 8	July 1 to Oct. 15	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year
3.	Arctic Class 7	Aug. 1 to Sept. 30	Aug. 1 to Nov. 30	July 1 to Dec. 31	July 1 to Dec. 15	July 1 to Dec. 15	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year	All Year
4.	Arctic Class 6	Aug. 15 to Sept. 15	Aug. 1 to Oct. 31	July 15 to Nov. 30	July 15 to Nov. 30	Aug. 1 to Oct. 15	July 15 to Feb. 28	July 1 to Mar. 31	July 1 to Mar. 31	All Year	All Year	July 1 to Mar. 31	All Year	All Year	All Year	All Year	All Year
5.	Arctic Class 4	Aug. 15 to Sept. 15	Aug. 15 to Oct. 15	July 15 to Oct. 31	July 15 to Nov. 15	Aug. 15 to Sept. 30	July 20 to Dec. 31	July 15 to Jan. 15	July 15 to Jan. 15	July 10 to Mar. 31	July 10 to Feb. 28	July 5 to Jan. 15	June 1 to Jan. 31	June 1 to Feb. 15	June 15 to Feb. 15	June 15 to Mar. 15	June 1 to Feb. 15
6.	Arctic Class 3	Aug. 20 to Sept. 15	Aug. 20 to Sept. 30	July 25 to Oct. 15	July 20 to Nov. 5	Aug. 20 to Sept. 25	Aug. 1 to Nov. 30	July 20 to Dec. 15	July 20 to Dec. 31	July 20 to Jan. 20	July 15 to Jan. 25	July 5 to Dec. 15	June 10 to Dec. 31	June 10 to Dec. 31	June 20 to Jan. 10	June 20 to Jan. 31	June 5 to Jan. 10
7.	Arctic Class 2	No Entry	No Entry	Aug. 15 to Sept. 30	Aug. 1 to Oct. 31	No Entry	Aug. 15 to Nov. 20	Aug. 1 to Nov. 20	Aug. 1 to Nov. 30	Aug. 1 to Dec. 20	Aug. 1 to Dec. 20	Aug. 1 to Dec. 20	Aug. 1 to Dec. 5	Aug. 1 to Dec. 5	Aug. 1 to Dec. 10	Aug. 1 to Dec. 20	Aug. 1 to Dec. 10
8.	Arctic Class 1A	No Entry	No Entry	Aug. 20 to Sept. 15	Aug. 20 to Sept. 30	No Entry	Aug. 25 to Oct. 31	Aug. 10 to Nov. 5	Aug. 10 to Nov. 20	Aug. 10 to Dec. 10	Aug. 1 to Dec. 10	Aug. 1 to Dec. 10	Aug. 1 to Dec. 10	Aug. 1 to Dec. 10	Aug. 1 to Dec. 10	Aug. 1 to Dec. 10	Aug. 1 to Dec. 10
9.	Arctic Class 1	No Entry	No Entry	No Entry	No Entry	No Entry	Aug. 25 to Sept. 30	Aug. 10 to Oct. 15	Aug. 10 to Oct. 31	Aug. 10 to Oct. 31	Aug. 1 to Oct. 31	Aug. 1 to Oct. 31	Aug. 1 to Oct. 31	Aug. 1 to Oct. 31	Aug. 1 to Oct. 31	Aug. 1 to Oct. 31	Aug. 1 to Oct. 31
10.	Type A	No Entry	No Entry	Aug. 20 to Sept. 10	Aug. 20 to Sept. 20	No Entry	Aug. 15 to Oct. 15	Aug. 1 to Oct. 25	Aug. 1 to Nov. 10	Aug. 1 to Nov. 20	Aug. 1 to Nov. 20	Aug. 1 to Oct. 31	Aug. 1 to Nov. 10	Aug. 1 to Oct. 22	Aug. 1 to Nov. 30	Aug. 1 to Dec. 5	Aug. 1 to Nov. 20
11.	Type B	No Entry	No Entry	Aug. 20 to Sept. 5	Aug. 20 to Sept. 15	No Entry	Aug. 25 to Sept. 30	Aug. 10 to Oct. 15	Aug. 10 to Oct. 31	Aug. 10 to Oct. 31	Aug. 1 to Oct. 31	Aug. 1 to Oct. 31	Aug. 1 to Oct. 25	Aug. 1 to Oct. 15	Aug. 1 to Nov. 30	Aug. 1 to Nov. 30	Aug. 1 to Nov. 10
12.	Type C	No Entry	No Entry	No Entry	No Entry	No Entry	Aug. 25 to Sept. 25	Aug. 10 to Oct. 10	Aug. 10 to Oct. 25	Aug. 10 to Oct. 25	Aug. 1 to Oct. 25	Aug. 1 to Oct. 15	Aug. 1 to Oct. 25	Aug. 1 to Oct. 10	Aug. 1 to Nov. 25	Aug. 1 to Nov. 25	Aug. 1 to Nov. 10
13.	Type D	No Entry	No Entry	No Entry	No Entry	No Entry	No Entry	Aug. 10 to Oct. 5	Aug. 15 to Oct. 20	Aug. 15 to Oct. 20	Aug. 5 to Oct. 20	Aug. 1 to Oct. 10	Aug. 1 to Oct. 20	Aug. 1 to Oct. 20	Aug. 1 to Oct. 20	Aug. 1 to Oct. 20	Aug. 1 to Oct. 31
14.	Type E	No Entry	No Entry	No Entry	No Entry	No Entry	No Entry	Aug. 10 to Sept. 30	Aug. 20 to Oct. 20	Aug. 20 to Oct. 15	Aug. 10 to Oct. 20	Aug. 1 to Sept. 30	Aug. 1 to Oct. 20	Aug. 15 to Sept. 20	Aug. 1 to Oct. 31	Aug. 1 to Nov. 5	Aug. 1 to Oct. 31

Figure 12.2 Zone Entry Dates in Canadian ASPPR

Item	Column 1 Type of Ship	Col. II American Bureau of Shipping	Col. III Bureau Veritas	Col. IV Det Norske Veritas	Col. V Germanischer Lloyd	Col. VI Lloyd's Register of Shipping	Col. VII Nippon Kaiji Kyokai ¹	Col. VIII Polski Rejestr Statkow ¹	Col. IX Register of Shipping of the USSR	Col. X Registro Italiano Navale	Col. XI Registru Naval Roman
1.	Type A	A1 ⊕ Ice strengthening Class AA AMS or A1 ⊕ Ice strengthening Class 1AA AMS	1 3/3 E glace I-super or 1 3/3 E Ice Class 1A Super	1 A 1 ICE A* or 1 A 1 ICE 1A*	100 A 4 E 4 MC	100 A1 Ice Class 1* LMC or 100A1 Ice Class 1A Super LMC	NS* (Class 1A Super Ice strengthening) MNS* or NS* Class AA 1S MNS*	*KM YLA or *KM YL	KM ⊕ YAA or KM ⊕ YA	100A-1.1 RG 1* or 100A-1.1 1AS	RNR ⊕ CM or RNR ⊕ CM or M G 60 O or M G 50 O
2.	Type B	A1 ⊕ Ice strengthening Class A AMS or A1 ⊕ Ice strengthening Class 1A AMS	1 3/3 E glace I or 1 3/3 E Ice Class 1A	1 A 1 ICE A or 1 A 1 ICE 1A	100 A 4 E 3 MC	100 A1 Ice Class 1 LMC or 100A1 Ice Class 1A LMC	NS* (Class 1A Ice strengthening) MNS* or NS* Class A 1S MNS*	*KM L1	KM ⊕ A1	100A-1.1 RG 1 or 100A-1.1 1A	RNR ⊕ CM or M G 40 O
3.	Type C	A1 ⊕ Ice strengthening Class B AMS or A1 ⊕ Ice strengthening Class 1B AMS	1 3/3 E glace II or 1 3/3 E Ice Class 1B	1 A 1 ICE B or 1 A 1 ICE 1B	100 A 4 E 2 MC	100 A1 Ice Class 2 LMC or 100A1 Ice Class 1B LMC	NS* (Class 1B Ice strengthening) MNS* or NS* Class B 1S MNS*	*KM L2	KM ⊕ A2	100A-1.1 RG 2 or 100A-1.1 1B	RNR ⊕ CM or M G 30 O
4.	Type D	A1 ⊕ Ice strengthening Class C AMS or A1 ⊕ Ice strengthening Class 1C AMS	1 3/3 E glace III or 1 3/3 E Ice Class 1C	1 A 1 ICE C or 1A1 ICE 1C	100 A 4 E 1 MC	100 A1 Ice Class 3 LMC or 100A1 Ice Class 1D LMC	NS* (Class 1C Ice strengthening) MNS* or NS* Class C 1S MNS*	*KM L3 or KM L4	KM ⊕ A3	100A-1.1 RG 3 or 100A-1.1 1C	RNR ⊕ CM or M G 20 O
5.	Type E	A1 ⊕ AMS	1 3/3 E	1 A 1	100 A 4 MC	100 A1 LMC	NS* MNS*	*KM	KM ⊕	100A-1.1	RNR ⊕ CM or M O

Figure 12.3 Equivalent Type Classes in the Canadian ASPPR rules.

Canadian Ice Regime System

Following an update of the ASPPR system in the 1980's, it was recognized that the improvements on the zone/date system were needed. The goal was to provide ship operators with a better indication of which ice was safe to operate in. The Arctic Ice Regime Shipping System (AIRSS) was developed in the late 1990s as a way to make a direct link between the actual ice conditions and the capability of a vessel to operate safely. Ice charts (e.g. Figure 4.10) use egg codes to show areas of similar conditions, indicating a mix of ice. The AIRSS approach uses this kind of information to calculate an Ice Numeral to be used to determine if the operations are likely to be safe. The Ice Numeral (IN) is computed by multiplying the concentration of each type of ice by the appropriate Ice Multiplier (IM) associated with that type of ice for the class of the ship, summed for all the types of ice present. Positive IN values indicate permissible conditions, while negative IN values indicate unsafe conditions.

$$IN = \sum_{\text{all ice types}} C_i \cdot IM_{i,c} \quad (12.1)$$

The table of multipliers is shown in Figure 12.4.

		EGG Code								
		-	4	5	8	9	1.	4.	8.	9.
		Stage								
Ice Class		Ice-Free	Grey	GW	TFY1	TFY2	MFY	ThFY	2nd	MY
	CAC1	2	2	2	2	2	2	2	2	2
	CAC2	2	2	2	2	2	2	2	2	2
	CAC3	2	2	2	2	2	2	2	1	-1
	CAC4	2	2	2	2	2	2	1	-2	-3
IAS	Type A	2	2	2	2	2	1	-1	-3	-4
IA	Type B	2	2	1	1	1	-1	-2	-4	-4
IB	Type C	2	2	1	1	-1	-2	-3	-4	-4
IC	Type D	2	2	1	-1	-1	-2	-3	-4	-4
NIS	Type E	2	1	-1	-1	-1	-2	-3	-4	-4

Figure 12.4 Table of Ice Multipliers used in the AIRSS.

AIRSS Example:

Consider a case of a Type A vessel (= FSICR 1ASuper) approaching an area of ice with 3/10th open water, 3/10th thin first year ice, 3/10th medium first year ice and 1/10th multiyear ice. The Ice Numeral would be;

$$IN = 3 \cdot 2 + 3 \cdot 2 + 3 \cdot 1 + 1 \cdot -4 = +11 \quad (12.2)$$

In this case the IN is positive and vessel would be allowed to proceed (with normal caution).

If the conditions had 3/10th multiyear (and 1/10th open water), the IN would be;

$$IN = 1 \cdot 2 + 3 \cdot 2 + 3 \cdot 1 + 3 \cdot -4 = -1 \quad (12.3)$$

In this case the IN is negative and vessel would not be allowed to proceed.

Note that the AIRSS system is only employed in the Canadian Arctic (North of 60 Lat.), and not in sub arctic areas such as the Gulf of St. Lawrence.

IMO Polaris System

Following the Development of the IACS Polar Rules, The International Maritime Organization (IMO) developed a safety standard of polar shipping called the Polar Code. One of the chapters of the Polar Code establishes a guidance system for polar ships that's is generally similar to AIRSS but with differences. The system is called the Polar Operational Limit Assessment Risk Indexing System (POLARIS). POLARIS is essentially an enhanced AIRSS approach, which also uses a sum of products;

$$RIO = \sum_{all \text{ ice types}} C_i \cdot RIV_{i,c} \quad (12.4)$$

Where RIO is Risk Index Outcome, and RIV is Risk Index Value. POLARIS uses finer gradation of ice conditions and a wide range of multipliers than AIRSS (see Figure 12.5).

POLARIS is meant for use in all polar waters. Canada permits the use of either AIRSS or POLARIS in Canadian arctic waters.

MSC.1/Circ.1519 6 June 2016

Class	EGG Code											
	1,2	4	5	8	7	9	1.	1.	4.	8.	9.	7.
Stage	OW	New Ice	Grey ice	Grey white Ice	Thin FY 1st	Thin FY 2nd	Med FY <1m	Med FY	thick FY	2nd Year	Lt MY <2.5m	Heavy MY
PC1	3	3	3	3	2	2	2	2	2	2	1	1
PC2	3	3	3	3	2	2	2	2	2	1	1	0
PC3	3	3	3	3	2	2	2	2	2	1	0	-1
PC4	3	3	3	3	2	2	2	2	2	0	-1	-2
PC5	3	3	3	3	2	2	1	1	0	-1	-2	-2
PC6	3	2	2	2	2	1	1	0	-1	-2	-3	-3
PC7	3	2	2	2	1	1	0	-1	-2	-3	-3	-3
IAS	3	2	2	2	2	1	0	-1	-2	-3	-4	-4
IA	3	2	2	2	1	0	-1	-2	-3	-4	-5	-5
IB	3	2	2	1	0	-1	-2	-3	-4	-5	-6	-6
IC	3	2	1	0	-1	-2	-3	-4	-5	-6	-7	-8
NIS	3	1	0	-1	-2	-3	-4	-5	-6	-7	-8	-8

↓
in this region +1 if ice is decayed

Figure 12.5 Table of Risk Index Values (RIV) used in the POLARIS.

POLARIS Example:

Consider the case of a FSICR 1ASuper vessel approaching an area of ice with 3/10th open water, 3/10th thin first year ice(1st stage), 3/10th medium first year ice (>1m) and 1/10th multiyear ice. The Risk Outcome Index would be;

$$RIO = 3 \cdot 3 + 3 \cdot 2 + 3 \cdot -1 + 1 \cdot -4 = +8 \quad (12.5)$$

In this case the RIO is positive and vessel would be allowed to proceed (with normal caution). If the conditions had 2/10th multiyear (and 2/10th open water), the IN would be;

$$RIO = 2 \cdot 3 + 3 \cdot 2 + 3 \cdot -1 + 2 \cdot -4 = +1 \quad (12.6)$$

In this case the RIO is positive and can proceed, though with caution because the RIO is almost 0.

The example makes it clear that there are fine differences between the AIRSS and POLARIS systems. Please note that both systems have more details than have been presented here.

To delve into the POLARIS system further, consider a situation of just open water and one type (thickness) of ice. Figure 12.6 shows situations that give a RIO of 0 (or greater). The thickness of 6m represents 'any ice', rather than an actual limit, while 4m represents the heaviest ice on the POLARIS Chart (Heavy Multiyear). PC1 and PC2 can go anywhere. Note that all ships, including non-ice class ships can enter conditions that include the heaviest ice, as long as the coverage is low enough. Non-ice class ships can go into 2/10ths of any ice thickness, but no ice at all greater than 8/10th. Figure 12.7 plots the same data with lines for various coverages.

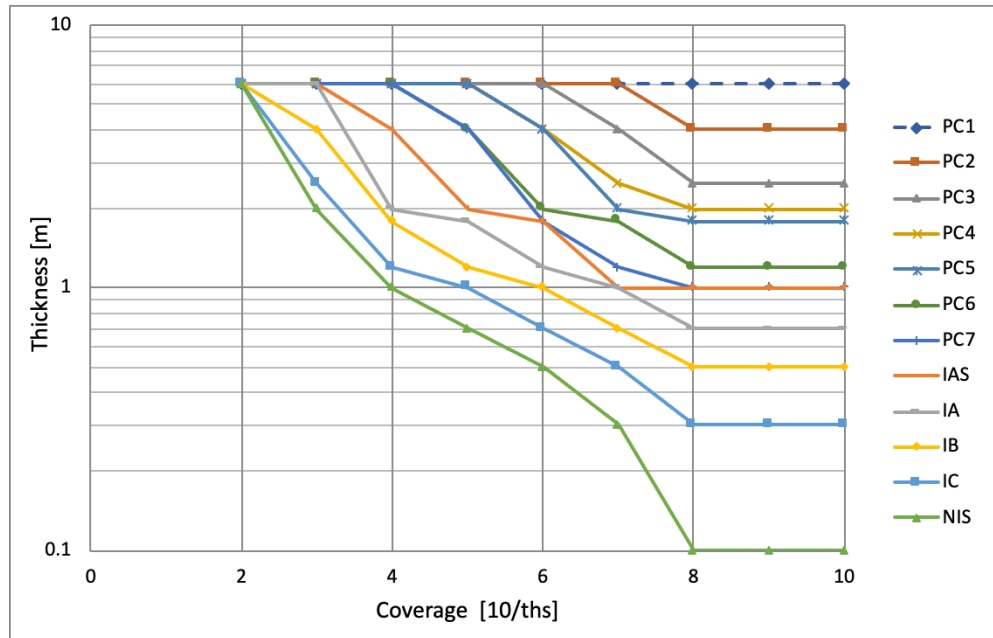


Figure 12.6 Combinations of Thickness, Coverage and Class that give an ROI of 0.

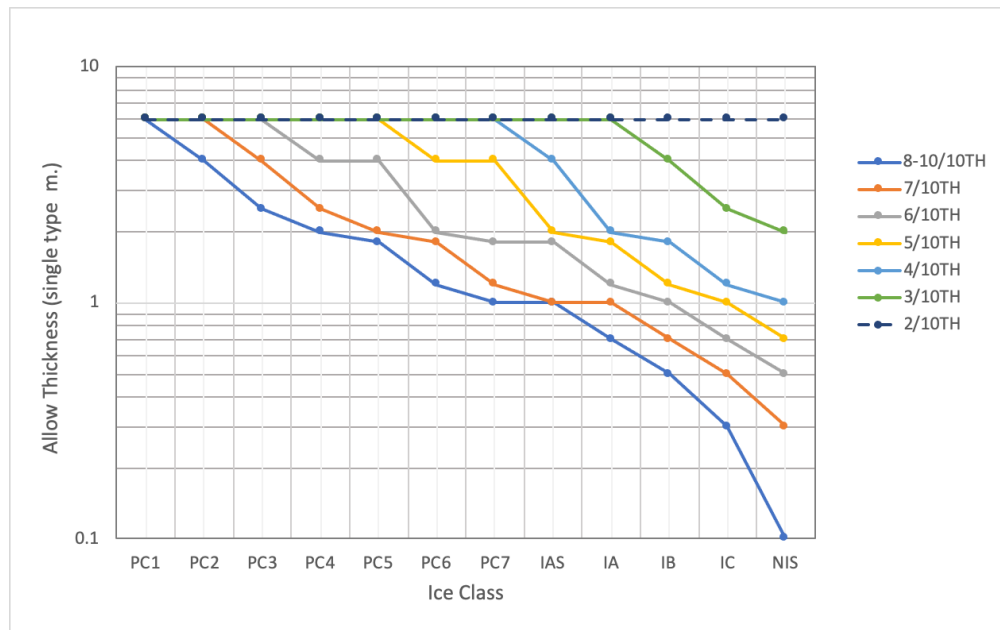


Figure 12.7 Combinations of Thickness, Class give an ROI of 0 (var. coverage).

Figure 12.8 gives an example of a comprehensive map of POLARIS RIO values for a PC5 vessel for March of 2017. This map was developed from a database of ice information from various countries, combined to calculate RIO values for the whole arctic region (courtesy ABS – see Appendix D). Such maps can show where ships could have safely gone at the time, and can give a general idea of what might be safe in future. For actual operations, current ice data is needed, and forward predications are useful.

