A review of guidelines on ice roads in Canada: Determination of bearing capacity

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Abstract

An ice road is a winter road that runs mostly on frozen water expanses. A significant number of guidelines (best practices, design codes, handbooks and manuals) currently exist for the construction, maintenance and usage of these structures. They are typically published by provincial jurisdictions, the private sector and some research organizations. They are also found in the scientific literature. These guidelines include various amount of information of different types, notably some background on the nature of the ice cover, how it should be used for transportation purposes and how to determine the maximum load it can safely sustain. For the latter, Gold's formula, or a version thereof, is almost always alluded to. Significant differences are noted in the guidelines' recommendations regarding the strength of white ice relative to clear ice, resulting in a large discrepancy in recommended maximum loads. Although white ice is mechanically weaker than clear ice, the influence of that difference on the bearing capacity has yet to be understood. New empirical data, numerical and analytical studies and physical testing are possibilities to investigate this issue.

Introduction

Ice roads are used in the North by local communities and the private sector to move both people and goods into areas that would otherwise not be accessible in the winter. Further, as activities in the North are expected to intensify, and in the context of a warming climate, a decrease in the average number of 'freezing degree-days' means that ice road builders will have to do more with less, i.e. increased activity with a reduced operational lifespan, without compromising the safety of the operations. Various means of counteracting this phenomenon may be envisaged. One is through an improved understanding of ice bearing capacity.

From a civil engineering perspective, floating ice covers in cold regions may be seen as an abundant, readily accessible and cost effective material for transportation infrastructures, notably ice roads. However, because ice roads are floating, they entail risks that other types of roads do not have to contend with, namely, that of a breakthrough. A large amount of information currently exists for the construction, maintenance and usage of these structures. They are published by federal, provincial and territorial jurisdictions, the private sector, research institutes and journals, standards' associations and community-based organizations. They take the form of handbooks, manuals, reports, journal papers, best practices and design codes. Information is also found in the scientific literature.

The aim of this paper is to present an overview of 14 such documents published in Canada and elsewhere (these will be collectively referred to as 'guidelines'). They generally offer a brief description on the nature of the ice cover, how it should be used for transportation purposes and how to determine the maximum load it can safely sustain. They differ in some respects – *e.g.* the factors for determining maximum loads, the difference between clear ice and white ice, and between freshwater ice and sea ice. Here, we will compare and discuss how each addresses maximum ice loading. In most cases, Gold's formula is alluded to for this purpose.

On the bearing capacity of ice roads

Definitions

A distinction is made between the terms *winter road*, *ice road* and *ice bridge*. A winter road is a road that runs over frozen land and frozen water, *i.e.* lakes, rivers and sea expanses. An ice road is a winter road that runs mostly on frozen water expanses. An ice bridge designates a short segment of a winter road that crosses a frozen water body, typically a river.

Natural ice covers

Ice roads typically run over naturally-grown ice covers. These can be quite uniform (or they can vary in thickness and internal structure (Figure 1 is a simplistic scenario). This will depend on many factors, notably initial freeze-up, growth history and internal deformation (e.g. thermal cracking, pressure ridges). These factors are, in turn, a function of air temperature, precipitations, winds, currents, wave regimes, water level changes and the size of the water body, amongst others. Since these factors vary throughout the winter, an ice cover will keep evolving, at least to some extent, until Spring break-up. Natural ice is therefore a complex material, and its usage as a transportation infrastructure has to be done carefully.

Clear ice versus white ice

Traditionally, frozen water has been divided into two types of ice: *clear* (also called ‘black’ or ‘blue’) ice and *white* ice (Figure 2). Clear ice is transparent because it is free of air entrapment. White ice, on the other hand, is white because of a high content of tiny air bubbles.

Natural white ice is sometimes called ‘snow ice’, because it often originates from a layer of snow on the ice cover that gets flooded by water that finds its way to the ice surface. At times, water may partially drain out of the snow, leading to a material with a substantially lower density. Artificial thickening of an ice cover by flooding it with water pumps is a procedure that also produces white ice (Figure 2 is an example).

Is the ice cover thick enough?

When an ice cover is pushed downward as is the case when it supports a load – *e.g.* a vehicle, it sinks under the load (Figure 3). As it does so, it displaces a volume of water whose weight is equivalent to the amount of loading. This is known as Archimedes’ principle. If a vehicle is at one location for a short amount of time, the deformation will be mostly recoverable. This is referred to as short-term static loading. The longer the vehicle remains at that location, the higher the amount of permanent (non elastic) deformation. A vehicle in motion will induce a more complicated loading scenario and associated ice response. This is sometimes referred to as ‘dynamic loading’, a topic that will not be discussed in this paper.