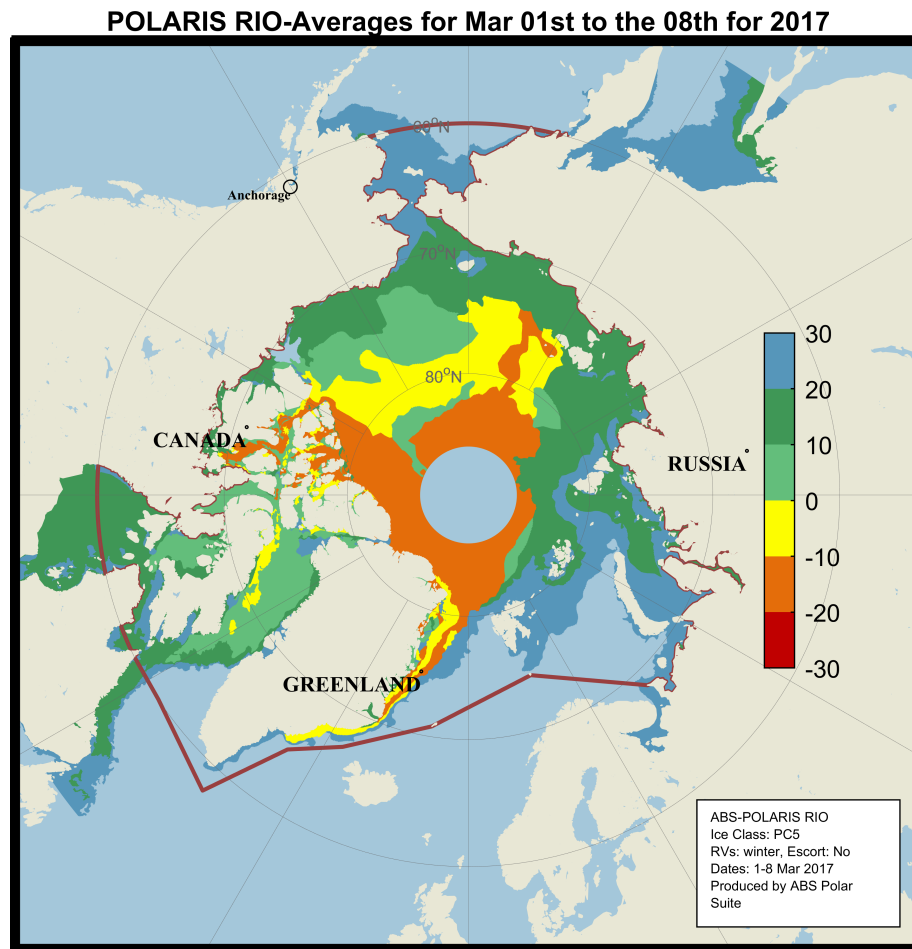


Figure 12.8 POLARIS ROI Map for PC5, March 2017
(from ABS Polar_suite3.1)

Chapter 12 Problems

1. Consider a case of a Type B vessel (= FSICR 1A) approaching an area of ice with $2/10^{\text{th}}$ open water, $2/10^{\text{th}}$ thin first year ice and $6/10^{\text{th}}$ medium first year ice. Compute the AIRSS Ice Numeral and the POLARIS ROI.
2. There is $5/10^{\text{th}}$ of ice ahead of the ship, all of one type of ice. What is the maximum thickness the ice can be so that the ROI is non-negative?
3. What is a ship supposed to do if it wants to enter a region of ice with an ROI of -5

13 Offshore Engineering Operations in Ice

Offshore engineering in Arctic, Antarctic or sub-arctic regions sometimes involves installing permanent equipment or structures or conducting various types of operations to support such installations, or to conduct drilling or scientific research. All these operations are collectively known as marine operations. These types of operations can include:

- Towing barges or ships or structures,
- Installing piling or other foundation components,
- Lifting parts of structures to place on barges or to place on fixed structures,
- Drilling or coring operations,
- Installation of Mooring components such as anchors, pre-laid chains or mooring buoys, or the
- Installation of fixed structures.

Ice introduces specific issues for all these types of operations and leads to a requirement for mitigation or management techniques to handle this additional environmental force. The following sections describe some of these issues and the ways in which they have been handled to date. Many of these operations have been performed on a very limited or experimental basis in icy areas and thus many procedures and techniques are developed on the fly. Experience with such operations and with so-called ice-management techniques is thus in the early stages of development and evolving as new operations are undertaken and experience grows.

Operational Limits

It can be impractical and/or uneconomical to plan to perform marine operations in extreme environmental conditions. Where such operations are to be conducted in ice covered waters or in the presence of icebergs, these factors introduce additional limitations. Consequently, Arctic/Antarctic marine operations are generally very weather and ice sensitive, requiring operational windows of minimum duration with specified limits on the environmental parameters during which the marine operations can be performed.

Obviously setting the operational limits too high can lead to unacceptable risk to equipment and people, whereas setting the limits too low can lead to excessive waiting times, which costs money. Often the choice of the optimum operational limit is a subjective judgement. In developing these operational criteria for marine operations the aim is to provide a realistic evaluation of the sensitivity of a given operation to ice and any other meteorological and oceanographic conditions. Establishing these criteria is an important first step to ensuring the safe execution of a marine operation in ice.

Other environmental characteristics influence the response of vessels and structures involved in a marine operation and they also influence the response of the ice. These factors include:

- Wind magnitude and direction;
- Wave height and period;
- Current magnitude and direction;
- Swell magnitude and direction.

13.1 Ice Forecasting

Ice forecasting can be divided into two broad categories, the first concerns long-term large-area trends in ice cover and are considered as part of the climate trend. The second type of ice forecast concerns the local movements of ice covers driven by regional weather conditions. The first category of forecast is relevant to considerations of seasonal operations (weather unrestricted) and the second applies to daily conduct of operations (weather restricted). The primary purpose of ice forecasting is to predict the concentration of ice in a given area and the drift direction and velocity. The drift direction is particularly important as this has a major influence on the conduct of ice management operations (covered in the following section).

Ice forecasting is important in selecting transit routes and in determining operational responses. Generally speaking, the transiting phase through pack ice is more straightforward than the operational phase; when positioning of the operational vessel(s) must be maintained for long periods of time in order to conduct the operation. Therefore ice forecasting during marine operations is essential for making decisions on how ice management is to be conducted, or decisions on the suspension of operations.

Ice forecasting is also used to establish if the operating limits for the operational vessel are likely to be exceeded if it has a dynamic positioning system or if it is positioned by a mooring. This would establish the expected maximum floe size, ice thickness and ice concentration, and allow an estimate of the minimum width of the open channel that might be maintained around the vessel.

Minimal ice conditions for ship and icebreaker operations in the Arctic generally occur during August and early September. Therefore most marine installation operations that require open water, or minimal ice conditions, begin during the first week of August and are limited in duration to 35 – 50 days, ending in early or mid-September.

13.2 Weather restricted and unrestricted operations

Operations can be defined as weather-restricted or weather-unrestricted depending on the definitions below. In dealing with ice or arctic environments, there is almost always some restriction associated with ice conditions or weather conditions, so operations that are entirely unrestricted are relatively rare. This requires that longer duration operations in ice have contingency plans that allow weather-unrestricted operations to be suspended if

necessary. This is a bit at odds with the classical concept of a weather-unrestricted operation (see definitions below).

Weather-restricted operations

A weather-restricted operation is a marine operation that can be completed within the limits of a favorable weather or ice forecast. Generally accepted practice is that the reliability of weather forecasts is such that weather-restricted operations should generally be completed within 72 h. However in some regions, particularly the Arctic, forecast models are less reliable and not well supported by data gathering, such that the reliability horizon for the forecast may be less than 72 hours.

Weather-unrestricted operations

The normal definition of a weather-unrestricted operation is one that can safely take place in any weather condition that can be encountered during a season. The weather condition(s) shall reflect the statistical extremes for the area and season concerned. However in the case of ice there may have to be some allowance for extreme ice conditions that cause the suspension of the operation.

Thus the concept of an entirely weather-unrestricted operation does not fully apply to cases of operations in ice. The implication of this is that most marine operations conducted in ice need to have an ice-related suspension scenario built into their operational plans. An example of this would be the Terra Nova FPSO which is a weather unrestricted operation for all conditions on the Grand Banks except the case of a large iceberg intrusion in which case there is a suspension and disconnection plan.

13.3 Environmental and Met-ocean criteria

Definition: *Met-ocean* is a term that is a blend of two words: "Meteorology" and "Oceanography". It is often used to describe the physical environment at a specific offshore location. The description often includes ice conditions, wind, wave, current, water level, visibility, air & water temperature, and icing.

For each specific phase of a marine operation, the limiting operational metocean criteria need to be defined. These design criteria are the set of values for the metocean parameters (ice conditions, wind, wave, current, water level, visibility, air & water temperature, and icing), for which design calculations are carried out, and against which the operation is checked. Ice conditions are frequently the driving criteria, and are defined in terms of ice thickness, ice concentration and drift velocity.

For weather-unrestricted operations, the operational met-ocean criteria are the same as the design criteria above, although lower values can be set for practical reasons. For weather-restricted operations, the operational met-ocean criteria are that set of values for the met-ocean parameters that are not exceeded at the start of the operation and which are forecast not to be exceeded for the duration of the operation.

Specified wind, wave, and ice conditions for marine operations depend on the planned duration of the operation including an allowance for contingency. Generally, operations with a planned duration of 3 or less days are treated as weather-restricted operations and a specific weather window is defined. Operations with duration of more than 3 days are considered as weather-unrestricted operations. Return periods of the metocean parameters defined for weather-unrestricted operations are estimated as a multiple of the operational duration; a general guide is to use a return period that is a minimum 10 times the expected duration of the operation.

Standards typically specify return periods such as those shown in Table 13.1, (From ISO 19901-6 Marine Operations). Return periods can depend on location, and in Arctic and Antarctic regions we need to forecast both weather and ice conditions. Forecasts for weather in these regions are known to be less reliable than in more temperate zones; so it is conservative to set shorter durations for weather restricted operations, and to use longer return periods for weather unrestricted operations.

Table 13.1 General guidance for return periods of metocean parameters for weather-unrestricted operations (ISO 19901-6 Marine Operations)

Duration of the operation	Return periods of metocean parameters
Up to 3 days	Specific weather window to be defined
3 days to 1 week	1 year, seasonal
1 week to 1 month	10 year, seasonal
1 month to 1 year	100 year, seasonal
More than 1 year	100 year, all year

Operational duration

In dealing with weather or ice restricted operations there is a tendency to underestimate the time required to complete the operation and over-estimate the reliability of a good weather forecast. It is important in scheduling a time-critical marine operation, that the plan and schedule for the operation be as realistic as possible.

An operational schedule should consider margins for:

- Inaccuracy (or optimism) in the operational schedule;
- Technical and/or operational delays;
- Extra margin for operations with vulnerable or critical equipment;
- Extra margin for operations in geographical areas and/or seasons where conditions are difficult to predict.

It is also appropriate to include a reduced allowance for operations based on previous similar operations. However this should be evaluated against the consequences of exceeding the allocated time.

Point of no return

Operations in areas where ice is part of the environment should be divided into phases where the operation can be suspended and brought to a safe condition should ice conditions change rapidly. The operational window in which conditions remain below the suspension criteria shall be of sufficient duration to reach a safe condition before proceeding beyond the point of no return (PNR).

The reliability of the ice forecast is crucial for the period between any PNR and the structure reaching a safe situation.

13.4 Transport Operations

Transport operations are those that require moving equipment, structures of vessels through ice-covered waters. During a transport or towing operation that requires icebreaking, the main objective is to transit efficiently through a region without vessel damage. The strategy generally involves picking a route, which may not be the shortest, to avoid thick ice, follow leads, and avoid ice features (for example ridges) that increase the risk of vessel damage or increase resistance to vessel passage.

13.5 Stationary Operations

Stationary operations are those that have to be performed at a specific location. In ice-covered waters this usually requires some form of ice monitoring or ice management to allow the operation to proceed or to allow it to be safely suspended or discontinued if ice conditions cannot be managed.

Ice Management - Theory

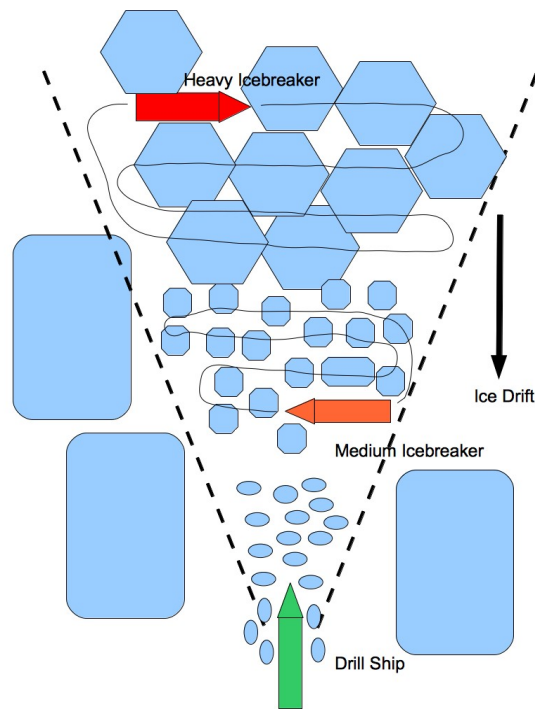


Figure 13.1 Ice Management scenario

As part of Beaufort Sea drilling operations during the 1980s, various oil companies and drilling contractors developed techniques for “managing” sea ice during drilling operations. The concept of ice management is developed by combining ice forecasting and ice monitoring techniques with icebreaking ship deployment to reduce the impinging floe size or to deflect large ice floes. The process incorporates methods for surveying regional and local ice conditions. Aerial surveillance by helicopter, photographs or radar images obtained by satellites and airplanes provide information used to forecast ice movement. Good ice management is dependent on good ice monitoring, ice forecasting and weather forecasting. Ice monitoring and forecasting is used to guide icebreaking and management operations on a continuous basis and sets ice management parameters such as icebreaker deployment distances from the operational vessel, headings for all vessels, and decisions on whether to break ice or move it away.

Figure 13.1 gives a schematic diagram of an ice management operation in which a large icebreaker is deployed upstream of an operational vessel (drillship in this case) and a medium icebreaker is deployed between the large icebreaker and the drillship. The first icebreaker reduces large ice floes to a medium size and the second icebreaker further reduces these floes to a size that the drillship can handle.

Ice management such as this requires direct engagement of impinging ice features to ensure that overly large floes do not impact the operational vessel. The ice management vessels must work following the direction of ice movement to ensure that the drilling vessel is not impacted by larger floes.

Typically, the largest icebreaker is positioned on average, 1-2 nautical miles upstream in the ice drift direction. This distance provides 2-3 hours of advance notice of ice conditions, assuming an average ice drift velocity of 0.5 kts. Both vessels operate in a funnel shaped envelope to provide an allowance for changes in the ice drift direction. The medium sized icebreaker, which is usually the more maneuverable vessel, typically works inside a 1 nautical mile radius of the drillship. This icebreaker seeks to further reduce the ice to small floe sizes and maintain open water space around the drilling platform to allow ice to drift past.

Ice Management - Practice

Experience from ODP Arctic Drilling Program

The following section and pictures are taken directly from a description of an actual ice management operation undertaken to support the Ocean Drilling Program's first Arctic Drilling Project. The description is contained in a paper by K. Moran et al (2006), and illustrates the difference between the somewhat tidy theoretical description of ice management above and the actual conduct of one of these operations.

“Overall, the Vidar Viking (Drillship) performed better than anticipated and was able to stay on location in very heavy ice. However, the Vidar Viking's DP system was not functional under these ice conditions, and a manual method had to be developed. The method that worked best was to provide the Vidar Viking with the near-real time ice drift predictions (speed and direction). The Vidar Viking would then set a course exactly counter to this direction. As large pieces of ice impacted the ship, the Vidar Viking “leaned” toward the broken ice by driving ~20 m upstream of the drill site location and then slowly drifting with the ice to ~20 m downstream from the drill site location before repeating the same process again. Thus, accurate ice drift direction was critical for positioning. When the prediction was wrong, the Vidar Viking would not drift back exactly over the drill hole. Once the vessel was off-track, it was difficult to move sideways back to the optimal track path again because of the heavy ice to port and starboard. When ice became too difficult, the Oden (medium icebreaker) broke ice close to the Vidar Viking so that the ship could maneuver sideways.”



Figure 13.2 ODP Ice management fleet

Because of the critical nature of the ice drift direction, predicting direction became a high priority for the ice management team. A new approach for measuring ice speed and direction was developed and used successfully during the Expedition. By helicopter, radar reflectors were placed on selected ice floes and their positions were tracked upstream of the drill site location. The biggest problem in predicting ice drift was when the wind speed dropped and wind measurements became unreliable. On these occasions, the whole ice sheet “stalled” and began to rotate because of Coriolis forces. This caused significant problems for the Vidar Viking because a regular heading could not be maintained and maneuvering became almost impossible. During some of these times, drilling was temporarily suspended (keeping the drill pipe in the hole) until ice began to move again in one direction. Station-keeping was best achieved during conditions of steady, predictable ice drift. However, even during these severe events, the watch circle limit (100 m) was never exceeded. The largest deviations from the center point occurred during conditions of no ice drift and when the ice sheet revolved 360°. The ice management team gained experience during the expedition and succeeded in making accurate predictions even during times of low wind speed, which improved the difficult situation for the drillship. The ice alert system used during Expedition 302, based on experience from the offshore industry in Sakhalin, served very well as a tool for documenting the operations but was of limited value during critical times when rapid decision-making was required. During these situations, the Fleet Manager relied most heavily on the ice drift and meteorological predictions.

Also, as operations continued, maneuvering and vessel coordination were fine-tuned, and this significantly reduced the amount of power required for icebreaking.

Conclusions

The multiple-ship concept, framed by the proponents in 1998, was the first of several keys to success. Success was also achieved through the efforts of first-rate fleet and ice management teams (made up of individuals with extensive Arctic icebreaking, ice prediction, and weather forecasting experience) and a team of hardworking, experienced, and innovative drilling experts. The captains of each of the three vessels individually, and as a team, developed the ice-breaking techniques on location that maintained the drillship within a fixed position with only two major drive-offs and for as long as 9 consecutive days.”

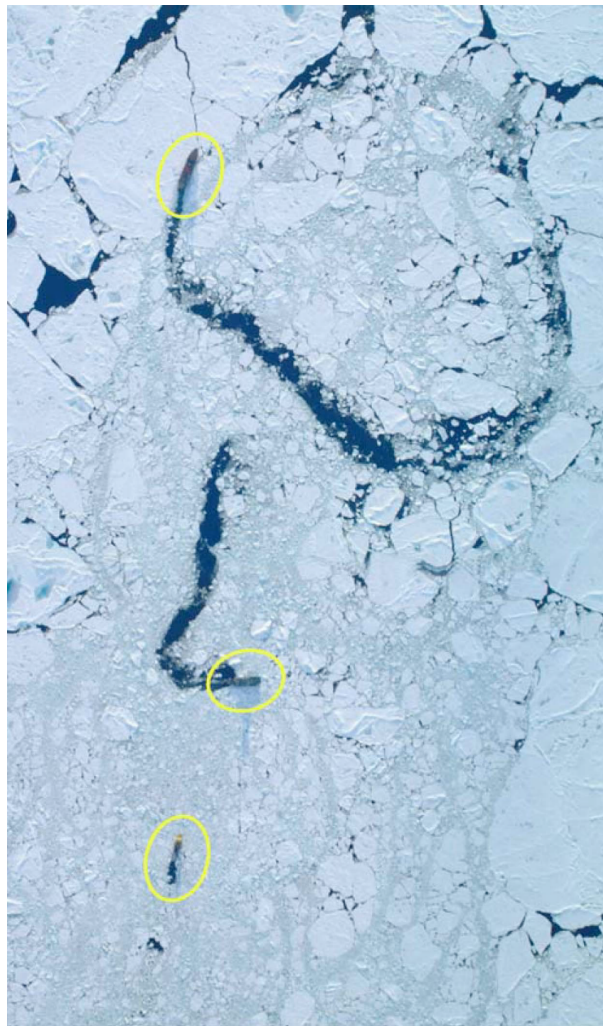


Figure 13.3 Ice management during drilling operations.

Ice drift direction is top to bottom. The *Sovetskiy Soyuz* (circled at the top of the image) is breaking a large floe. The *Oden* (middle circle) is breaking the broken floes into smaller and smaller pieces. The *Vidar Viking* is holding position (bottom circle) (photo taken by Per Frejvall).

This description illustrates a practical ice management operation under difficult conditions which was significantly adapted and improved on the fly during the operation.

13.6 Environmental Impact

As a final note, the Arctic and Antarctic are recognized as environmentally sensitive regions of the world and stringent pollution protection procedures must be followed in all operations in these waters. Arctic marine operations are sometimes conducted in international (or disputed) waters where environmental regulations jurisdiction is unclear. In all these cases it is prudent to follow the most stringent standards available. There is currently an IMO guideline for Arctic operations. There are also Antarctic environmental guidelines for marine operations and there is a newly issued ISO standard for marine operations, which has a regional annex for arctic marine operations. It is likely that additional documents will be developed as interest in the Arctic (and Antarctic) increases.

The Arctic is an area that is particularly vulnerable to adverse impacts from oil pollution. This is due to the particular environmental conditions of low temperature, long periods with little light or complete darkness, and the wide extent of ice cover. Low temperatures lead to reduced evaporation of oil components. Dark winters lead to reduced ultraviolet radiation and/or biological decomposition of oil. In areas covered by ice, oil dispersal from wave action is also reduced. Oil in iced areas will be trapped between ice floes or under the ice, and only partly transported to the ice surface. All these factors result in a slower decomposition of oil in the Arctic than in temperate regions. The period in which a particular oil spill can be harmful to the environment is thus comparatively longer in the Arctic.

The highest risk of oil spills is connected with transportation activities and production of oil as well as, to a lesser degree, exploration activities. Their occurrence will depend on the level of activity in the Arctic, the technical standards of the activity and the preventative measures taken.

The constraints caused by Arctic conditions lead to particular technological challenges regarding oil spill cleanup. Effective methods and techniques for containing and cleaning up oil spills from water and ice are limited. The presence of ice is a particular challenge to detecting and removing oil. It is evident that operations in the Arctic and Antarctic are increasingly likely to be restricted by the ability to mitigate or manage potential oil pollution in ice covered waters.

Chapter 13: Problems

1. Explain what is meant by “Point of No Return”.
2. Describe some examples of ice management in offshore operations.

14 Future of Ice Class Ships

14.1 Introduction

Design of ice class ships may be about to undergo significant change. To understand these coming changes, it is worthwhile to briefly review the history of ice class ship design. We are likely coming to the end of an era in ice class design that began in the 1970s. Prior to the 1970s, and going back to the 1920s, ships intended for ice operations were required to have a % increase in plating, extra frames, and other similar prescriptive enhancements (see Figure 14.1). There were no ice load or strength formulae. This was in line with the norms of most ship rules of the day. Prior to the 1960s, rules for steel ship construction contained mainly tables of required structure, with few formulae. Earlier, in the 19th century, the first ice class ship requirements had even fewer specifications and were mainly focused on equipment, such as the requirement that skis be carried.