Gold’s formula

Gold’s formula is alluded to implicitly or explicitly in most guidelines. In the 1950s, Lorne Gold, a scientist with the National Research Council in Ottawa, was looking for a way to help ice road users determine how much weight an ice cover of a given thickness can safely sustain. Analytical methods already existed at the but they were not practical for most ice road users. Some of these methods also made assumptions (e.g. uniform ice, no cracking) that were not representative of real ice.

Gold collected information from the Pulp and Paper industry on breakthroughs that had occurred, including data on ice thickness and weight, of the vehicles and horses that caused the ice to fail (Gold, 1960; 1971). From this information, he used this formulation:

$P = Ah^2$

where

- P: Allowable load
- h: Ice thickness
- A: Empirical parameter with pressure units (corresponding to those used for P and h)

This formulation is based on 'empirical' evidence – it relies on observations of real events, not solely on theoretical concepts. Gold's formula is a curve-fitting exercise – a best-fit line that describes the relationship between two parameters, namely ice thickness and loads. For complex loading scenarios, it can be used to obtain a rough approximation of bearing strength as a preliminary step, before engaging in more elaborate, site-specific analyses (P. Spencer, Ausenco, pers. comm.).

Some guidelines show Gold's relationship in tabulated form, *e.g.* BMT Fleet Technology (2011). Most often, it is shown as a plot. Figure 4 is an example, where centimeters and kg-force are used as units for load and thickness, respectively. Some guidelines recommend a specific value for the coefficient 'A', which may or may not be those reported by Gold (e.g. CRREL, 2006; CSST, 1996; Government of Saskatchewan, 2010); others provide a range within which the ice road operator can choose, depending on factors such as road construction methods and risk assessments (Government of Alberta, 2013; IHSA, 2014; Proskin et al., 2011).

Load duration

Gold's formula is not meant to be used for loads that remain at one location for a certain time period – the limit is often quoted as being two hours (CSST, 1996; IHSA, 2014), which is also what Gold (1971, p. 179) prescribed. The reason is that, with time, the stresses induce non-elastic deformation in the form of micro-cracks (e.g Sinha, 1989). These develop into large cracks and, ultimately, breakthrough, even with good quality ice cover and a load that is less than that indicated by Gold's formula.

The heavier the load, the less time it should be allowed to remain on the ice. If a load has to remain on the ice, some guidelines advise to monitor the freeboard by drilling a hole through the ice. When the water level reaches the ice surface (i.e. the freeboard reduces to zero), the load has to be removed. This practice is supported by the analyses of Frederking and Gold (1976) and has been vindicated by a number of sources (e.g. CSST, 1996; IHSA, 2014; Masterson, 2009). BMT Fleet Technology (2011), on the other hand, recommends to use a time-dependant reduction factor if the load duration is to exceed 15 minutes – the longer the duration, the lower the allowable load. Government of the NWT (2015) advises to consult with a professional engineer for long term loads.

Guidelines on using floating ice for transportation

Following is a short summary of the guidelines discussed in this paper. Most are from Canada but a few others from elsewhere are also included. The latest editions, known to the author as of this writing, have been consulted.

Federal, territorial and provincial guidelines

CSST (1996)

The *Commission de la Santé et de la Sécurité au Travail* (a Quebec Health and Safety organization) published guidelines for industry workers and the recreational usage of ice covers. They do not apply to operations involving heavy loads or to those on saline (sea) ice. The guidelines begin by describing a hypothetical scenario on the growth of an ice cover, involving various ice types. It warns of unusual current patterns responsible for ice thickness variation. Sections through the ice cover are required to monitor thickness and ice type over the planned working area. Ice bearing capacity is a function of ice type, thickness and expected loads. A relationship similar to that of Gold is used for that purpose, taking into account spacing between loads. Load duration, cracks, extreme variations in air temperatures and vehicle speed (i.e. dynamic loading) have to be taken into consideration. Signing, maintenance (snow removal) and safe driving and emergency procedures are also discussed briefly.

Treasury Board of Canada (2002)

This document, referred to as a 'safety guide', focusses on freshwater ice and can only be used for loads up to 22.5 metric tons. Its purpose is to: "(a) specify rules of good safety practice for all Public Service employees engaged in operations on ice covers; (b) provide information on the thickness of ice required to support moving and stationary loads; (c) specify methods for determining ice thickness and quality; and (d) outline approved methods for the preparation and maintenance of ice bridges." It contains general information on ice formation, ice 'color', ice thickness, the bearing capacity determination for static and moving loads, effects of cracks and some considerations about spring thaws. It also contains information about the construction of ice bridges, which it defines as "a natural untouched ice cover, a built-up, or a combined reinforced and built-up crossing route". This includes flooding, maintenance and precautions to be considered during operation. Information for snowmobile drivers is included.

Government of Saskatchewan (2010)

Saskatchewan's Ministry of Highways and Infrastructure produced a handbook on winter roads meant for winter road contractors, "intended for use on winter road alignments built in the same general vicinity each year". Information is provided on ice formation, snow clearing and flooding procedures. Types of ice and thickness determination and equipment for rivers and lakes are also discussed. Bearing capacity is assessed on the basis of Gold formula, taking into account extreme temperature changes, presence of cracks (and ways to deal with the larger ones), road usage and loading modes (moving, multiple, long term). Recommendations on equipment are made: outriggers, floatation device, careful use of trawler tractors and other vehicles. A full section on signing is presented, along with environmental considerations (e.g. spill management), winter road safety (training, protective equipment, communications), safety guidelines for ice road workers and ice road users, accident response, survival information and general road management.

Government of Manitoba (2012)

The Government of Manitoba published a "Contractor's manual for the construction and maintenance of Manitoba infrastructure and transportation winter roads". This is the 8th edition. Means of ensuring safe usage include proper thickness assessment, considerations of factors such as currents, angle with the shoreline, appropriate clearing width and procedures, load duration, vehicle speed and flooding operations. Recommendations are also provided on how to test the ice for thickness, ice types, reporting, using Gold's formula, types of cracks, effects of air temperature changes, pressure ridges and how to 'bridge' large cracks. Comments about equipment for working on ice roads refer to the use of outriggers and floatation devices, and point out to a number of safety procedures: means of escape from a vehicle, maximum speeds, careful use of tire chains, hydraulic buckets and flex track equipment.

Government of Alberta (2013)

The Government of Alberta's published an extensive 'Best practice' whose purpose is to cover "the basic steps for planning, design, construction, operation and closure of an over-ice project". It is for short-term loading scenarios and does not apply to saline ice and very large loads. It provides a background on ice type, cracking/rupture modes and their origin, load duration, and factors (climate, terrain,…) influencing route selection. It then discusses procedures for ice design, including Gold's formula (to be used in combination with hazard control), ice thickness determination, effects of extreme temperature changes, how to deal with stationary loads, recommended lane dimensions and dynamic effects (from a moving vehicle). Ice monitoring and maintenance controls and the development of an ice safety plans are other aspects that are covered in that document.

IHSA (2014)

In January 2010, IHSA amalgamated with the Construction Safety Association of Ontario (CSAO), the Electrical & Utilities Association (E&USA) and the Transportation Health & Safety Association (THSAO). Its purpose is to work with employers and workers in Ontario to prevent occupational injury and illnesses (source: www.ihsa.ca). They published "The best practices for Building and Working Safely on Ice Covers in Ontario". This document is essentially the same as the 2013 edition of Alberta's own safe practice (described above).

Government of the NWT (2015)

These guidelines begin with a short description of the various ice types, with recommendations as to what to consider when determining the effective thickness of the ice cover. Various construction and operation levels are outlined (routine, enhanced, acute). Temporary loads, stationary and moving loads on a natural ice cover are discussed. An extensive section on hazard control describes the factors that adversely affect the integrity of the ice cover (e.g. cracks, snowbanks, high winds, water level changes), load and ice thickness monitoring (manual and GPR), hole spacing and data recording. Gold's formula is adapted to specific circumstances for the (pre-)construction or operation phases. 'A' values (4, 5 or 6) vary as a function of ice road (bridge, on lake, along a river) and for each safety levels, taking into account all control measures (e.g. frequency of thickness measurements and method, loading control, enforcement). Information on ice cover management is provided (speed limits and spacing, inspections, traffic enforcement, signing, temporary road closure, public information, training, monitoring and reporting). Recommendations on means of extending the safe operation at the end of the season are also presented.

Design codes and standards

Design codes and standards provide information about important features of product, service or system (SCC, 2014). In most cases, compliance is voluntary; in others, it is mandatory and monitored by regulatory bodies. These documents are continuously being improved upon, with new editions appearing from time to time; others may be withdrawn. They are overseen by various national or international committees, and can be quite different even though they address similar issues. The following two documents contain guidelines on ice roads.