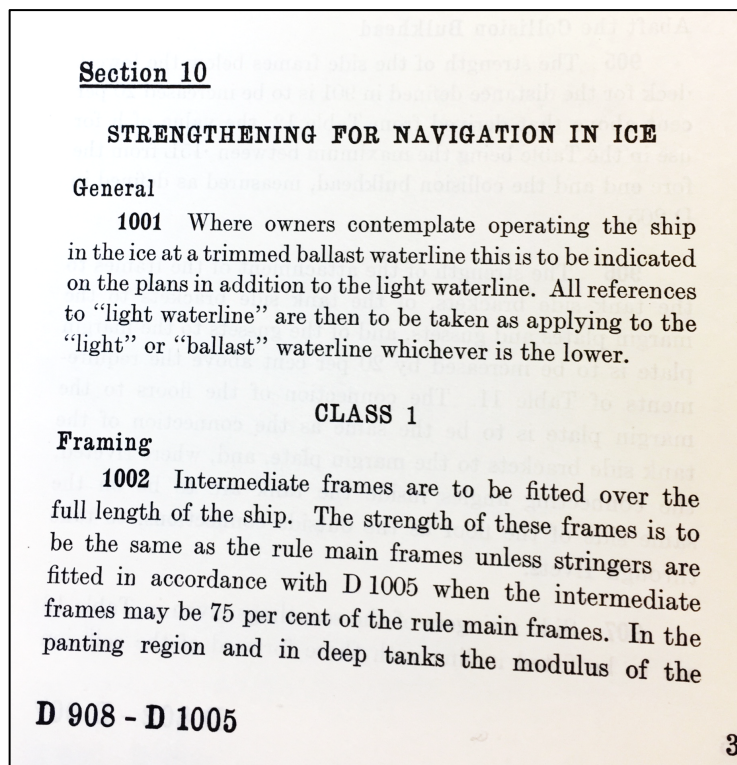


Figure 14.1 Extract from Lloyd's Register Rules 1961.

Starting in the 1960s and 70s, regular and ice class ship rules changed to become what we are familiar with today. Today structural requirements are expressed as formulae. The structural parameters are specified as functions of load (e.g pressure), material (e.g yield strength) and arrangement (eg. Frame spacing) parameters (see Figure 14.2). The current approach is seen by most people as the only way to formulate ice class rules. This highlights one of the problems with Codes and Standards. Standardization sets a bar to ensure that unsafe practices are prevented. Unfortunately, it also can make innovation much more difficult. New approaches must meet standards that were not set with the new

approach in mind. This is a problem in all industries but is especially challenging in the world of shipbuilding. Most ships are either unique or one of a small number of identical ships. It is uneconomic to spend a lot of money developing a truly innovative ship. Getting the ship classed (to existing standards) is crucial for the owner. Otherwise insurance may be impossible to get and the authorities in the world's ports (so-called port-state authorities) will prevent the ship from operating. The economics are very different from the aircraft industry (where there are very few makers of large numbers of identical planes), or the car industry (also making large numbers of identical cars). This situation means that the shipbuilding world will only change when there are very significant changes in technology or demand.

4.3.2 Plate thickness in the ice belt

For transverse framing the thickness of the shell plating

$$t = 667 s \sqrt{\frac{f_i \cdot p_{PL}}{\sigma_y}} + t_c [\text{mm}]$$

Figure 14.2 Shell plating formulation typical of current requirements.

Since the 1990s a range of new technologies have been developed that have the potential to change how ice class ships are designed, built and operated. This chapter will discuss these various technologies and how they may change the status-quo.

Ice Mechanics

When the current ice class rule systems were formulated, ice load mechanics was much less well understood than it is today. The first ideas about pressure-area effects began to emerge around 1980. The pressure-area relationship was initially treated as a kind of ice property. There were all kinds of differing models to explain it. In time we learned that this relationship is really nothing more than a kind of sampling issue. Ice loads are relatively small in scale (compared to the ship) and tend to form dendritic (branching) patterns of high pressure, surrounded by regions of much lower pressure. When such pressures are measured by a coarse array of sensors (which was all we had in the 1990s), the fine detail is lost and the data exhibits pressure-area relationships. It is only recently that pressure sensor technology has given us large amounts of test data that is making it much easier to understand the ice crushing process. The experimental evidence is getting quite extensive. There are still no standard numerical techniques that can reliably simulate all the aspects of ice crushing and extrusion, especially not when considering the effects of submergence, ice edge shape, collision speed and tangential motions. Nevertheless, numerical methods are rapidly improving and some of these, especially various discreet element approaches, appear to be very promising. It is entirely possible that highly realistic simulation of ice crushing will be available during the coming decade.

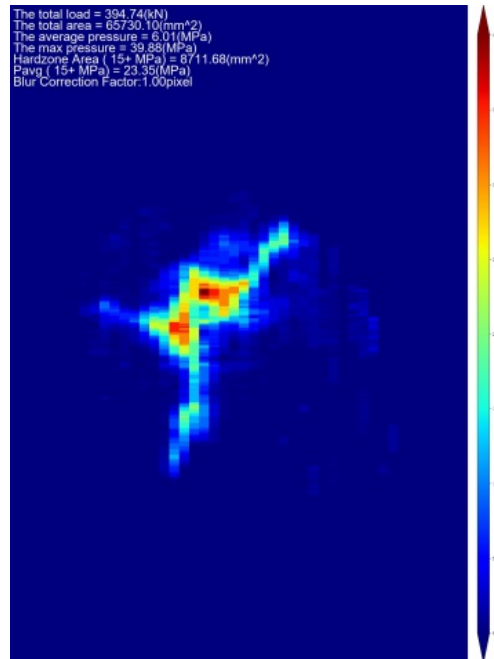


Figure 14.3 High resolution measurement of ice pressure (Gagnon et al 2020).

Another aspect of ice mechanics that is developing fast is the ability to simulate ship-ice interaction at the operational scale. These models use a variety of implementations of ship-ice interaction models for large impacts, level ice breaking, pack-ice interaction and similar ship operations in ice. One example from 2014 is shown in Figure 14.4. These types of simulations are constantly improving and can be expected to play an increasing role in both design and operations of ships in ice.

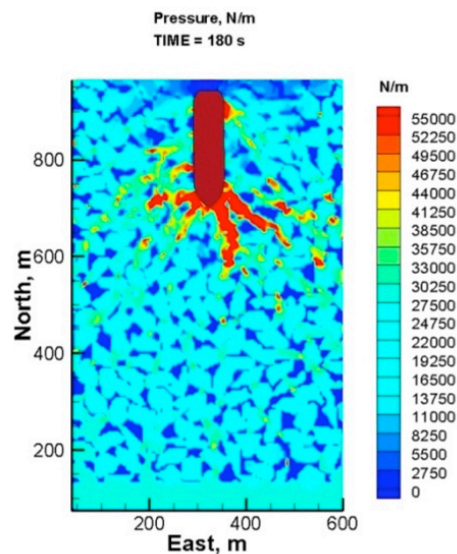


Figure 14.4 Simulation of ship in pack ice. (Sayed et al 2014).

Structural Analysis

Structural analysis has improved greatly in the past 20 years. When the Polar Rules were being formulated in the 1990s, non-linear structural analysis was still mainly a topic of research in universities and institutes. Back then, only the most advanced companies made much use of non-linear structural analysis. Today this has changed. Non-linear structural analysis is increasingly employed in industry. There are a wide range of programs and methods that can be called non-linear analysis. These range from relatively simple elasto-plastic analysis of steel structures, to general multi-physics solvers. Some of these programs are extensions of the standard finite-element methods, while others are quite novel methods, including many discrete element methods, SPH (smoothed particle hydrodynamics), and fluid-structure interaction methods with links to CFD (computational fluid dynamics). Programs such as ABAQUS (from Dassault Systems) and LS_Dyna (from Livermore Software Technology Corporation, recently acquired by ANSYS Inc.) are becoming standard industry tools to model complex multi-body problems such as ship-ice interaction. Figure 14.5 shows a sequence of LS_Dyna results during ship-ice interaction.

This new generation of structural analysis tools are capable of high-fidelity non-linear assessments of ice class ship structures. Twenty years ago, the available structural analysis methods lacked the sophistication for use as a design tool and would likely have introduced more problems than they solved. Today these tools, when properly used, permit ships to be designed with much greater understanding of the true structural capability than any set of ‘rule equations’ ever could.

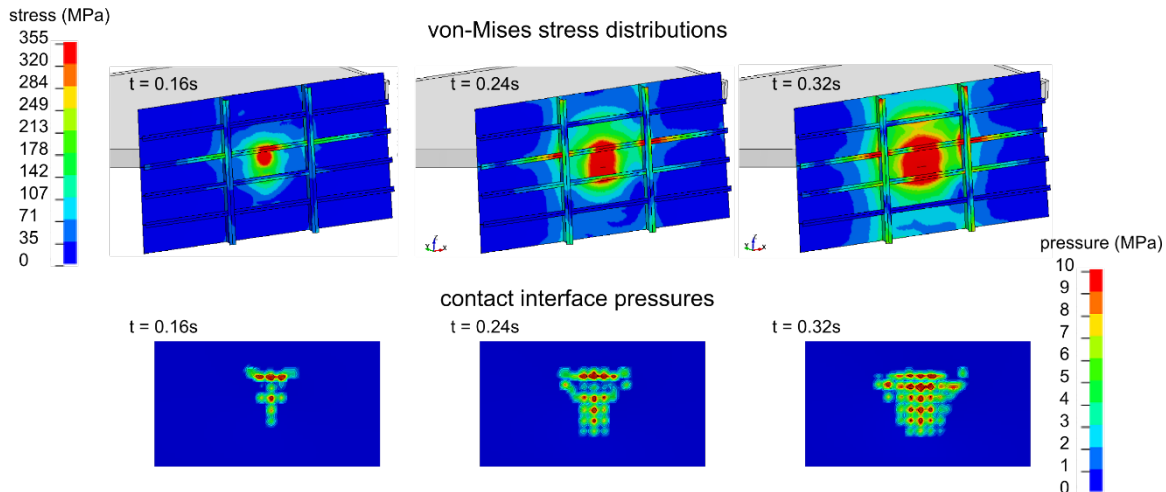


Figure 14.5 Ice-structure interaction simulation (Daley et al 2017)

Ship Simulations

In recent years there have been many examples of new software that can simulate large scale ship operations in ice. Figure 14.6 shows an example of a simulation of a military vessel operating in pack ice. The simulation is not just modelling the vessel's maneuvers, but also the multiple ice impacts. The loads are computed with sufficient resolution to assess structural response and structural risk. Programs like this combine the issues of

powering, hull form, maneuvering, structural safety, fuel consumption and economic parameters into a single simulation. All these issues are connected, but until recently they have all been treated in isolation.

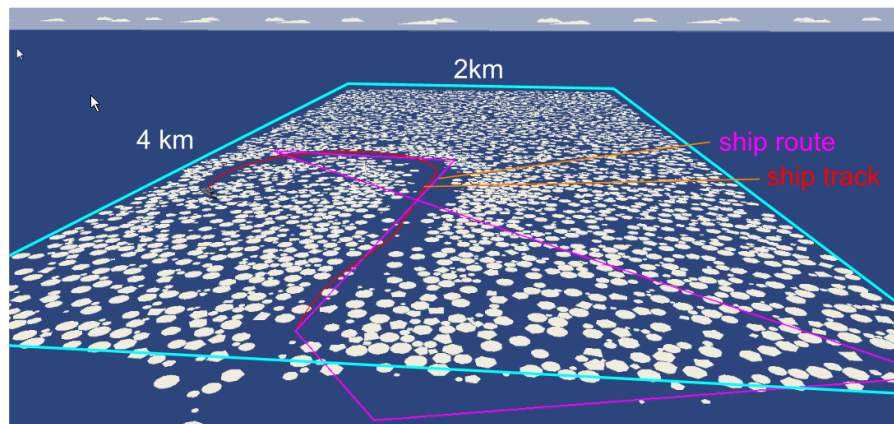


Figure 14.6 The GEM simulation of operations in pack ice (Daley et al 2017)

Sensors and Telecommunications

The available technology of sensors and telecommunications is improving at a tremendous rate. Current ice load sensing technology is still largely a matter of installing strain gauges on the frames of ships to infer ice loads. One can expect that in the near future, with the rapid improvements on digital imaging and analysis, it will be feasible to monitor ice loads and structural response with much higher fidelity. Figure 14.7 shows an example of strain imaging, a technology that is common in laboratories and will likely soon be used for practical ice load monitoring on ships.

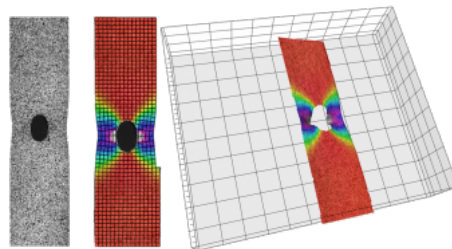


Figure 14.7 Speckle imaging top measure strain fields (LaVision)

Starting in late 2019, SpaceX began launching a constellation of low earth orbit satellites that will provide high bandwidth, low latency internet connectivity to users everywhere. SpaceX plans to deploy up to 42,000 satellites for this service (see Figure 14.8). Other companies are planning similar systems. Real time connectivity will permit a whole new approach to ship operations in ice.

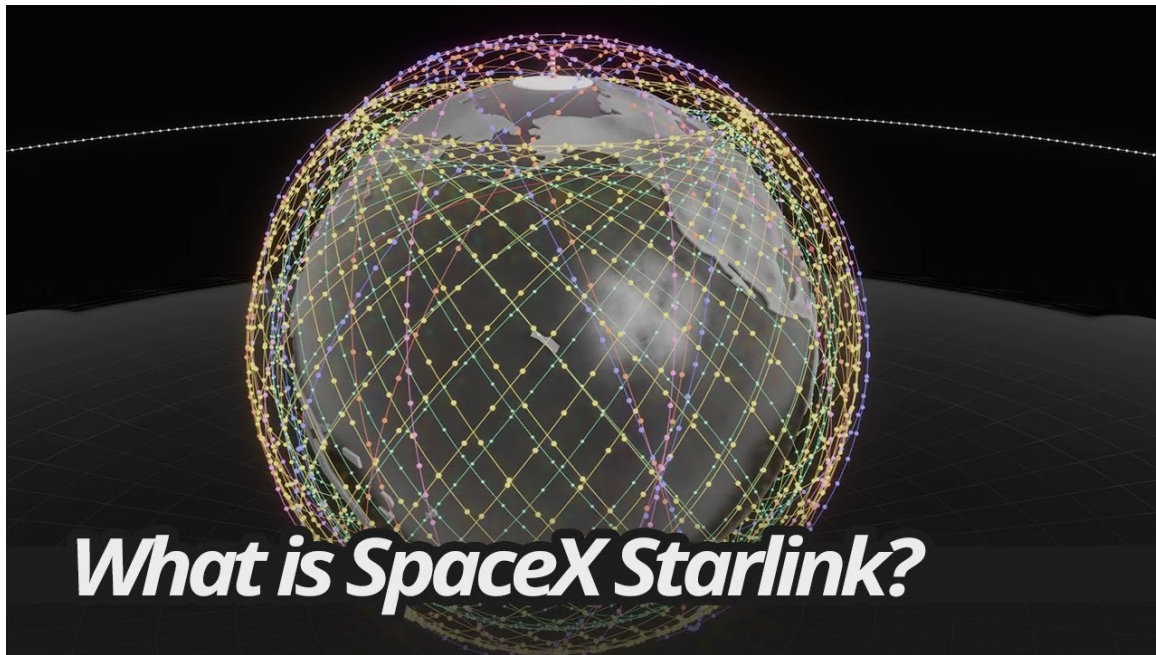


Figure 14.8 SpaceX Starlink network (inverse.com)

Looking Ahead

The above sections have described a variety of current and near-future technologies. When these new technologies are combined, a whole new approach to ice class ship design and operation will be possible. Ships will be able to be designed for highly realistic loads, representative of the full range of realistic ice conditions. Ship operations will be conducted with much more precise knowledge of the actual conditions that the ship is entering. Live digital connections with operations centers will permit the use of digital-twins to continually monitor vessel progress and safety. Much like the revolution coming in automobiles, ships will benefit from a synthesis of environmental, structural, machinery and navigation information.

Chapter 14: Problems

15 General Review Questions

1. On Hudson's first voyage what did he expect to find at the north pole?
2. In ice mechanics, what is polarized light is used for?
3. Which of the following is not an area of ice engineering interest: Chukchi Sea, Norwegian Offshore, Fox Basin, Pechora Sea?
4. What does the word "Albedo " refer to?
5. How many forms of ice crystals are there?
6. How many forms of ice crystals are found naturally on earth?
7. What is "Nilas"?
8. What is the water temperature (approx.) at the bottom of a frozen pond or small lake?
9. In ice mechanics, a ring test is used to measure what?
10. The word "comminution " refers to what?
11. Process pressure-area refers to what?
12. On Hudson's third voyage what did he find?
13. In ice mechanics, a microtome is used do what?
14. The word "basal" refers to what?
15. Latent Heat refers to what?
16. "First Year" ice is at least _____ cm thick.
17. Secondary ice is _____.
18. Pancake ice is round because _____.
19. The term "C-axis" refers to _____.
20. Name one of the legs (straits, channels ..) in the Northwest Passage.

Finish the following sentences:

21. The preferred direction for ice crystal growth is
 - a) vertical.
 - b) along the c-axis.
 - c) horizontal.
 - d) across the c-axis.
 - e) all directions.
22. the axes of the phase diagram for h₂O (water ice steam) have units of:
 - a) density and pressure
 - b) pressure and volume
 - c) temperature and volume
 - d) pressure and temperature
 - e) density and temperature
23. The angle of the hydrogen bonds in water is
 - a) 79.3 degrees
 - b) 120 degrees
 - c) 104.5 degrees
 - d) 90 degrees
 - e) 122.7 degrees

24. Freshwater ice is 10cm thick. The air temp is -10 (water 0). In another 20 minutes, the additional ice growth will be
a) 7.8 mm b) 2.7 mm c) 0.86 mm d) 13.2 cm e) 19 mm
25. Which of the following is considered new ice?
a) Grey ice b) Dark Nilas c) Ice Rind d) Shuga e) Thin first-year ice
26. Frazil ice
a) forms on ships due to sea spray
b) is the name for the small ice pieces in a ship's track
c) grows vertically in water
d) is a slurry of flakes
e) contains brine channels
27. Pancake ice
a) only forms in sheltered bays
b) is the result of waves moving through new ice
c) is the result of ice stacking up (rafting)
d) ranges in size from 1 to 100 ft in Diameter
e) forms in rivers due to currents
28. Freezing degree days
a) are any days that are below 0 C
b) are the square root of the number of days of freezing
c) is the time integral of temperature difference (freezing temp – temp)
d) can be used to estimate the ice coverage
e) is found on ice charts
29. Which of the following will tend to result in a greater rate of ice growth?
a) snow on the ice surface b) strong winds
c) thicker ice d) water currents e) clear skies
30. This change would cause the most change in trans-arctic shipping
a) increased melting of glaciers in Greenland
b) formation of many open leads through the polar pack
c) 50% loss of multiyear ice
d) loss of all summer ice
e) 50% increase in the price of oil
31. An ice sail
a) is a triangular-shaped ice floe
b) is the ice jutting below a pressure ridge that is acted on by currents
c) is the tall narrow dry portion of a pressure ridge
d) is a sail used by explorers like Franklin to provide extra power in ice
e) none of the above

32. The month with the least arctic ice is
a) August b) June c) July d) September e) May
33. The heaviest sea ice is in the waters near
a) USA b) Canada c) Norway d) Greenland e) Russia
34. Ice Ages happen about every
a) 200,000 years b) 20,000 years c) 50,000 years
d) 100,000 years e) 1,000,000 years
35. The arctic loses the most ice
a) through the Strait between Alaska and Russia
b) through the Strait between Canada and Greenland
c) through the Strait between Spitsbergen and Greenland
d) through the Strait between Russia and Norway
e) through the Queen Elizabeth Islands of Canada
36. Which of the following is not a failure mode for a cylinder of ice in compression?
a) Axial fracture
b) Plastic bulging
c) Complete fragmentation
d) Conical fracture
e) Shear faulting
37. Which of the following would have least effect on an ice strength test (given that other factors were constant)?
a) Grain size
b) Strain rate
c) Temperature
d) Geographic location
e) Size of the test sample

15.38

- a) List two ice class systems? ...
b) In ice mechanics, a cantilever beam is used to...
c) Icebreakers have bows which are ...
d) The term "FDD" refers to ...
e) Latent Heat refers to ...
f) Popov is from _____ and Lynqvist is from _____
g) Primary ice is ...
h) Ice floats because ...
i) The term "pressure ridge" refers to ...
j) Croasdale is known for ...