API RP 2N (2007)

The API RP 2N version (2nd edition) reviewed in this report, published in 1995 and reaffirmed in 2007, is a recommended practice. Its purpose is to provide the latest knowledge for planning, designing and constructing arctic systems. It is targeted at sea ice, which is not what his report is about, but it is of interest for information purposes. Unlike in the other guidelines, the bearing capacity for static loads is determined analytically – no reference is made of a Gold-like formulation. This may be because offshore operations typically involve very high loads, best dealt with analytically, on a case-by-case scenario. Other information is provided on how to deal with moving vehicles and long term loads, snow removal, road signs and cracking. These are mostly consistent with other guidelines. Tidal effects are alluded to and using freshwater ice as a crack fill material is recommended. Mat ice bridges across a crack and emergency equipment are also included.

CSA-ISO 19906 (2011)

This is the standard's first edition, and an adoption without modification of the document produced by the International Standards Organisation known as ISO 19906. The standard provides recommendations for offshore structures in cold regions. As with all ISO standards, it is divided into a normative section (what the user should or must do) and a longer informative section (what the user should know, i.e. background knowledge). The normative part mentions that 'expert guidance' should be used in determining design thickness, construction technique and operating procedures. Two guiding principles must be followed: "the ice shall not fail in flexure" and "the freeboard shall remain positive". Strength testing procedures, driving speed, weight determination procedures (equipment and vehicles), ice inspection for cracks and flooding instructions are also provided.

Other guidelines

Following are other sources of information that also provide guidance in the construction, maintenance and usage of ice roads.

CRREL (2006)

U.S. Army's Cold Regions Research and Engineering Laboratory (CRREL) produced an 'Ice Engineering' manual that has a chapter on the bearing capacity of floating ice sheets. It begins by suggesting means of measuring ice thickness, then it examines the bearing capacity of floating ice sheets analytically and empirically. In the latter case, a Gold-like formula is used. Information on moving loads and long-term loads is also provided.

Luleå University of Technology (Fransson, 2009)

The Luleå University of Technology, in Sweden, published an 'Ice Handbook' which includes a section on ice bearing capacity that is of interest. At the onset, a discussion is provided on the cracking activity under loads and how to go about determining the ice thickness. Bearing capacity is assessed analytically. Calculation of first crack load and a semi-empirical formula to determine the breakthrough load are shown.

Rideau Canal Skateway (BMT Fleet Technology, 2011)

These guidelines apply to the Rideau Canal Skateway in Ottawa. It is not an ice road, strictly speaking, but it is designed to support motor vehicles. The report provides guidance for two vehicle classes: a two-axle vehicle and one pulling a trailer. Information on vehicle separation distance, ice thickness definition/measurements and effects of temperature is included. They make recommendations about how to handle static loading of vehicle, and also during special events held on the ice – a 'show' with a large audience, where the surface area occupied by the crowd is factored in.

Transportation Association of Canada (Proskin et al., 2011)

The Transportation Association of Canada published a succinct overview of the winter road classification, including an instructive perspective on the differences between various types of over-land and over-ice roads. Ice roads planning, routing and usage are discussed, as well as ice types and cracks in the ice cover. It alludes to Gold formulation as a means of determining safe ice loading, while specifying the 'A' value depends on the hazard control procedures and level of risks. Short discussions are presented on analytical determination of ice thickness, ice road width, ice deflections resulting from long-term loading and hydrodynamic effects of a moving load. This document comprises chapters on ice road constructions (e.g. methods, quality assurance and control, thickness measurements), on road user safety (hazard assessment/control, incident response plan) and on environmental protection (water quality, terrain degradation, spill prevention). It includes a comparison between various recommendations made by six of the most accessible federal, provincial and territorial guides to winter roads.

Canadian Red Cross (2015)

The Canadian Red Cross provides a small amount of information on its website about 'ice safety' (last consulted in April 2015). This includes ice color and recommendation for determining adequate thickness for pedestrians and snowmobiles, as well as instructions as to what to do when someone breaks through the ice. By having this information displayed on its website, it is readily available to its entire readership. Environment Canada refers to that site for information regarding ice safety.

Scientific literature

There are a large number of documents published in the scientific literature that address the bearing capacity of floating ice. These are published in specialized journals and in a various conference proceedings. The article by Gold (1971) mentioned earlier is often the starting point of later studies, many of which tend to be more technical, as they often contain analytical treatments. Frederking and Gold (1976) and Kerr (1996) are examples. Kuryk (2003) provides some recommendations about planning and construction of ice bridges in Manitoba. The reader might also be interested in the review by Masterson (2009), which is well illustrated and provides technical background on mechanical principles and methodology for ice road design.

Overview

Is white ice weaker than clear ice?

Guidelines have different ways of approaching that question.