15.39

- a) In the notes the third 'leg' of ice engineering is said to be _____

- b) Who came first, Franklin, Hudson or Davis? _____
- c) What was the key artic 'event' of the 19th century? _____
- d) The word Albedo refers to: _____
- e) 60 cm thick sea ice is termed: _____
- f) Dark Nilas is: _____
- g) Comminution means _____
- h) The development of pressure/area with indentation is called: _____
- i) The highest Baltic Ice Class is called: _____
- j) Hobson's Choice is: _____

15.40

- a) The word used by specialists to refer to the science of ice is _____
- b) On his third voyage, Henry Hudson was chartered to go to _____
- c) Which of the following is not an area of ice engineering interest:
Kara Sea, Pechora Sea, Melville Sea, Bohai Bay, Caspian Sea: _____
- d) The Finnish word Murtaja (name of first Finnish icebreaker) means _____
- e) The name of the standard ice crystal (found on earth) is: _____
- f) The chemical formula for ice is: _____
- g) The density of pure ice is about: _____
- h) a slurry of ice flakes suspended in water, is called _____
- i) The letter S in the ice type designation S2b means _____
- j) The steady deformation of ice under constant stress is called: _____

15.41

- a) The Kara Sea is located: _____
- b) A cantilever beam test measures; _____
- c) In addition to ice science (glaciology) and Newtonian and continuum mechanics, the field of ice engineering is supported by (based upon); _____
- d) The place name "Lachine" used by the explorer Cartier refers to _____
- e) Which of the following is an area of ice engineering interest:
Beaufort Peninsula, Prudhoe Sea, Melville Sea, Bohai Strait, Caspian Sea: _____
- f) The chemical formula for ice is: _____
- g) The density of pure water is about: _____
- h) The energy needed to change the phase of ice from solid to liquid is called _____
- i) The initial ice crystals formed from ice slurry are designated with the letter: _____
- j) During secondary creep deformation the ice stress is: _____

15.42

- a) If you stand on thin ice and it starts to crack, the orientation of the first cracks will be: _____
- b) A ring test measures _____.
- c) Typical average salinity of first year sea ice is about: _____
- d) Typical average salinity of old ice is about _____.
- e) In 'P' ice the c-axis is oriented _____

- f) Korzhavin's equation describes what type of ice failure? _____
- g) Ice creep stresses are mainly influenced by _____ and _____
- h) A slurry of ice flakes suspended in water, is called _____
- i) The 'c' axis in 'Secondary' ice is: _____
- j) Referring to ice strength, the phrase "Transition region" refers to: _____

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17 Useful Web Sites

IACS Polar Rules: <http://iacs.org.uk/publications/unified-requirements/ur-i/>

Transport Canada Arctic Shipping : <https://www.tc.gc.ca/eng/marinesafety/debs-arctic-menu-303.htm>

Finnish Ice Classes: <https://www.traficom.fi/en/transport/maritime/ice-classes-ships>

IMO Polar Code: <http://www.imo.org/en/MediaCentre/HotTopics/polar/Pages/default.aspx>

US National Oceanographic and Atmospheric Admin. <https://www.noaa.gov/>

Canadian Ice Service Archive : <https://iceweb1.cis.ec.gc.ca/Archive/page1.xhtml?lang=en>

ABS Guide for Low Tem OPs: https://ww2.eagle.org/content/dam/eagle/rules-and-guides/archives/special_service/151_vesseloperatinginlowtemperatureenvironments/pub151_lte_guide_dec08.pdf

Appendix A : Sea Ice (and other marine ice) Terminology

Sea Ice: Any form of ice found at sea which has originated from the freezing of sea water.

Ages of Sea Ice

New Ice: A general term for recently formed ice which includes frazil ice, grease ice, slush and shuga. These types of ice are composed of ice crystals which are only weakly frozen together (if at all) and have a definite form only while they are afloat. In Canada, the term 'new ice' is applied to all recently formed sea ice having thickness up to 10 cm. This includes ice rind, light nilas and dark nilas.

Nilas: A thin elastic crust of ice, easily bending on waves and swell and under pressure growing in a pattern of interlocking "fingers" (finger rafting). Nilas has a matte surface and is up to 10 cm thick and may be subdivided into dark nilas and light nilas.

Shuga: An accumulation of spongy white ice lumps having a diameter of a few centimetres across; they are formed from grease ice or slush and sometimes from anchor ice rising to the surface

Slush: Snow which is saturated and mixed with water on land or ice surfaces or as a viscous floating mass in water after a heavy snowfall.

Slush or Sludge: The initial stages in the freezing of sea-water, when its consistency becomes gluey or soupy. The term is also used (but not commonly) for brash-ice still further broken down.

Grey Ice: Young ice 10 to 15 cm thick which is less elastic than nilas and breaks on swell. Usually rafts under pressure.

Grey-White Ice: Young ice 15 to 30 cm thick. Under pressure more likely to ridge than raft.

First-Year Ice: Sea ice of not more than one winter's growth, developing from young ice; thickness 30 cm to 2 m. May be subdivided into:

Thin First-Year Ice: 30-70 cm thick

Medium First-Year Ice: 70-120 cm thick

Thick First-Year Ice: over 120 cm thick

Old Ice: Sea ice which has survived at least one summer's melt. Most topographic features are smoother than on first-year ice. May be subdivided into:

Second-Year Ice: Old ice which has survived only one summer's melt. Summer melting produces a

regular pattern of numerous small puddles. Bare patches and puddles are usually greenish blue.

Multi-Year Ice: Old ice up to 3 m or more thick which has survived at least two summer's melt. They have hummocks that are even smoother than in second-year ice, and the ice is almost salt-free. The colour, where bare, is usually blue. Melt patterns consist of large interconnecting irregular puddles and a well-developed drainage system.

Concentrations of Sea Ice

Concentration is the ratio expressed in tenths describing the amount of the sea surface covered by ice as a fraction of the whole area being considered. Total concentration includes all stages of development that are present, partial concentration may refer to the amount of a particular stage or a particular form of ice and represents only a part of the total. The following terms are used:

Compact Ice: Floating ice in which the concentration is 10/10 and no water is visible.

Consolidated Ice: Floating ice in which the concentration is 10/10 and the floes are frozen together.

Very Close Ice: Floating ice in which the concentration is 9/10 to less than 10/10.

Close Ice: Floating ice in which the concentration is 7/10 to 8/10, composed of floes mostly in contact.

Open Ice: Floating ice in which the concentration is 4/10 to 6/10 with many leads and polynyas, and the floes are generally not in contact with one another.

Very Open Ice: Floating ice in which the concentration is 1/10 to 3/10 and water preponderates over ice.

Open Water: A large area of freely navigable water in which sea ice is present in concentration less than 1/10. No ice of land origin is present.

Ice Free: No ice present. If ice of any kind is present this term shall not be used.

Bergy Water: An area of freely navigable water in which ice of land origin is present in concentrations less than 1/10. There may be sea ice present, although the total concentration of all ice shall not exceed 1/10.

Forms of Sea Ice

Fast Ice: Sea ice which forms and remains fast along the coast where it is attached to the shore, to an ice wall, to an ice front, between shoals or grounded icebergs. Vertical fluctuations may be observed during changes of sea level. Fast ice may be formed in situ from sea water or by freezing of floating ice of any age to the shore and may extend a few metres or several hundred kilometres from the coast.

Floating Ice: Any form of ice found floating in water. The principal kinds of floating ice are lake ice, river ice, and sea ice which form by the freezing of water at the surface, and glacier ice (ice of land origin) formed on land or in an ice shelf. The concept includes ice that is stranded or grounded.

Ice Floe: Any relatively flat piece of sea ice 20 m or more across. Floes are subdivided according to horizontal extent as follows:

Giant: over 10 km across

Vast: 2 to 10 km across

Big: 500 to 2 km across

Medium: 100 to 500 m across

Small: 20 to 100 m across

Ice Cake: Any relatively flat piece of sea ice less than 20 m across.

Brash Ice: Accumulations of floating ice made up of fragments not more than 2 m across, the wreckage of other forms of ice.

Pancake Ice: Predominantly circular pieces of ice 30 cm to 3 m in diameter and up to 10 cm in thickness, with raised rims due to the pieces striking one another.

Strip: A long narrow area of floating ice about 1 km or less in width, usually composed of small fragments detached from the main mass of ice, and run together under the influence of wind, swell or current

Ice Patch: An area of floating ice less than 10 km across.

Surface Features of Sea Ice

Lead: Any fracture or passageway through sea ice which is navigable by surface vessels. If the passageway lies between drift ice and the shore it is termed a shore lead. If it lies between drift ice and fast ice it is called a flaw lead.

Puddle: An accumulation on ice of meltwater, mainly due to melting snow, but in the more advanced stage also to the melting of ice. Initial stage consists of patches of melted snow.

Slush: Snow which is saturated and mixed with water on land or ice surfaces, or as a viscous floating mass in water after a heavy snowfall.

Thaw Holes: Vertical holes in sea ice formed when surface puddles melt through to the underlying water.

Rafted Ice: Type of deformed ice formed by one piece of ice overriding another.

Ridge: A line or wall of broken ice forced up by pressure. May be fresh or weathered. The submerged volume of broken ice under a ridge, forced downwards by pressure, is termed an ice keel.

Hummock: A hillock of broken ice which has been forced upwards by pressure. May be fresh or weathered. The submerged volume of broken ice beneath the hummock, forced downward by pressure, is termed a bummock.

Polynya: Any non-linear shaped opening enclosed in ice. Polynyas may contain brash ice and / or be covered with new ice, nilas or young ice; submariners refer to these as 'skylights'. Sometimes the polynya is limited on one side by the coast and is called a shore polynya or by fast ice and is called a flaw polynya. If it recurs in the same position every year, it is called a recurring polynya.

Rotten Ice: Sea ice which has become honeycombed and which is in an advanced stage of disintegration.

Glacial Ice Terminology

Glacial ice originates on land as snow, compressed at great depths in glaciers. When glaciers flow into the sea, icebergs and other forms of floating glacial ice are created. As the larger pieces break up, the smaller forms are created. Note that icebergs and other glacial ice are in the sea but are not “sea ice”. Rather they are “ice of land origin”.

Shapes of Glacial Ice

Tabular Iceberg: A flat-topped iceberg. Most show horizontal banding.

Domed Iceberg: An iceberg which is smooth and rounded on top.

Pinnacled Iceberg: An iceberg with a central spire or pyramid, with one or more spires.

Wedged Iceberg: An iceberg which is rather flat on top and with steep vertical sides on one end, sloping to lesser sides on the other end.

Drydocked Iceberg: An iceberg which is eroded such that a U-shaped slot is formed near or at water level, with twin columns or pinnacles.

Blocky Iceberg: A flat-topped iceberg with steep vertical sides.

Sizes of Glacial Ice

Growler: Piece of ice smaller than a bergy bit and floating less than 1 metre above the sea surface, a growler generally appears white but sometimes transparent or blue-green in colour. Extending less than 1 metre above the sea surface and normally occupying an area of about 20 square metres, growlers are difficult to distinguish when surrounded by sea ice or in high sea state.

Bergy Bit: A piece of glacier ice, generally showing 1 to less than 5 metres above sea level, with a length of 5 to less than 15 metres. They normally have an area of 100-300 squared metres.

Small Iceberg: A piece of glacier ice extending 5 to 15 metres above sea level and with a length of 15 to 60 metres.

Medium Iceberg: A piece of glacier ice extending 16 to 45 metres above sea level and with a length of 61 to 120 metres.

Large Iceberg: A piece of glacier ice extending 46 to 75 metres above sea level and with a length of 121 to 200 metres.

Very Large Iceberg: A piece of glacier ice extending more than 75 metres above sea level and with a length of more than 200 metres.

Ice Island: A large piece of floating ice protruding about 5 metres above sea level, which has broken away from an Arctic ice shelf. They have a thickness of 30-50 metres and an area of from a few thousand square metres to 500 squared kilometres or more. They are usually characterized by a regularly undulating surface giving a ribbed appearance from the air.

Ice Island Fragment: Piece of an ice island that has broken away from the main mass.

Forms of River and Lake Ice

River Ice: Ice formed on a river, regardless of observed location.

Ice Jam: An accumulation of broken river ice or sea ice caught in a narrow channel.

Batture Floes: Fragments of grounded or shore-fast ice common to the upper St. Lawrence that have broken away and drifted downstream. They may be large, thick and uneven and are frequently discoloured with ground deposits.

Lake Ice: Ice formed on a lake, regardless of observed location, with subcategories;

New Lake Ice: recently formed ice less than 5 cm thick

Thin Lake Ice: 5 - 15 cm thick

Medium Lake Ice: 15 - 30 cm thick

Thick Lake Ice: 30 - 70 cm thick

Very Thick Lake Ice: greater than 70 cm thick

Other Ice Terms Common to Shipping

Beset: Situation of a vessel surrounded by ice and is unable to move.

Difficult Area: A general qualitative expression to indicate, in a relative manner, that the severity of ice conditions prevailing in an area are such that navigation is difficult.

Easy Area: A general qualitative expression to indicate, in a relative manner, that ice conditions prevailing in an area are such that navigation is not difficult.

Icebound: A harbour, inlet, etc. is said to be icebound when navigation by ships is prevented on

account of ice, except possibly with the assistance of an icebreaker.

Ice Under Pressure: Ice in which deformation processes are actively occurring and hence a potential impediment or danger to shipping.

Other Ice Terms

bare ice – ice without snow

belt – refers to a band of pack ice

concentration – the ratio of ice floe area to total area (rest is water), usually measured in 1/10ths

consolidated ridge – the ice blocks in the ridge have frozen together

crack - any sort of fracture or rift in the sea-ice covering.

deformed ice – ice that has rubbled up due to pressure

diffuse ice edge – edge comprised of open pack

diverging – ice that is opening up, drifting apart

drift-ice - loose open ice, where the area of water exceeds that of ice. Generally drift-ice is within reach of the swell, and is a stage in the breaking down of pack-ice, the size of the floes being much smaller than in the latter. (Scoresbys use of the term drift-ice for pieces of ice intermediate in size between floes and brash has, however, quite died out). The Antarctic or Arctic pack usually has a girdle or fringe of drift-ice.

fast-ice boundary – boundary between the static and dynamic ice

fast-ice edge - ditto

ice field - a sheet of ice of such extent that its limits cannot be seen from the masthead.

finger rafted ice – thin ice that rafts in a repetitive fingering pattern

finger rafting - ditto

floating ice – ice that is not grounded

ice floe or ice flow - an area of ice, level or hummocked, whose limits are within sight. Includes all sizes between brash on the one hand and fields on the other. Light-floes are between one and two feet in thickness (anything thinner being young-ice). Those exceeding two feet in thickness are termed heavy floes, being generally hummocked, and in the Antarctic, at any rate, covered by fairly deep snow.

floeberg – a large and thick ice floe, usually with a significant hummock

flooded ice – ice with water on it

fracture – a crack through the ice floe (separating the floe in two).

fracture zone – area of many fractures

fracturing – duh.

frost smoke – condensing (and freezing) vapour

grounded hummock – hummocks are refrozen rubble ice (frozen blocks) that are almost iceberg-like but were originally sea ice. When they form in or drift to shallow water, they ground.

hummocking - includes all the processes of pressure formation whereby level young ice becomes broken up and re-consolidated into hummocks.

Hummocky Floes. The most suitable term for what has also been called old pack and screwed pack by David and Scholleneis by German writers. In contrast to young ice, the structure is no longer fibrous, but becomes spotted or bubbly, a certain percentage of salt drains away, and the ice becomes almost translucent.

ice boundary – the edge of pack ice

ice cover – the ice on the water surface

ice field - ditto

ice limit – edge of ice

ice rind - a brittle, shiny crust of ice formed on a quiet surface by direct freezing or from grease ice, usually in water of low salinity. It has a thickness of about 5 centimetres. Easily broken by wind or swell, commonly breaking into rectangular pieces

ice under pressure – ice pack that is 9+/10ths and is converging further

ice-bound – a ship surrounded and stopped by ice

ice-free – open water

lead – an open water passage between ice floes

lead or lane - where a crack opens out to such a width as to be navigable. In the Antarctic it is customary to speak of these as leads, even when frozen over to constitute areas of young ice.

level ice – ice without ridges or rubble

medium ice field – field comprised of medium floes

pack-ice. Ice comprised of separate floes, whether open or close.

pools - any enclosed water areas in the pack, where length and breadth are about equal.

rafted ice – level ice floes on top of other level floes

rafting – floes moving over other floes

ridged ice – an area where there are many ridges in the ice floes

ridged ice zone - ditto

ridging – the formation of ridges

rubble field – area of deformed (ridged) ice that has become almost all rubble (ridges grow until all ice is broken into pieces)

sea ice – frozen sea water

shearing – ice moving transverse to other ice

small floe – floes 20-100 m across

small ice field – field comprised of small floes

snow-covered ice – duh.

Snowdrift – like a sand dune, but made of snow

stranded ice – grounded ice

strip – a collection of ice floes in an elongated arrangement, surrounded by water

thaw hole – a melt hole right through an ice floe

The Pack is a term very often used in a wide sense to include any area of sea-ice, no matter what form it takes or how disposed. The French term is *banquise de derive*.

very close ice – 9/10ths ice pack

very open ice – 1/10 to 3/10ths ice pack

young ice - applied to all unhummocked ice up to about a foot in thickness. Owing to the fibrous or platy structure, the floes crack easily, and where the ice is not over thick a ship under steam cuts a passage without much difficulty. Young ice may originate from the coalescence of pancakes, where the water is slightly ruffled or else be a sheet of black ice, covered maybe with ice-flowers, formed by the freezing of a smooth sheet of sea-water.

See:

<https://www.canada.ca/en/environment-climate-change/services/weather-manuals-documentation/manice-manual-of-ice.html>

Appendix B: Detailed Derivation of Popov Mass Equations

This appendix shows the derivation of the Popov mass reduction coefficient C_o . This approach was developed by Popov (1969). A collision taking place at point $p(x,y,z)$ (see Figure B.1). A force along the normal F_n , will accelerate point p , and a component of the acceleration will be along the normal vector, with a magnitude a_n . The collision can be modeled as if the point P were a single mass (1 degree of freedom system) with an equivalent mass M_e of;

$$M_e = \frac{F_n}{a_n} \quad (B.1)$$

The effective mass is a function of the inertial properties (mass, radii of gyration, hull angles and moment arms) of the ship. The effective mass is linearly proportional to the mass (displacement) of the vessel, and can be expressed as;

$$M_e = \frac{M_{ship}}{C_o} \quad (B.2)$$

where C_o is the mass reduction coefficient. The components of the mass reduction equation are presented below. The full derivation follows.

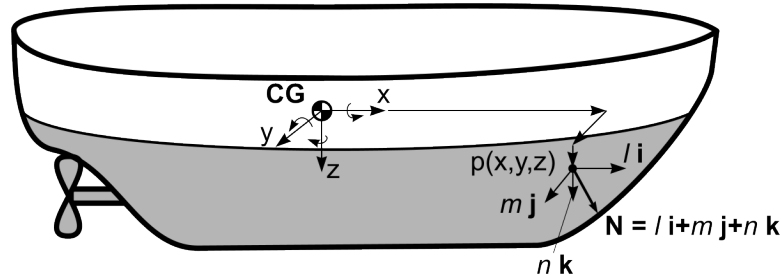


Figure B.1 Collision point geometry

The inertial properties are as follows. The vessel has a mass M . Because the vessel has six degrees of freedom and because of the added inertia of the water is different for each direction, there are six inertial quantities (3 masses and 3 mass moments of inertia). In the x , y and z (surge, sway and heave) directions the masses are;

$$M_x = M (1 + AM_x) \quad (B.3)$$

$$M_y = M (1 + AM_y) \quad (B.4)$$

$$M_z = M (1 + AM_z) \quad (B.5)$$

The rotary inertia of a body can be expressed as the mass time the radius of gyration squared. So, for the rotation about the x, y and z axes (roll, Pitch and yaw) the mass moments of inertia are;

$$I_x = M r_x^2 (1 + AM_{roll}) \quad (B.6)$$

$$I_y = M r_y^2 (1 + AM_{pit}) \quad (B.7)$$

$$I_z = M r_z^2 (1 + AM_{yaw}) \quad (B.8)$$

The fluid added masses are expressed as proportions of the physical mass (added mass factors). Popov provided equations to estimate these quantities, which were intended to be valid for typical ice class ships. Added mass was treated in this simple way by Popov, but this is an area that likely deserves additional study, with emphasis on the transient added mass during collisions, rather than the more common added mass used in seakeeping analysis. Figure B.2 illustrates the six inertial quantities of the vessel.

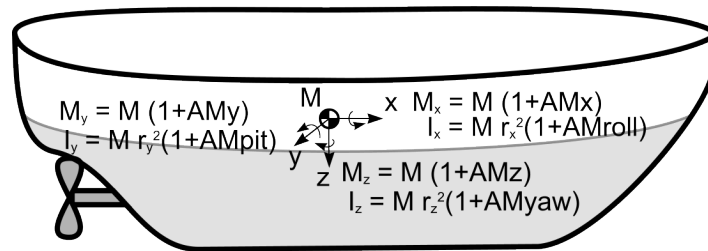


Figure B.2 Inertial properties of the vessel

At the point of ice impact, the hull is assumed to be locally flat, with angles as shown in Figure B.3, at point p:

- α = waterline angle
- β = frame angle
- β' = normal frame angle
- γ = sheer angle

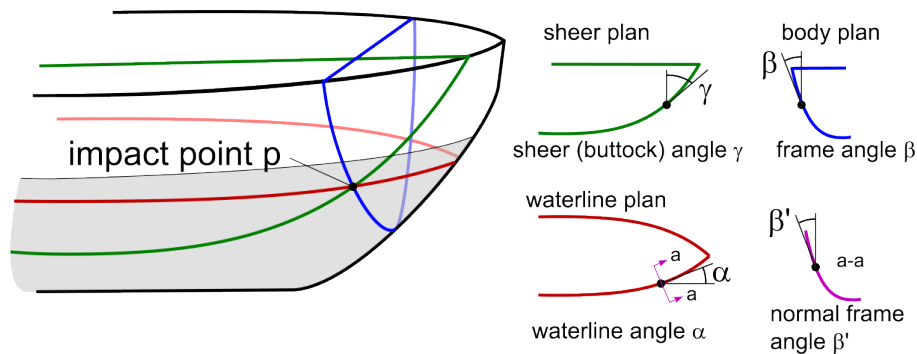


Figure B.3 Hull angle definitions.

The various angles are related as follows,

$$\tan \beta = \tan \alpha \cdot \tan \gamma \quad (B.9)$$

$$\tan \beta' = \tan \beta \cdot \cos \alpha \quad (B.10)$$

Based on these angles, the direction cosines, l, m, n are

$$l = \sin \alpha \cdot \cos \beta' \quad (B.11)$$

$$m = \cos \alpha \cdot \cos \beta' \quad (B.12)$$

$$n = \sin \beta' \quad (B.13)$$

The direction cosines are the x, y and z components of the unit normal vector. We assume the unit normal to be outward pointing. We are examining a location on the hull where the coordinates are all positive and the outward normal vector has all positive coordinates. We will examine how the point p accelerates along the normal for a force acting along the normal. The ice load would be inward pointing and so, negative. This does not matter as the accelerations are all proportional to the force and the effective mass will turn out the same regardless of the direction of the force. Mass always resists movement, and so is always positive.

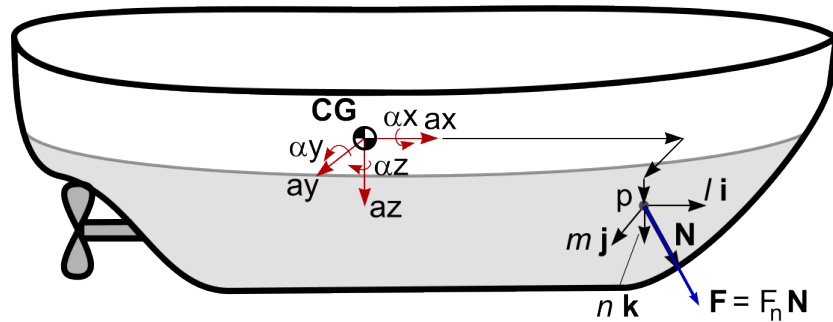


Figure B.4 Force at p and resulting body accelerations.

With the above properties, we will now go through the sequence of steps that leads to the equation for the effective ship mass at the contact point p. This derivation could be done with vectors and matrices (linear algebra), but to keep all the steps as clear as possible we will show the derivations using the x, y, z components of force and acceleration. We start by assuming that a normal force F is applied at the point p, as shown in Figure B.4. The x,y,z force components are;

$$F_x = F_n l \quad (B.14)$$

$$F_y = F_n m \quad (B.15)$$

$$F_z = F_n n \quad (B.16)$$

These three forces cause accelerations in all six degrees of freedom at the center of gravity of the ship. We use the mass and added mass properties as described above. Each value is essentially a version of $a = \text{force}/\text{mass}$. The translation accelerations are;

$$a_x = \frac{F_n l}{M (1 + AM_x)} \quad (B.17)$$

$$a_y = \frac{F_n m}{M (1 + AM_y)} \quad (B.18)$$

$$a_z = \frac{F_n n}{M (1 + AM_z)} \quad (B.19)$$

The rotary accelerations are a bit more complex. For each rotary degree of freedom, we use the rotary inertias as show above, together with a calculation of the moment. Each moment component is the result of two of the force components. The 3 moments are;

$$M_x = F_z y_p - F_y z_p = F_n (n y_p - m z_p) \quad (B.20)$$

$$M_y = F_x z_p - F_z x_p = F_n (l z_p - n x_p) \quad (B.21)$$

$$M_z = F_y x_p - F_x y_p = F_n (m x_p - l y_p) \quad (B.22)$$

We define the x,y,z moment arms (see above) as;

$$\lambda_1 = n y_p - m z_p \quad (B.23)$$

$$\mu_1 = l z_p - n x_p \quad (B.24)$$

$$\eta_1 = m x_p - l y_p \quad (B.25)$$

The three rotary accelerations α at the CG are thus;

$$\alpha_x = \frac{F_n (n y_p - m z_p)}{M r_x^2 (1 + AM_{roll})} \quad (B.26)$$

$$\alpha_y = \frac{F_n (l z_p - n x_p)}{M r_y^2 (1 + AM_{pit})} \quad (B.27)$$

$$\alpha_z = \frac{F_n (m x_p - l y_p)}{M r_z^2 (1 + AM_{yaw})} \quad (B.28)$$

We now have the six accelerations at the CG. We need to transfer these back to the ice impact point p. We are only interested in the translation components, but these are a function of all six components at the CG.

$$a_{px} = a_x + \alpha_y z - \alpha_z y \quad (B.29)$$

$$a_{py} = a_y + \alpha_z x - \alpha_x z \quad (B.30)$$

$$a_{pz} = a_z + \alpha_x y - \alpha_y x \quad (B.31)$$

With these three translation accelerations at p we next compute the acceleration at p along the normal direction. This is done by taking the dot product of the acceleration vector at p with the normal;

$$a_n = [(a)_{px}, \alpha_{py}, p_{pz}) \cdot (l, m, n) = a_{px} l + a_{py} m + a_{pz} n \quad (B.32)$$

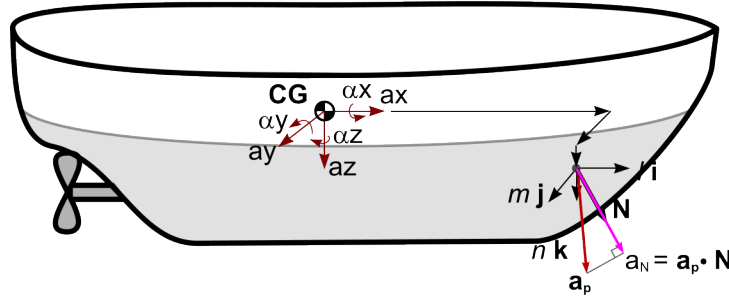


Figure B.5 Hull angle definitions.

With the above equations we can now write;

$$a_n = a_x l + \alpha_y z l - \alpha_z y l + a_y m + \alpha_z x m - \alpha_x z m + a_z n + \alpha_x y n - \alpha_y x n \quad (B.33)$$

Now substituting for the a and α terms, and collecting the terms that become the moment arms (λ_1, μ_1, η_1) we get;

$$\begin{aligned} & a_n \\ &= F_n/M \left(l^2/(1 + AM_x) + m^2/(1 + AM_y) + n^2/(1 + AM_z) \right. \\ & \quad \left. + (\lambda_1^2)/(rx^2 (1 + AM_{rol})) + (\mu_1^2)/(ry^2 (1 + AM_{pit})) \right. \\ & \quad \left. + (\eta_1^2)/(rz^2 (1 + AM_{yaw})) \right) \end{aligned} \quad (B.34)$$

Now we make use of equations (B.1) and (B.2) to get;

$$C_o = \frac{M}{F_n} a_n \quad (B.35)$$

So, the mass reduction coefficient C_o is

$$\begin{aligned} C_o &= \frac{l^2}{1 + AM_x} + \frac{m^2}{1 + AM_y} + \frac{n^2}{1 + AM_z} \\ &+ \frac{\lambda_1^2}{rx^2(1 + AM_{rol})} + \frac{\mu_1^2}{ry^2(1 + AM_{pit})} + \frac{\eta_1^2}{rz^2(1 + AM_{yaw})} \end{aligned} \quad (B.36)$$

And finally, the effective mass of the ship at the collision is;

$$M_e = \frac{M}{C_o} \quad (B.37)$$

Popov suggested the following empirical formulae for the added mass terms;

$$AM_x = 0 \quad (B.38)$$

$$AM_y = 2 \frac{T}{B} \quad (B.39)$$

$$AM_z = 2/3 (B Cwp^2)/(T(Cb(1 + Cwp))) \quad (B.40)$$

$$AM_{rol} = 0.25 \quad (B.41)$$

$$AM_{pit} = B/((T(3 - 2Cwp)(3 - Cwp))) \quad (B.42)$$

$$AM_{yaw} = 0.3 + 0.05 L/B \quad (B.43)$$

Popov also suggested the mass radii of gyration (squared) as;

$$rx^2 = Cwp \frac{B^2}{11.4 Cm} + \frac{H^2}{12} \quad (B.44)$$

$$ry^2 = 0.07 Cwp L^2 \quad (B.45)$$

$$rz^2 = \frac{L^2}{16} \quad (B.46)$$

This completes the calculation of the effective mass of the ship. The same approach would be used for the ice flow. In the original work Popov assumed a round ice flow, which simplifies the problem. In that case the yaw moment arm is zero, and the sway and surge parameters are the same. If the ice flow is some general polygon, the mechanics would have to be computed using general concepts of kinematics. The added masses would have to be obtained or assumed. In the case of a collision with a finite ice flow, there will be an effective mass for the ship $M_{e,ship}$ and a separate one for the ice $M_{e,ice}$. These can be combined to a single effective impact mass M_{eff} for the impact; as

$$M_{eff} = \frac{1}{\frac{1}{M_{e,ship}} + \frac{1}{M_{e,ice}}} \quad (B.47)$$

Note that in a case of a ship hitting a massive ice flow, the effective mass for the collision will just be the effective mass of the ship. This is the case for the design scenario used for the IACS Polar Rules. In the reverse case of an ice mass much smaller than the ship, the effective mass for the collision will just be the effective mass of the ice.

Appendix C: Ice edge Crushing Geometry Cases

Chapter 9 describes how to solve ship-ice impact, and illustrates the problem with the case of a wedge-shaped ice edge.

$$F_n = p_o \cdot fa \cdot \zeta_n^{fx-1} \quad (C.1)$$

The fa and fx terms are derived from the geometry. To find the normal area of contact you can use the following relationship;

$$A_n^{1+ex} = fa \cdot \zeta_n^{fx-1} \quad (C.2)$$

Or

$$A_n = fa^{\frac{1}{1+ex}} \cdot \zeta_n^{\frac{fx-1}{1+ex}} \quad (C.3)$$

Which looks complicated, but it is relatively simple in practice. For instance, in case 1;

$$A_n = \left(\frac{\tan \frac{\phi}{2}}{\sin \beta' \cos^2 \beta'} \right)^{\frac{1+ex}{1+ex}} \cdot \zeta_n^{\frac{3+2ex-1}{1+ex}} \quad (C.4)$$

Which becomes;

$$A_n = \frac{\tan \frac{\phi}{2}}{\sin \beta' \cos^2 \beta'} \cdot \zeta_n^2 \quad (C.5)$$

Table C.1 lists the fx and fa equations for a wide variety of ice edge geometries. The first case is the standard case used in the IACS Polar Rules. The third case was the one Popov considered in his original development. These cases cover situations for both ships and offshore structures.

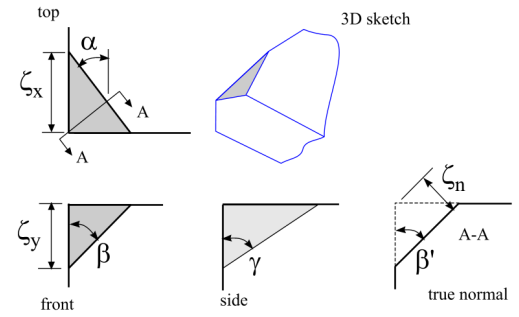
Table C.1 Ice edge crushing geometry cases.

Case	fx	fa	Sketch
1.			
General	$fx = 3 + 2 ex$	$fa = \left(\frac{\tan \frac{\phi}{2}}{\sin \beta' \cos^2 \beta'} \right)^{1+ex}$	

2.
Right
Angle
Wedge

$$fx = 3 + 2 ex$$

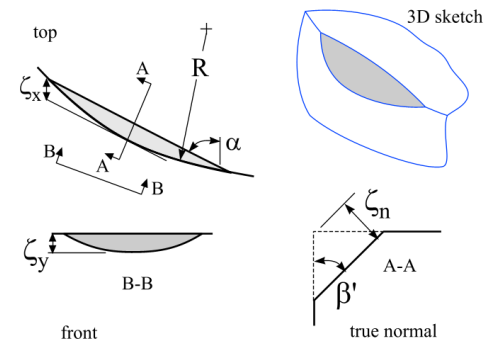
$$fa = \left(\frac{1}{\sin \alpha \cos \alpha \sin \beta' \cos^2 \beta'} \right)^{1+ex}$$



3.
Round
Edge

$$fx = 2.5 + 1.5 ex$$

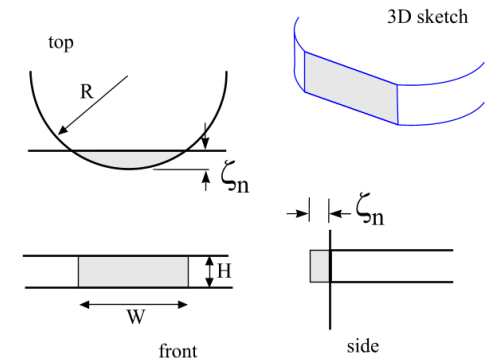
$$fa = \left(\frac{4}{3 \sin \beta' \cos^{1.5} \beta' \sqrt{2R}} \right)^{1+ex}$$



4.
Round
Ice, Flat
structure

$$fx = 1.5 + 0.5 ex$$

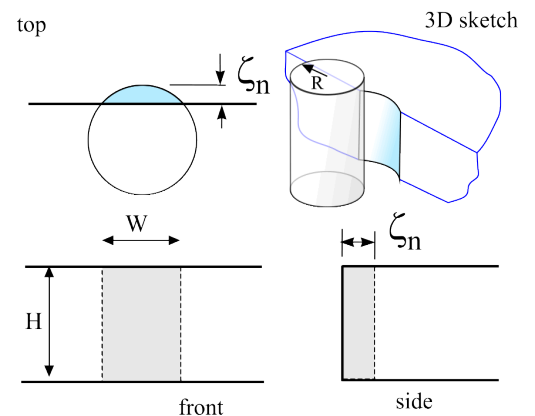
$$fa = (2 H \sqrt{2R})^{1+ex}$$



5.
Straight
Ice Edge.
Round
Cylinder

$$fx = 1.5 + 0.5 ex$$

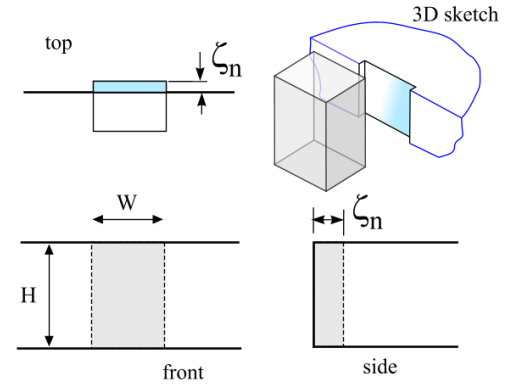
$$fa = (2 H \sqrt{2R})^{1+ex}$$



6.
Right
Rect.
Cylinder

$$fx = 1$$

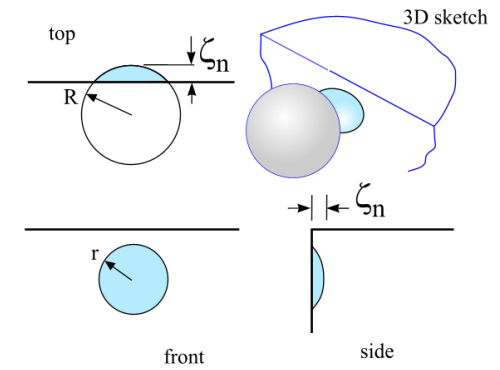
$$fa = (HW)^{1+ex}$$



7.
Sphere

$$fx = 2 + ex$$

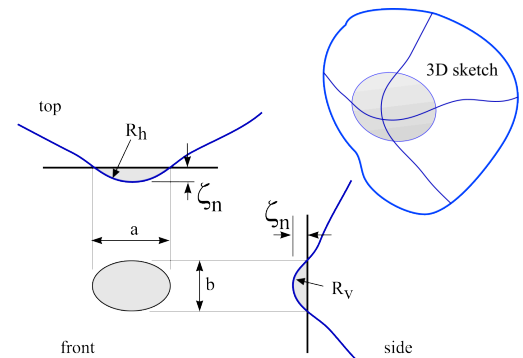
$$fa = (2\pi R)^{1+ex}$$



8.
Ellipsoid

$$fx = 2 + ex$$

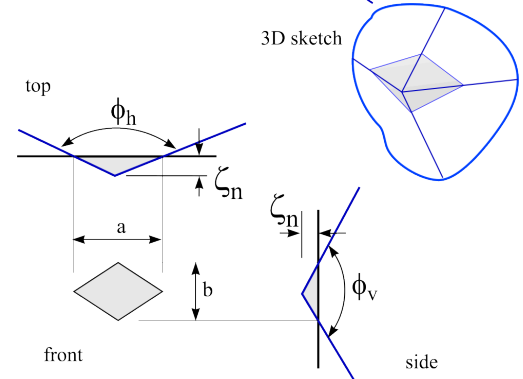
$$fa = (2\pi \sqrt{R_h} \sqrt{R_v})^{1+ex}$$



9.
Unequal
Diamond

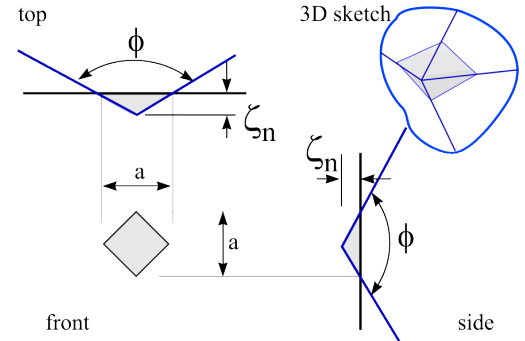
$$fx = 3 + 2ex$$

$$fa = \left(2 \tan \frac{\phi_h}{2} \tan \frac{\phi_v}{2}\right)^{1+ex}$$



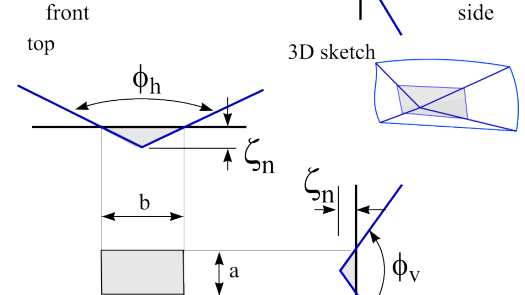
10.
Diamond $fx = 3 + 2ex$

$$fa = \left(\sqrt{2} \tan \frac{\phi}{2} \right)^{2+2ex}$$



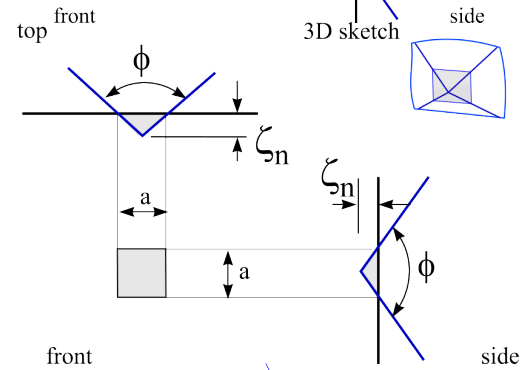
11
Unequal
Pyramid $fx = 3 + 2ex$

$$fa = \left(4 \tan \frac{\phi_h}{2} \tan \frac{\phi_v}{2} \right)^{1+ex}$$



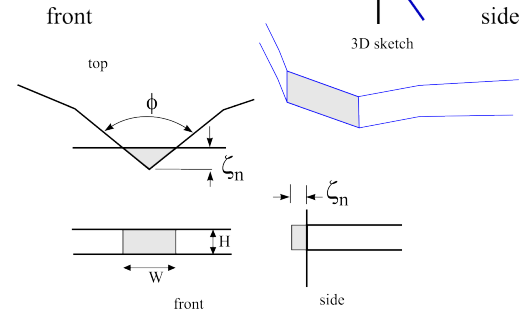
12
Pyramid $fx = 3 + 2ex$

$$fa = \left(2 \tan \frac{\phi}{2} \right)^{2+2ex}$$



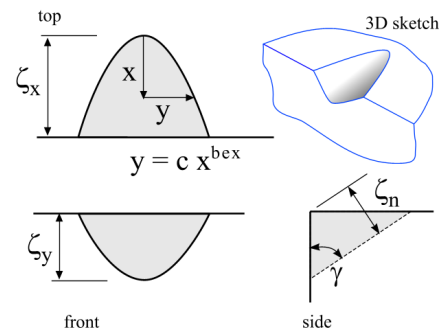
10.
Flat
Wedge $fx = (2 + ex)$

$$fa = \left(2 H \tan \frac{\phi}{2} \right)^{1+ex}$$



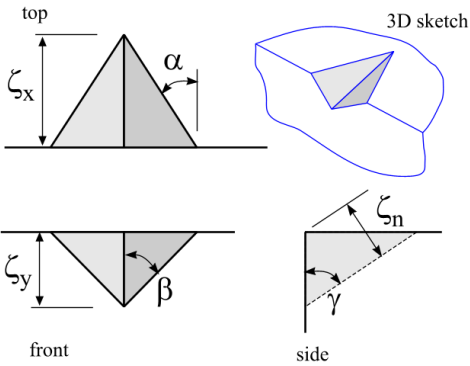
11.
Spoon
Bow $fx = ((bex + 1)(1 + ex) + 1)$

$$= \left(2 \left(\frac{1}{\cos \gamma} \right)^{bex+1} \frac{fa}{(bex + 1) \sin \gamma} \right)^{1+ex}$$



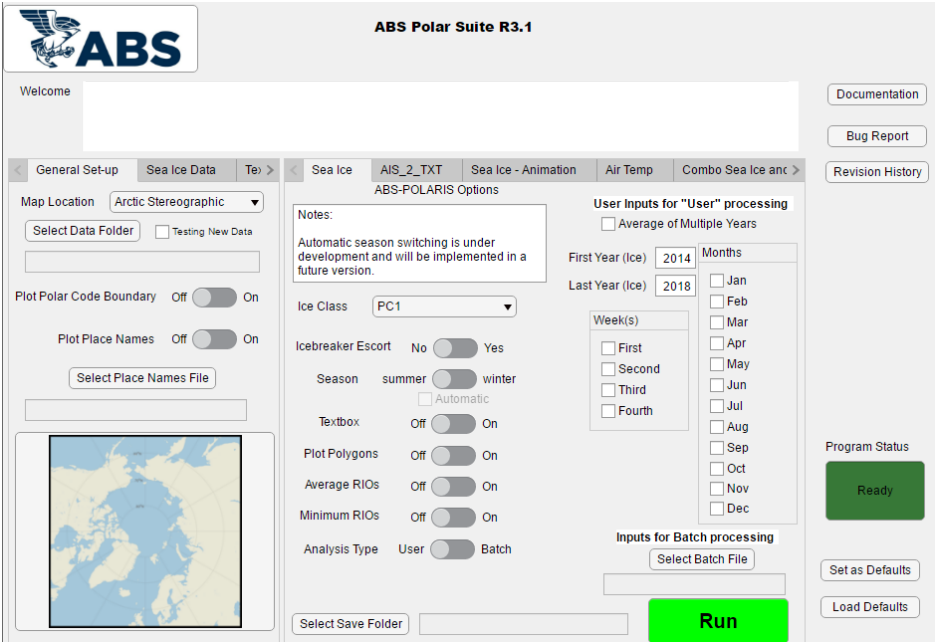
12.
Wedge $fx = 3 + 2 \, ex$
Bow

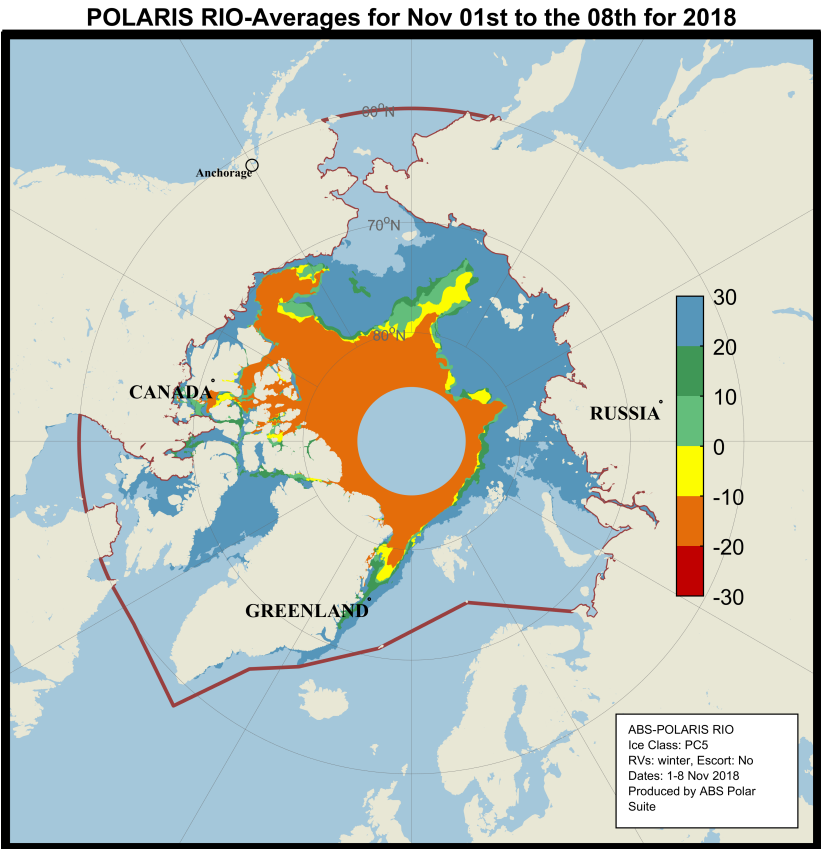
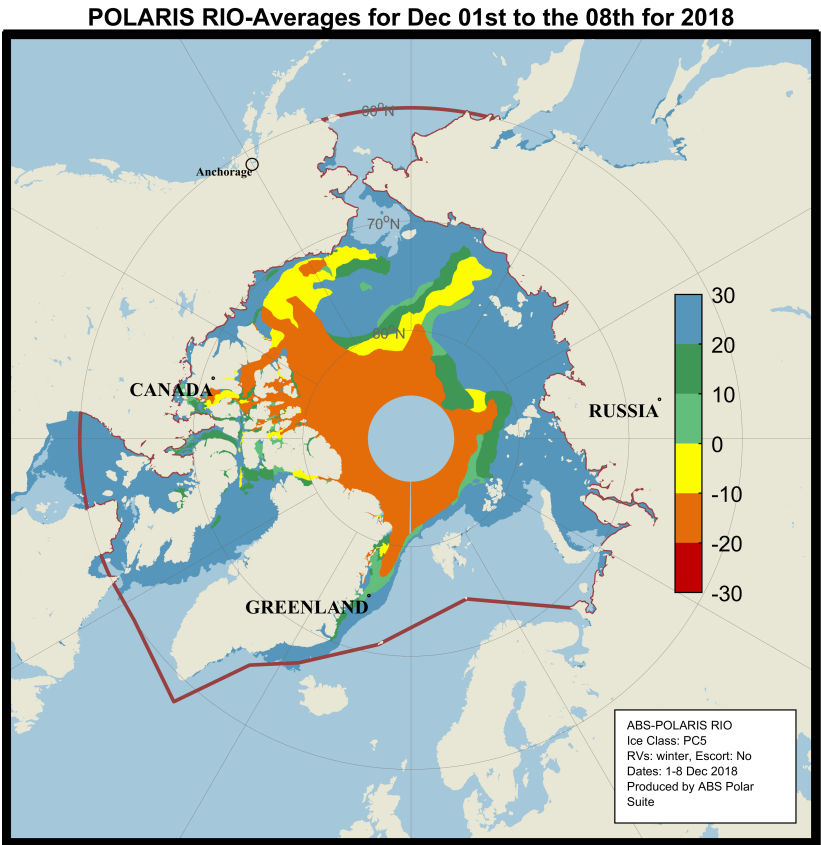
$$fa = \left(\frac{\tan \alpha}{\cos^2 \gamma \sin \gamma} \right)^{1+ex}$$

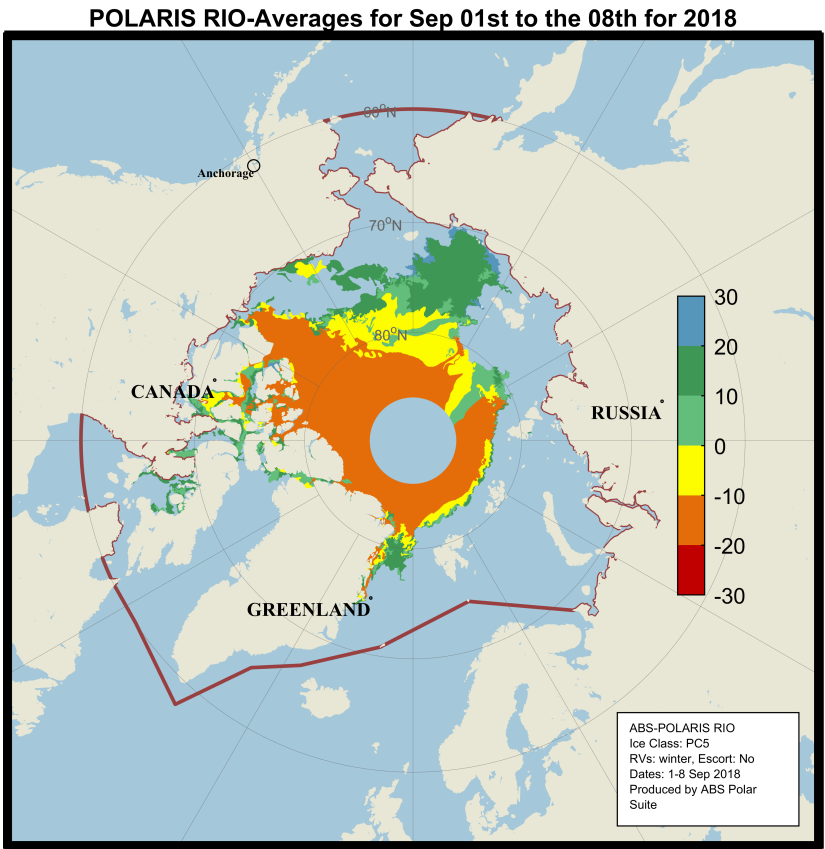
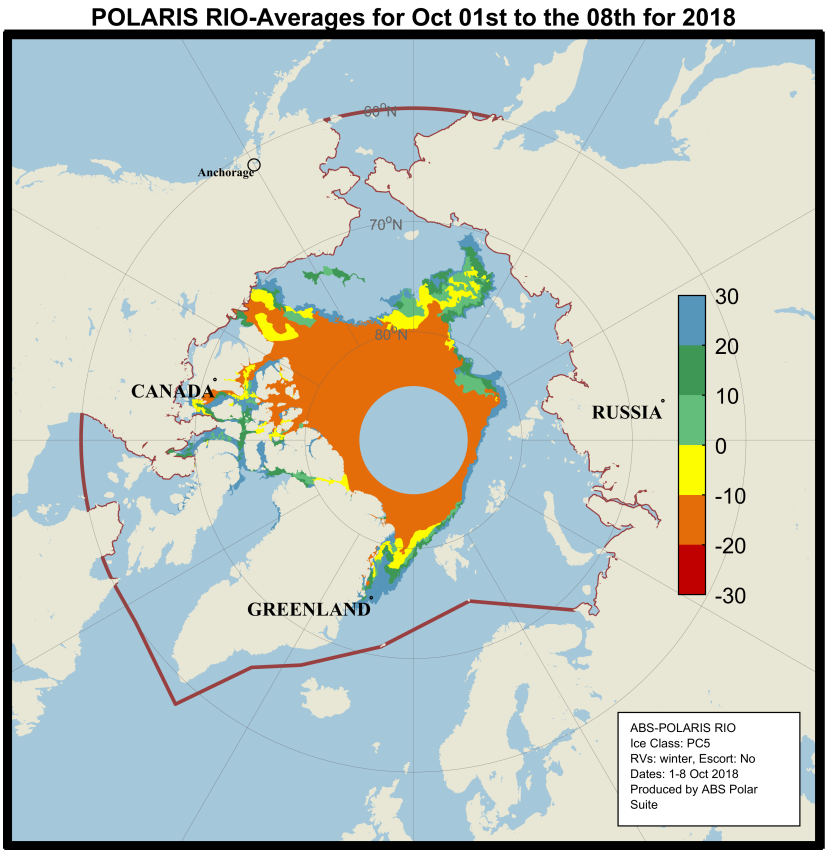


Appendix D: Sample POLARIS RIO Maps

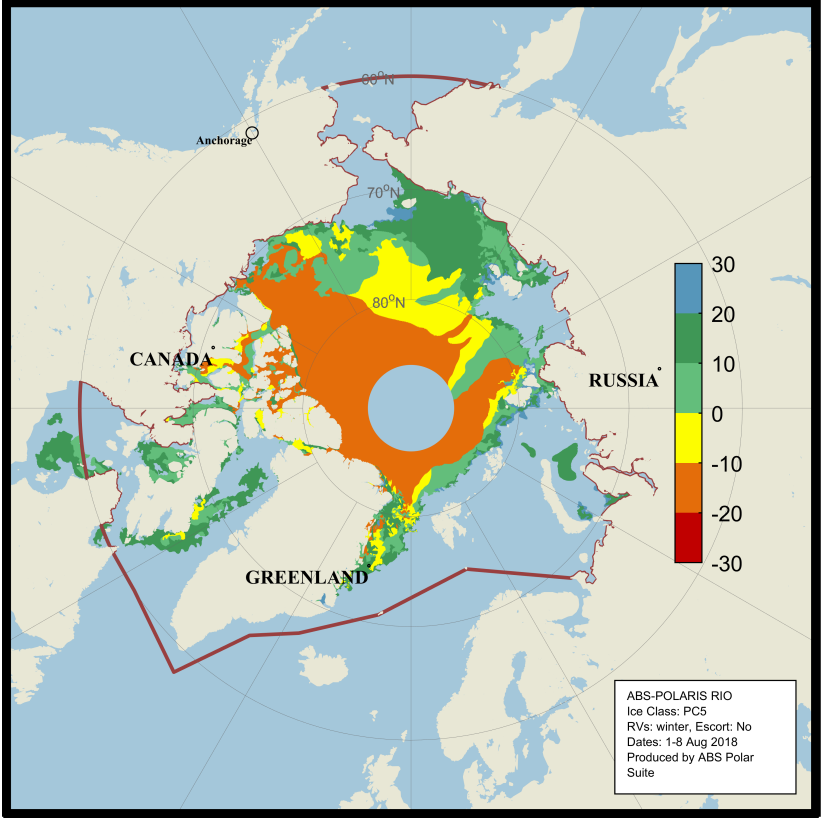
The maps below show the results of a POLARIS Risk Index Outcome (RIO) assessment for a PC5 vessel over the 2018 year. The maps indicate which week the assessment applies. These maps have been produced by an in-house program at the American Bureau of Shipping. The program is called ABS Polar Suite (ver 3.1) is used for a variety of Winterization studies for ship operations, such as calculation the Mean Daily Low Temperature (MDLT) as is required by the IMO Polar Code. Examples of these temperature plots were published in the ABS Guide for Vessels Operating in Low Temperature Environments. The RIO maps make use of publicly available ice and weather information from a variety of countries.



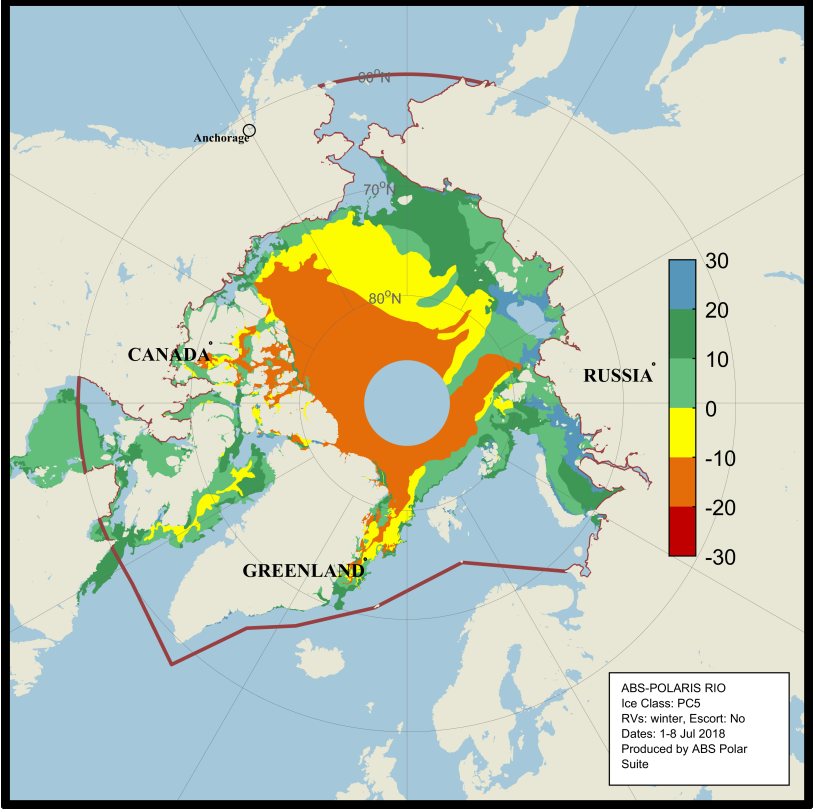




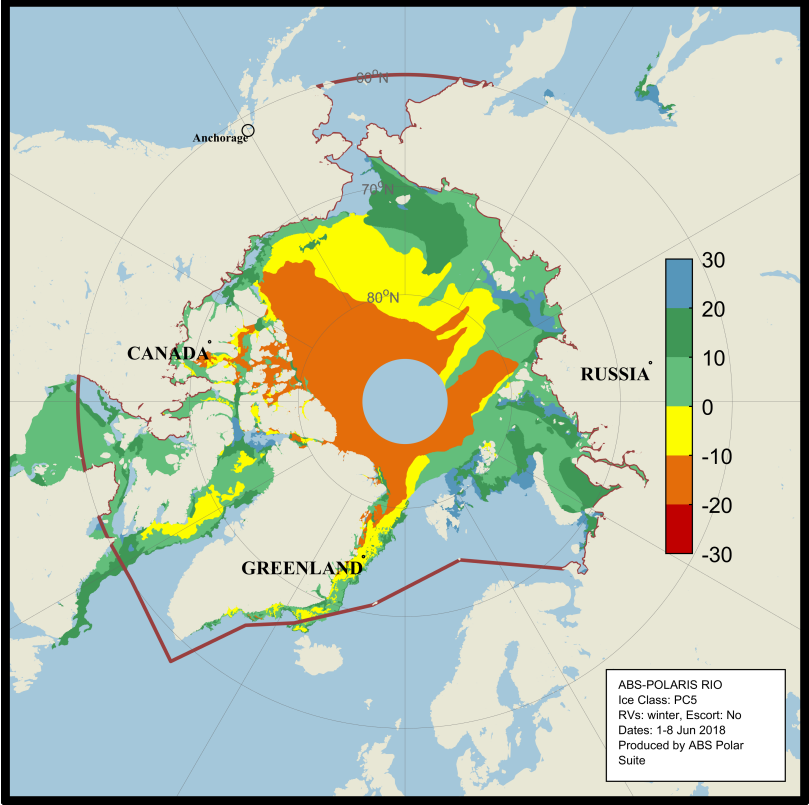
POLARIS RIO-Averages for Aug 01st to the 08th for 2018



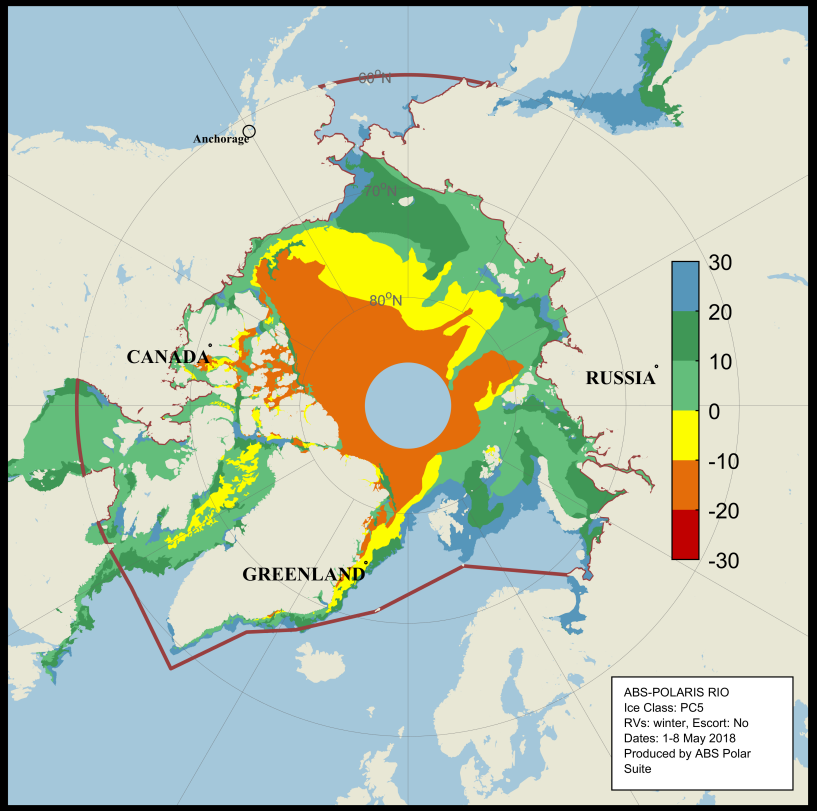
POLARIS RIO-Averages for Jul 01st to the 08th for 2018



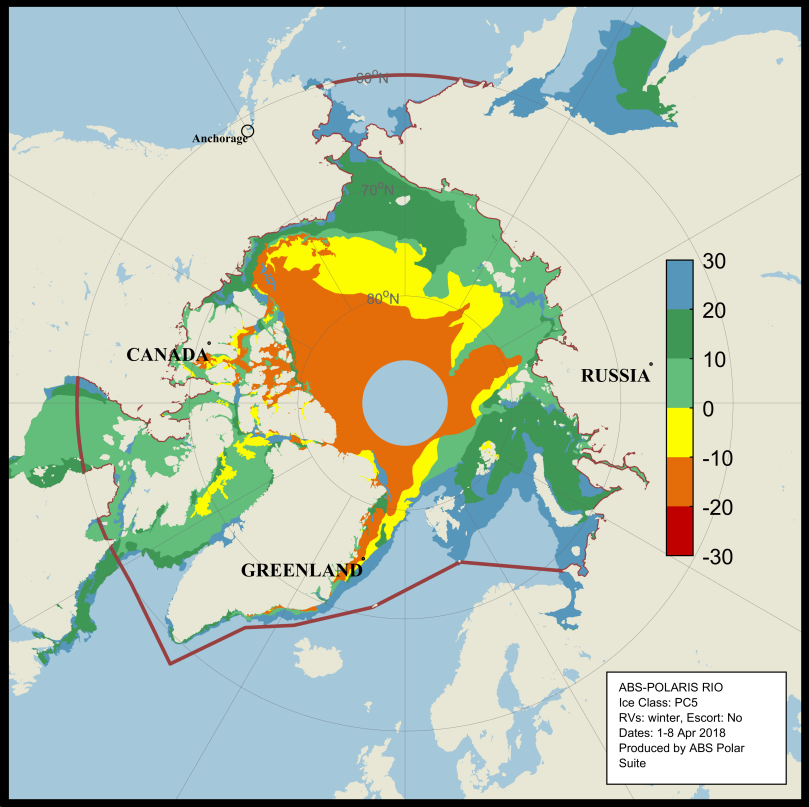
POLARIS RIO-Averages for Jun 01st to the 08th for 2018



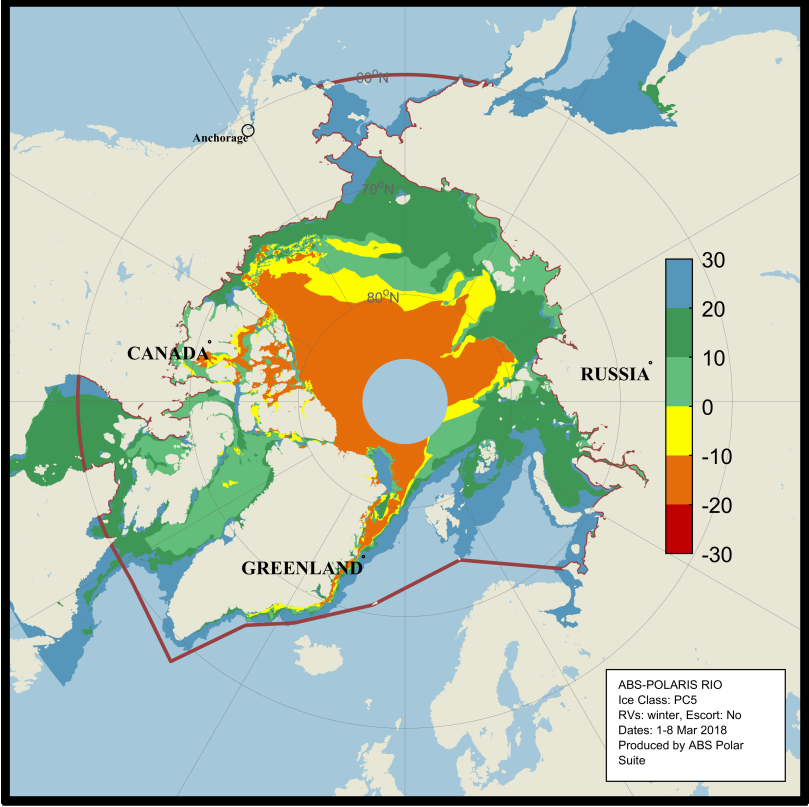
POLARIS RIO-Averages for May 01st to the 08th for 2018

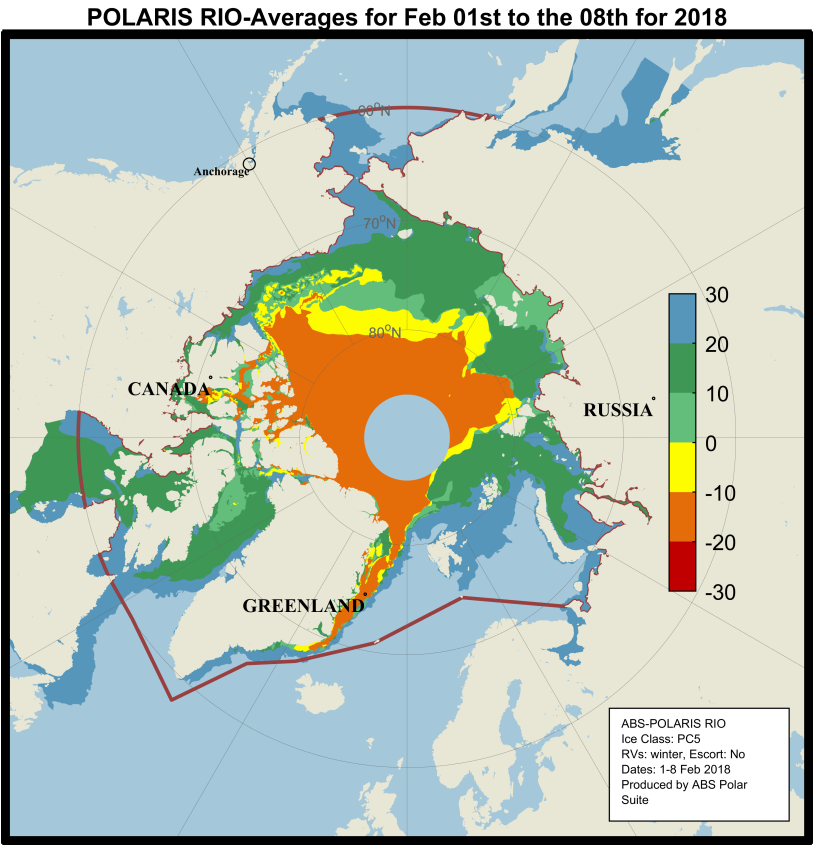


POLARIS RIO-Averages for Apr 01st to the 08th for 2018



POLARIS RIO-Averages for Mar 01st to the 08th for 2018





Appendix E: Modeling Dynamic Problems with Spreadsheets

Most ice load cases on floating bodies are dynamic. Solving impact or vibration problems can often appear quite difficult. This appendix will present a relatively simple and practical way to solve a wide range of dynamic mechanical problems using any spreadsheet. The approach does not require any programming (or macros) and so should be quite quick to set up.

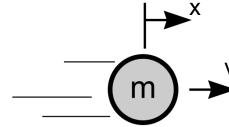
The methods presented here are all “explicit” in the sense that at each time step, the new values are only based on values from the last time step (which are ‘known’) or on other known information. There is no need for any ‘trial and error’ search, or iteration or any such approach that would likely require a computer program (e.g excel macro) to obtain a solution.

Case 1 – steady motion

The simplest dynamic system is a mass, in interstellar space (i.e. no gravity), moving at constant speed. The equation of motion can be stated as $F = m a$, but since $F = 0$ then $a = 0$ and velocity stays constant. Modelling the motion in x (assuming x is the direction of the motion) is easy.

At time $t=0$ we define $x=x_0$, $v = v_0$, which we provide. We also decide on a timestep dt . A time step integration of the motion would have the following components;

i	t_i	x_i	v_i
0	0	x_0	v_0
1	dt	$= x_0 + v_0 dt$	$= v_0$
2	$2 dt$	$= x_1 + v_1 dt$	$= v_1$
:	:	:	:
n	$n dt$	$= x_{n-1} + v_{n-1}dt$	$= v_{n-1}$

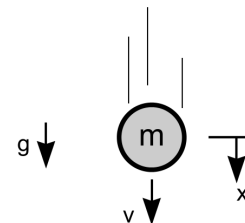


Case 2 – falling in constant gravity

The next simplest dynamic system is a mass subject to a constant force (i.e. gravity), and so moving with constant acceleration. The equation of motion can be stated again as $F = m a$, but since $F = mg$ then $a = g$ and velocity increases steadily. Modelling the motion in x (assuming x is the direction of gravity and the motion) is easy.

At time $t=0$ we define $x=x_0$, $v = v_0$, which we provide. We also decide on a timestep dt . A time step integration of the motion would have the following components;

i	t_i	x_i	v_i	a_i
0	0	x_0	v_0	$a_0 = g$
1	dt	$= x_0 + v_0 dt + a_0/2 dt^2$	$= v_0 + a_0 dt$	$= a_0$
2	$2 dt$	$= x_1 + v_1 dt + a_1/2 dt^2$	$= v_1 + a_1 dt$	$= a_1$
:	:	:	:	:
n	$n dt$	$= x_{n-1} + v_{n-1}dt + a_{n-1}/2 dt^2$	$= v_{n-1} + a_{n-1} dt$	$= a_{n-1}$

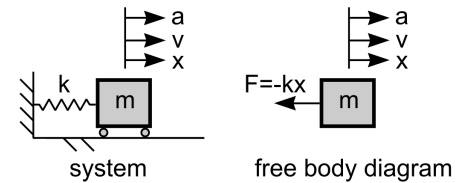


The two cases shown above are not especially useful, but they illustrate how a time history of body position and velocity can be found by numerically integrating an equation in a spreadsheet.

Case 3a – undamped vibration (a spring-mass system)

This case can illustrate some of the difficulties of numerical simulation. We will use three different approaches to show the potential problems and solutions.

The system and free body diagram are shown at the right. The equation of motion is still;



$$F = m a$$

But now we can express the force as a function of position;

$$-kx = m a$$

And we can write the acceleration as a function of x;

$$a = \frac{-k x}{m}$$

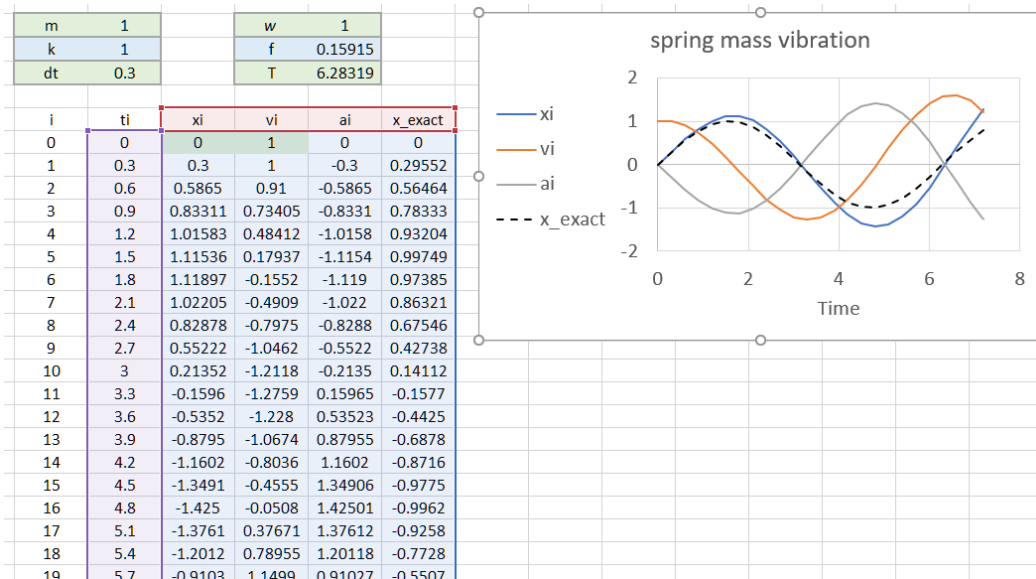
Note that this equation contains both x and a , which is the double derivative of x . The equation expresses Newton's second law and is valid at any moment of time. However, at any one instant in time x and a are different and are, in a sense, separate variables. A single equation in two unknown variables is not solvable, because there are an infinite number of solutions (any combination of x and a as long as $x = m a/k$). There is a very well known algebraic solution of this classic differential equation, one that is covered in most introductory courses in differential equations and every course in mechanical vibrations. But whether you know that solution or not (helps a bit if you do) you can solve this system quite easily in a spreadsheet.

The numerical solution starts by assuming initial values for x and v . The initial value of a is determined from the initial value of x . The next value of x , at a time dt after the first step, is found based on the x , v and a values in the previous time step. The next value of v is similarly found based on v and a from the previous step. In this way, each value is found based on value that are known. The spreadsheet will solve and will not report any "circular references".

i	t_i	x_i	v_i	a_i
0	0	x_o	v_o	$= -k x_o/m$
1	dt	$= x_o + v_o dt + a_o/2 dt^2$	$= v_o + a_o dt$	$= -k x_1/m$
2	$2 dt$	$= x_1 + v_1 dt + a_1/2 dt^2$	$= v_1 + a_1 dt$	$= -k x_2/m$
:	:	:	:	:
n	$n dt$	$= x_{n-1} + v_{n-1}dt + a_{n-1}/2 dt^2$	$= v_{n-1} + a_{n-1} dt$	$= -k x_n/m$

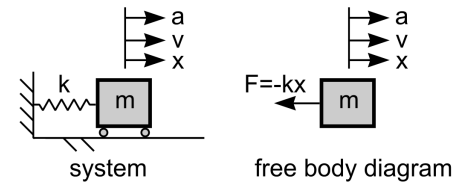
Note that we have selected a timestep dt , and that time marches forward in increments of dt . The image below shows what an actual spreadsheet looks like for a mass of 1 kg attached to a spring of 1 N/m. We've used a timestep of 0.3 seconds and we seem to have a reasonable result. Note the exact result shown. This shows that the numerical result follows the exact result at the start, but even the first peak of the sine wave is in error. The actual magnitude of the error depends on the size of dt . In this case we have a cycle time of about 6 seconds, with a timestep of 0.3 seconds. This gives us 20 steps per cycle which is reasonable. This simple

algorithm is not too bad when you are just interested in the initial response, which is often the case for an impact. A better solution will be shown next.



Case 3b – undamped vibration (a spring-mass system) (more accuracy)

This case is similar to 3a, but we will add additional terms. The problem with vibration and many collision problems is that the acceleration and forces are not constant. Case 2 has a constant force and is perfectly accurate, but Case 3a is not. We will add another term, called jerk which is the derivative of acceleration, to improve the accuracy



The system and free body diagram and the forces and acceleration are as in Case 3a. The definition of jerk is the rate of change of acceleration;

$$j = \frac{da}{dt} = \frac{d^3x}{dt^3}$$

We will find the jerk numerically by the formula;

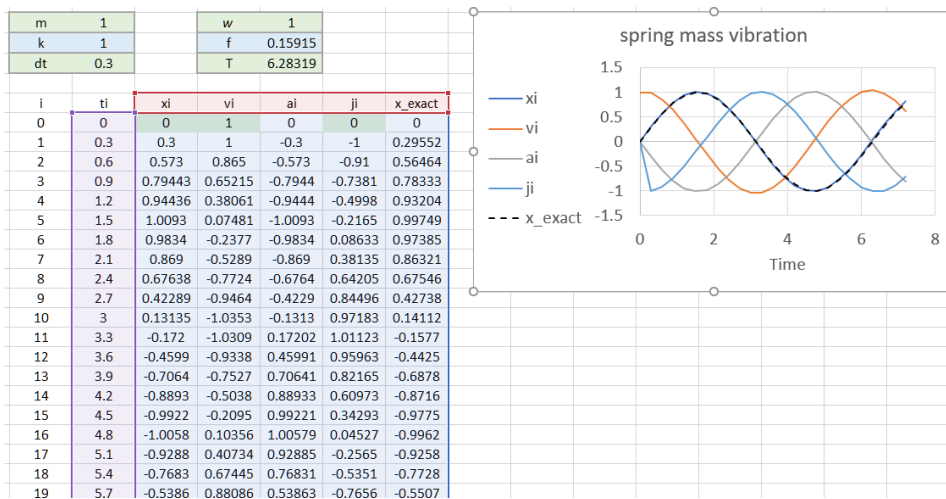
$$j_n = \frac{a_n - a_{n-1}}{dt}$$

The numerical solution is quite similar to 3a, with a few additions. Once again, each value is found based on values that are known. The spreadsheet will solve and will not report any “circular references”.

i	t _i	x _i	v _i	a _i	j _i
0	0	x ₀	v ₀	= -k x ₀ /m	0
1	dt	= x ₀ + v ₀ dt + a ₀ /2 dt ² + j ₀ /2 dt ³ *	= v ₀ + a ₀ dt + j ₀ /2 dt ²	= -k x ₁ /m	=(a ₁ -a ₀)/dt
2	2 dt	= x ₁ + v ₁ dt + a ₁ /2 dt ² + j ₁ /2 dt ³	= v ₁ + a ₁ dt + j ₁ /2 dt ²	= -k x ₂ /m	=(a ₂ -a ₁)/dt
⋮	⋮	⋮	⋮	⋮	⋮
n	n dt	= x _{n-1} + v _{n-1} dt + a _{n-1} /2 dt ² + j _{n-1} /2 dt ³	= v _{n-1} + a _{n-1} dt + j _{n-1} /2 dt ²	= -k x _n /m	=(a _n -a _{n-1})/dt

* This 2 in the j term is not an error – see below

In this case as you see below, the system solves very accurately for the entire first cycle of the oscillation. In fact, this algorithm can solve the vibration of an undamped oscillator for a long time. Even after 1000 cycles there is no noticeable change in amplitude. For collision problems, we only need the initial response, so this approach is ideal.



Notes on Numerical Integration in Structural Dynamics. For those who are interested in this topic, please note the following. The equations used in 3a and 3b above are really just the first terms of a Taylor series expansion of the function of x and v. A full Taylor series would be;

$$x(t) = x(a) + \frac{\dot{x}(a)}{1!}(t-a) + \frac{\ddot{x}(a)}{2!}(t-a)^2 + \frac{\dddot{x}(a)}{3!}(t-a)^3 + \dots \infty$$

$$v(t) = v(a) + \frac{\dot{v}(a)}{1!(t-a)} + \frac{\ddot{v}(a)}{2!}(t-a)^2 + \dots \infty$$

In our case this would become;

$$x_n = x_{n-1} + v_{n-1}dt + \frac{a_{n-1}}{2}dt^2 + \frac{j_{n-1}}{6}dt^3 + \dots \infty$$

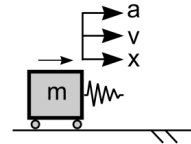
$$v_n = v_{n-1} + a_{n-1}dt + \frac{j_{n-1}}{2}dt^2 + \dots \infty$$

Cases 2 and 3a truncated the series after the acceleration terms, while Case 3b truncated the terms after the jerk, *sort of*. Actually, if you look closely there is a small change from what would otherwise be a simple truncation of the Taylor expansion. In the x calculation, the jerk term was divided by 2 instead of 6. This improves the long-term accuracy of the calculations. Exactly why this works is still under study. It may be that this small change corrects for the truncations of an infinite series, though this is not proven.

For further reading, including an explicit integration approach that is even more accurate than the 'jerk' approach presented above, see: <http://people.duke.edu/~hpgavin/cee541/NumericalIntegration.pdf>

Case 4 – Impact

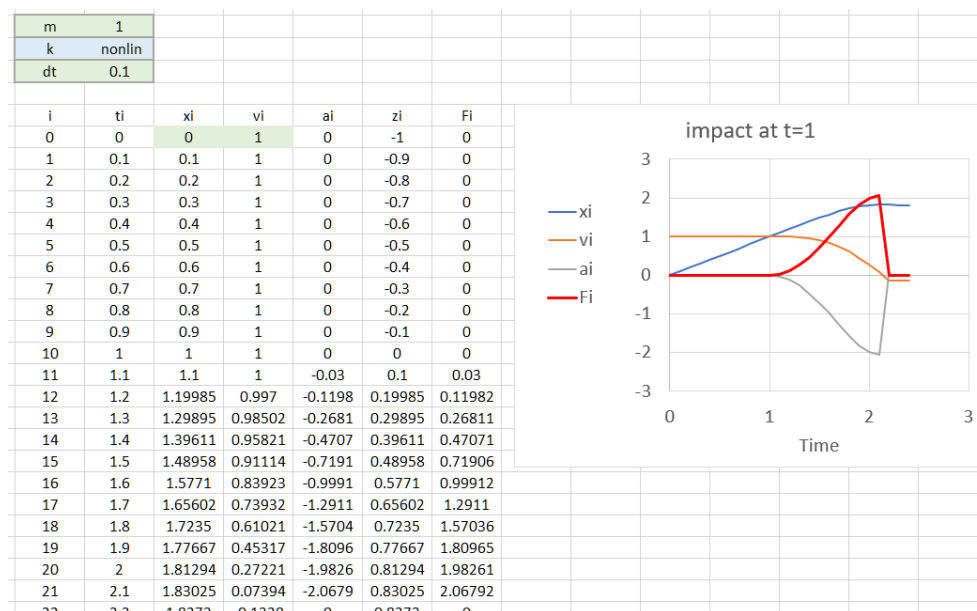
Now we will look at a case where the forces involved are more complicated. This is a case where the mass is moving freely until at $t=1$ (and $x=1$) the impact occurs. The impact force builds up in proportion to the penetration distance squared. So we create a working variable z which tracks the amount of penetration (its just $x-1$). Then we can compute the force. We also don't want the force to exist in the rebound phase (the contact is destructive and cant rebound – its not elastic). This requires two if statements in the force calculation, one to only calculate force when $z>0$, and one to only calculate force when z is growing. For the sake of brevity of the presentation we have left out the 'jerk' terms in the calculation of x_i and v_i , but these would normally be included. While there should be no rebound, you see that a small rebound has occurred in the example spreadsheet. This is just due to the finite size of the timestep, and would be smaller if we chose a smaller timestep.



contact spring hits wall when $x=1$,
 z is spring compression
spring crushed (no rebound)
 $z=x-1$ $F(z) = 3z^2$ if $z>0$

This is the type of case that are needed to model ice impacts. Another small change here is the calculation of the acceleration, which just divides the force by the mass.

i	t_i	x_i	v_i	a_i	z_i	F_i
0	0	x_0	v_0	$=-F_0/m$	$=x_0-1$	$=0$
1	dt	$=x_0 + v_0 dt + a_0/2 dt^2$	$=v_0 + a_0 dt$	$=F_1/m$	$=x_1-1$	$=if(z_1>0, 3*z_1^2*if(z_1>z_0, 1, 0), 0)$
2	$2 dt$	$=x_1 + v_1 dt + a_1/2 dt^2$	$=v_1 + a_1 dt$	$=F_2/m$	$=x_2-1$	$=if(z_2>0, 3*z_2^2*if(z_2>z_1, 1, 0), 0)$
:	:	:	:	:	:	:
n	$n dt$	$=x_{n-1} + v_{n-1}dt + a_{n-1}/2 dt^2$	$=v_{n-1} + a_{n-1} dt$	$=F_n/m$	$=x_n-1$	$=if(z_n>0, 3*z_n^2*if(z_n>z_{n-1}, 1, 0), 0)$



This approach can be used when there are a variety of forces (springs, dampers, fluid drag, ice). Each force is computed in its own column, and the acceleration calculation just divides the sum of the forces by the mass, with signs as appropriate.

Appendix F: Solutions to Selected Problems

3.17

$$h_1 = .025\sqrt{FDD_1} = .06\text{m}$$

$$h_2 = .025\sqrt{FDD_2} = .08\text{m}$$

$$FDD_1 = 5.76 \text{ deg-days}$$

$$FDD_2 = 10.24 \text{ deg-days}$$

$$\Delta FDD = 4.48 \text{ deg-days}$$

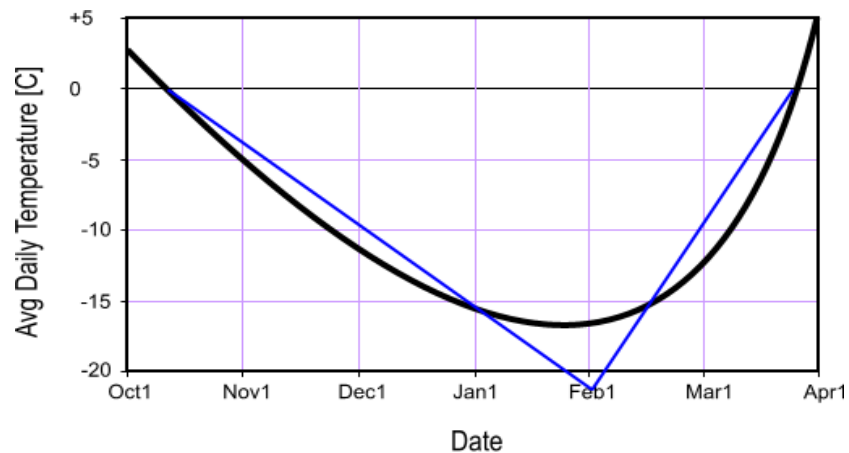
$$\text{@ } -20\text{C, time} = .224 \text{ days}$$

$$= 5.4 \text{ hrs} \quad \leftarrow \text{ANS}$$

3.8

- ① water molecules form ice particles
- ② larger ice flakes form
- ③ frazil forms (a slurry of ice flakes)
- ④ primary ice forms as water calms and slurry floats to a cold surface (P3b ice - fine grain random c-axis ice)
- ⑤ ice grows from the bottom of the primary ice forming secondary ice (S2b ice- large columnar grains with horizontal c-axis)

3.9



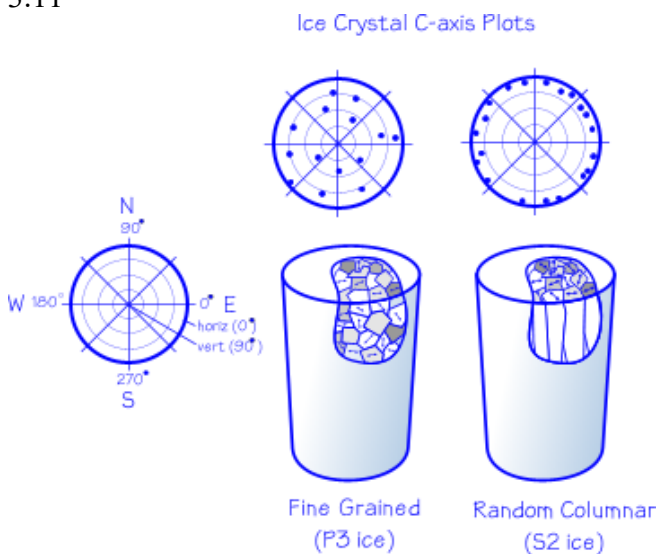
From Oct 10 to March 23 (est) is 164 days.

Avg temp. = -11C

total FDD = 1804 deg-days

$$\text{Using } h_{ice} = .025\sqrt{FDD} = 1.06\text{m}$$

3.11



3.12

use the equation:

$$h_i = .025 \sqrt{FDD} \quad \text{m, deg C}$$

$$FDD = \left(\frac{h_i}{.025} \right)^2 = 1600 h_i^2$$

to reach 5cm , it takes:

$$FDD = 1600 (.05)^2 = 4 \text{ FDD}$$

$$@-25C = .16 \text{ days} = 3.84 \text{ hrs}$$

to reach 10cm , it takes:

$$FDD = 1600 (.1)^2 = 16 \text{ FDD}$$

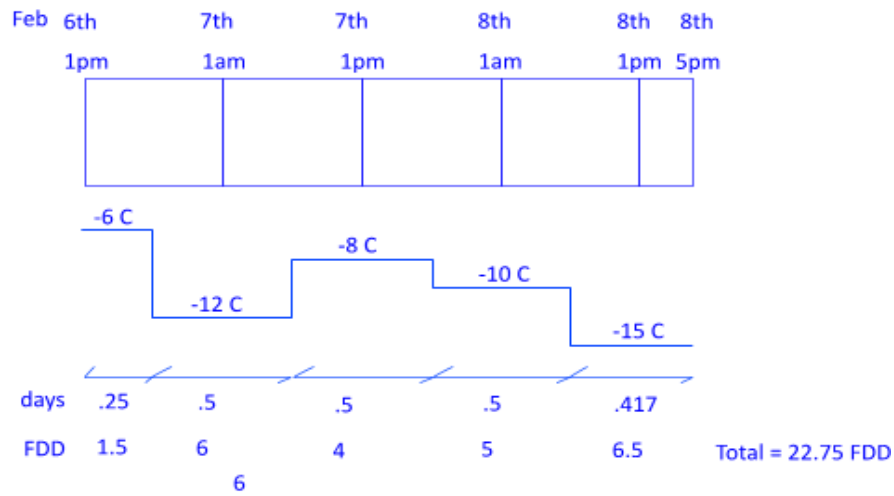
$$@-25C = .64 \text{ days} = 15.36 \text{ hrs}$$

to go from 5cm to 10cm takes:

$$11.52 \text{ hrs} \quad \leftarrow \text{ANS}$$

3.16

we assume that the 1pm and 1 am temperatures are valid for the 6 hrs befor and after:



First we find the FDD needed to freeze the 1cm of ice that we started with:

$$h_{\text{start}} = 0.01 \text{ m}$$

$$h_{\text{start}} = .025 \sqrt{\text{FDD}_{\text{start}}}$$

$$.01 = .025 \sqrt{\text{FDD}_{\text{start}}}$$

$$\text{FDD}_{\text{start}} = \left(\frac{.01}{.025} \right)^2 \quad \text{FDD}_{\text{start}} = 0.16 \text{ FDD}$$

Now we add the additional FDD and find the final thickness:

$$\text{FDD}_{\text{end}} = .16 + 22.75 = 22.91 \text{ FDD}$$

$$h_{\text{end}} = .025 \sqrt{22.91}$$

$$h_{\text{end}} = 0.1196 \text{ m} = 12 \text{ cm} \leq \text{ANS}$$

the final ice thickness is 12 cm

6.2

- a) 2407 N
- b) 23652 N
- c) 0.491m

7.2

simple capacity formula:

$$W = .5 \sigma_{flex} h^2$$

flex strength formula:

$$\sigma_t = 0.82 \left(1 - \frac{V_b}{142} \right)$$

$$= .625 \text{ MPa}$$

$$W = .5 \times .625 \times .29^2$$

$$= .09067 \text{ MN}$$

$$= 9.2 \text{ tonnes} \quad \leq \text{ANS}$$

7.3

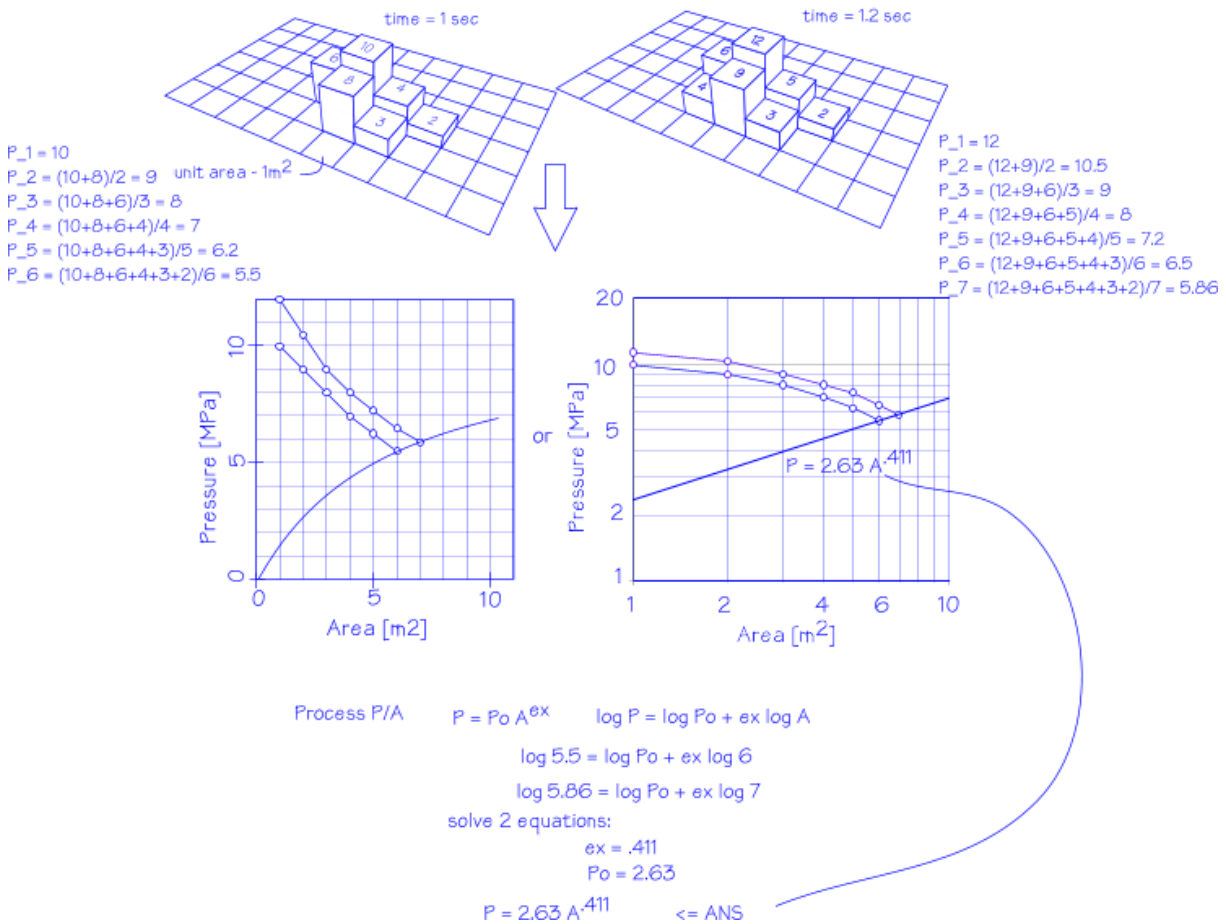
the speed is: $.001 \text{ m} / 60 \text{ s} = .0000167 \text{ m/s} = 1.67 \times 10^{-5}$

the strain rate is: $.0000167 \text{ m/s} / 1000 \text{ m} = 1.67 \times 10^{-8} \text{ strain/sec}$

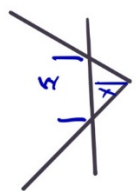
the creep stress from figure 1 is approx 0.3 MPa $\leq \text{ANS}$

8.2

Pressure/Area Calculation
Panel Pressures in MPa

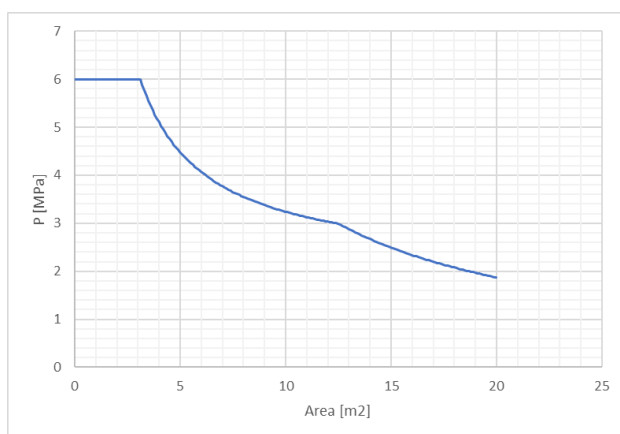


8.7

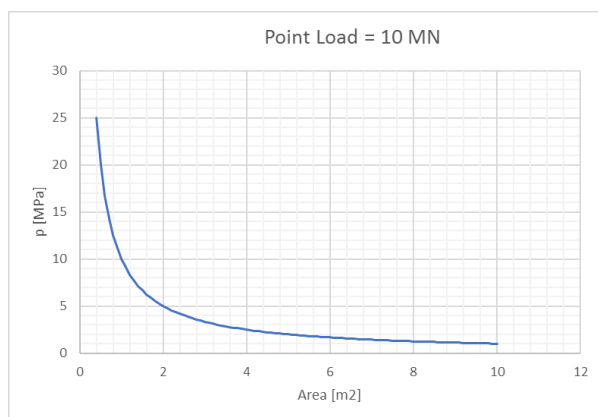


$$\begin{aligned}
 W(x) &= 2x \quad h=1 \\
 A(x) &= W \cdot h = 2x \\
 P &= 2(2x)^{-1} \\
 F &= 2(2x)^{0.9} \\
 &= 3.732 x^{0.9} \\
 E &= \int F dx = 3.732 \frac{x^{1.9}}{1.9} = 1.9643 x^{1.9}
 \end{aligned}$$

8.8 a)



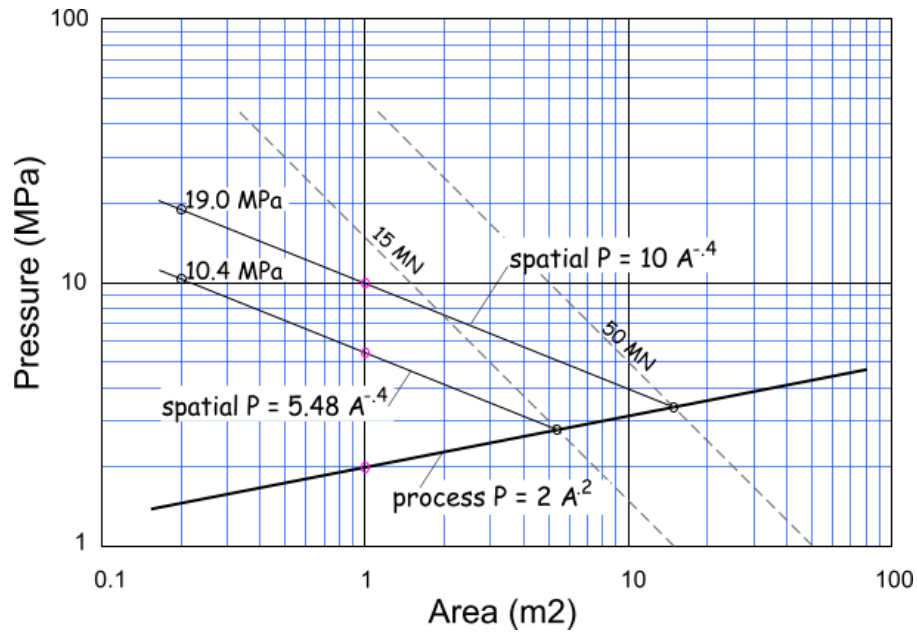
b)



8.11

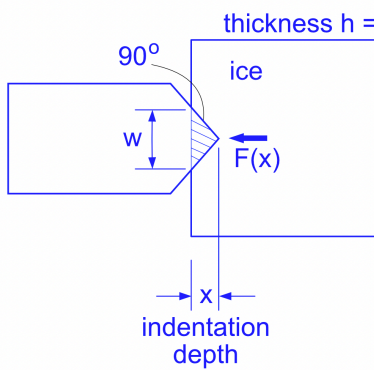
Pressure area Curves.

a) Plot the process pressure-area curve,



- b) at $P=2.8 \text{ MPa}$, $A= 5.36 \text{ m}^2$
- c) $C = 5.48$
- d) 10.4 MPa
- e) 19 MPa

9.4



$$\begin{aligned}
 \text{ice mass} &= 8 \times 8 \times 0.25 \times 917 = 14672 \text{ kg} \\
 \text{ice kinetic energy} &= .5 \times 14672 \times 1 \\
 KE &= 7336 \text{ N-m} = 0.0073 \text{ MN-m} \\
 w &= 2 \tan(90/2) x = 2x \\
 A &= w h = .5x \\
 P &= 2 A^{-5} \\
 F &= 2 A^{-5} \times A = 2 A^{-4} = 1.414 x^{-5} \text{ (MN)} \\
 IE &= \int F dx = .943 x^{-1.5} \\
 IE = KE : .943 x^{-1.5} &= .0073 \rightarrow x = (.0073/.943)^{.667} \\
 x &= .039 \text{ m} \\
 F &= 1.414 .039^{-5} = .280 \text{ (MN)} = 280 \text{ kN} \leq \text{ANS}
 \end{aligned}$$

Korzavin

$$P_{ice} = I m k \sigma_c$$

I - indentation factor, say 3.0 (est)

m - shape factor, = 0.715 (formula)

k - contact factor, say 0.8(est)

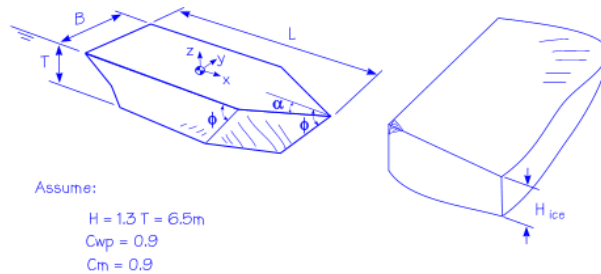
σ_c - uniaxial strength = 5 MPa (given+)

$$P_{ice} = 3 * 0.715 * 0.8 * 5 = 8.58 \text{ MPa}$$

$$F = 2 * 0.039 * .25 * 8.58 = 0.167 \text{ MN} = 167 \text{ kN} \leq \text{ANS}$$

=

9.5



$$F_N = \left[P_0 \left(\frac{\tan \theta_{f_0}}{\sin \beta \cos^2 \beta} \right)^{(1+ex)} \right]^{\frac{1}{(3+2ex)}} \left[\frac{1}{2} M_e V_n^2 (3+2ex) \right]^{\frac{(2+2ex)}{(3+2ex)}}$$

Ship Main Parameters

		units
Ship Name	SN	M.V.Test text
Length	Loa	100.0 m
Beam	B	20.00 m
Draft	T	5.00 m
Height	H	6.50 m
Block Coef.	CB	0.8 nd
Waterplane Coef	Cwp	0.9 nd
Midship Coefficient	Cm	0.9 nd
Mass	M	8200 tonnes
Initial Values		
Ship Speed	Vs	3.0 m/s

Popov Terms

x dirn cosine	l	0.3410 nd
y dirn cosine	m	0.7313 nd
z dirn cosine	n	0.5907 nd
roll moment arm	λl	2.9533 m
pitch moment arm	μl	-26.5798 m
yaw moment arm	ηl	31.2042 m

Hull Angles and coordinates

Alpha	α	25 deg	0.4363 rad
Beta	β	38.93 deg	0.6794 rad
Beta prime	β'	36.20 deg	0.6319 rad
gamma	γ	60.0 deg	1.0472 rad
x coordinate	x	45.0 m	
y coordinate	y	5.0 m	
z coordinate	z	0 m	

Surge Added Mass	Amx	0.0000nd
Sway Added Mass	Amy	0.5000nd
Heave Added Mass	Amz	1.4211 nd
Roll Added Mass	Amrol	0.2500 nd
Pitch Added Mass	Ampit	1.5873 nd
Yaw Added Mass	Amyaw	0.5500 nd

roll gyrad(squared)	rx2	38.6086m2
pitch gyrad(squared)	ry2	630.00m2
yaw gyrad(squared)	rz2	625.00 m2

Ice Crushing Terms

Ice strength term	Po	1 Mpa
Ice exponent (process PA)	ex	0.1
Wedge angle	ϕ	90 deg 1.57 rad
Ice Thickness	hi	10.00 m
Ice flex. Strength	sf	10.00 MPa
form factor 1	fx	3.20
form factor 2	fa	2.86
Flexural for limit	Ff	2031.62 MN
Flex limit on pen	ζ_{nlim}	19.77 m

Mass Reduction Coef.	Co	2.2362 nd
Effective mass	Me	3666917 kg
Normal Speed	Ve	1.023 m/s
Kinetic Energy	KEe	1918979 kg-m2/s2
Impulse	le	3751463 kg-m/s

Results

pen(n)	ζ_n	1.270 m
Normal Force	Fn	4.84 MN

9.10

$$I = \frac{1}{2} l \pi 0.8^2 = 0.0533 \text{ kg m}^2$$

$$a_{vc} = \frac{F}{m} = \frac{1}{1} = 1 \text{ m/s}^2$$

$$\alpha_c = \frac{M}{I} = \frac{1 \cdot 0.2}{0.0533} = 3.75 \text{ r/s}^2$$

$$a_p = a_{vc} + \alpha_c \cdot l$$

$$= 1 + 3.75 \times 0.2 = 1.75$$

$$m_{eq} = \frac{F_p}{a_p} = \frac{1}{1.75} = \underline{\underline{0.571 \text{ kg}}}$$

11.1

- a) The water is shallow enough for a bottom founded structure but is deep enough to consider a floating structure. Possible types to be considered would be a tall concrete GBS (gravity-based structure), a tower with anchor cables, a spar platform (which is a floating cylinder with a mooring system), a FPSO (which is a large ship-shaped production platform). The details of the design will depend on what the ice loads are and whether a disconnect strategy is to be employed.
- b) Northern Baffin Bay could either be in Canadian or Greenland waters. In either case there are numerous regulations covering safety, environment, impact on and benefits for local people, and resource access.
- c) The threat of icebergs would represent the largest risks. Multiyear ice would be a major design concern. In large sea areas such as Baffin Bay, ice pressure is another significant threat. The details of the risk assessment will depend on the active systems built into the design (both ice management and disconnection strategies)
- d) The main codes are the ISO standard for arctic offshore structures, as well as various arctic vessel standards such as the IACS polar rules. There are various national regulations in Canada and different ones in Greenland.

15.38 –

- a. IACS Polar Class Rules, and Finnish-Swedish Ice Class Rules
- b. Flexural strength of the whole ice sheet
- c. Shaped to break and clear ice. Normally very large angles from vertical
- d. Freezing Degree Days
- e. The energy needed to change ice from solid to liquid
- f. Russia. Finland.
- g. A surface layer of polycrystalline ice that forms initially out of frazil
- h. It is less dense than water.
- i. A linear region of rubble ice that forms between two converging ice floes

j. His limit load concepts

15.39

- a) field observations + guesswork
- b) Davis
- c) Loss of Franklin
- d) reflectivity
- e) thin First Year Ice (2nd stage)
- f) thin new sea ice around 5cm thick
- g) Breakup of a solid by itself
- h) process pressure-area
- i) 1ASuper
- j) An Ice Island where the medium scale ice experiments took place

15.40

- a) Glaciology
- b) north of Russia
- c) Melville Sea
- d) The Breaker
- e) 1h
- f) H₂O
- g) 900kg/m³
- h) frazil
- i) Secondary
- j) creep

15.41

- a) north of Russia
- b) flexural strength
- c) field and lab observations
- d) China
- e) Caspian Sea
- f) H₂O
- g) 1000 kg/m³
- h) latent heat of fusion
- i) P
- k) constant

15.42

- a) *radial*
- b) *tension*
- c) *5-10 ppt*
- d) *0.5 - 4 ppt*
- e) *randomly*
- f) *crushing*
- g) *temperature and strain rate*
- h) *frazil*
- i) *horizontal*
- j) *change from ductile to brittle crushing*