- Gold (1971, p. 173) states that white ice has a lower strength than the clear ice, although he also points out that "No studies have been undertaken to verify this assumption".
- A few guidelines followed suit on that recommendation to reduce the strength of white ice to half that of clear ice (CRREL, 2006; CSAO, 2009; CSST, 1996; MNRO, 2002).
- Others (BMT Fleet Technology, 2011; Treasury Board of Canada, 2002) further distinguish white ice created by flooding operations, as is normally done by the crew, from white ice resulting from frozen saturated snow or slush. In the former case, the ice has a density of about 0.9 g/cm^3 and is considered 'dense ice'; the latter should be of lower density and its strength is assumed to be 50% that of clear ice.

- Kuryk (2003) distinguishes between clear and white ice but only by considering the former and ignoring the latter in thickness determination. Information does exist indicating a reduction in ice strength with increased porosity (Murat and Tinawi, 1986), although this is for saline ice. But exactly how that translates into flexural capacity is an issue that has been poorly documented to date.
- It is stated in Government of Alberta (2013) and IHSA (2014) that “Overflow ice, caused by natural water overflow onto the ice surface, usually contains high air content and should not be relied upon in calculating effective ice thickness. White opaque ice, or snow ice is normally considered to be only half as strong”.

The results of an experimental program on clear ice and white ice from flooding procedures (Barrette, 2011) provided evidence that what would be considered by BMT Fleet Technology (2011) as ‘good quality’ white ice was, on average, weaker than clear ice (Figure 5). The flexural strength of white ice was down to about 50% that of clear ice close to the melting temperature. This information should, of course, be carefully assessed. The strength data in Figure 5 and Figure 6 is from failure of the ice beams along the surface that was in tension. They are not truly representative of real scenarios, where white ice is typically in the upper part of the ice cover, which is in a compressive state when the ice cover is under load. On the other hand, there is evidence elsewhere that white ice is weaker than clear ice in compression (e.g. Sinha, 1984).

Barrette (2011) also showed an increase in flexural strength with an increasing density (Figure 6). Note that BMT Fleet Technology (2011) assumed 0.90 for white ice from proper flooding procedures, but that number was found to be consistently lower (Figure 6). Would this ice then be considered of a lesser quality? There is no doubt it looked well-bonded. This raises the question as to where to draw the line between what is good white ice and what is not.

The ‘effective’ ice thickness

The most recent guidelines (Government of Alberta, 2013; Government of the NWT, 2015; IHSA, 2014; Proskin et al., 2011) warn against natural white ice variability, and recommend excluding it from ice thickness measurements if deemed of poor quality. Effective ice thickness in Government of Alberta (2013) and IHSA (2014) is defined as “Good quality, well-bonded, white and blue ice that is measured in an ice cover”, and excludes “Poor quality or poorly bonded ice” in the measurement of ice thickness”. In Government of the NWT (2015), a line is drawn between what is considered full strength ice (clear ice) and ice that is not reliable. According to that source, the effective ice thickness should not include ‘natural overflow ice’ but does include flooded ice “using sound construction practices”.

The above observations notwithstanding, additional information is required to address this issue. The influence of white ice in the road’s bearing capacity also has yet to be properly assessed.

Comparison between guidelines

With a few exceptions (e.g. API RP 2N, 2007), Gold’s relationship is alluded to for determining the required ice thickness for an ice road operation. That formula is not seen as an answer in itself – it has to be used in combination with experience and good judgment. Some guidelines prescribe one particular value for ‘A’, while providing background information about ice covers as further guidance (CSST, 1996). Others provide a range of ‘A’ values and guiding principles based on risk levels and hazard control of procedures to help decide which of these values is the most appropriate (Government of Alberta, 2013; Proskin et al., 2011). Doing so, the latter are moving toward a performance-based approach (from a prescriptive one).

The safety of an ice road operation, to be sure, depends on many factors, i.e. any breakthrough is most likely a combination of a number of them, not only design ice thickness. But since Gold's formula appears to be a starting point in most guidelines, it may be instructive to compare what that starting point would be for two hypothetical scenarios used for the purpose of that comparison. The first one (Figure 7) assumes a total ice thickness of 100 cm, made entirely of clear ice. This might be representative of a large lake at higher latitudes (where the winter is cold and long). The other scenario (Figure 8) assumes a total ice thickness of 40 cm made of clear ice and white ice in equal proportion. In that scenario, the white ice component is assumed to be from natural flooding (as opposed to from artificial ice thickening procedures). This scenario may be regarded as more representative of lakes further south. For the purpose of this exercise, we will assume the quality of the white ice has not been ascertained throughout the full length of the road, and has been deemed of lesser quality. Also, when no recommendation is provided in the guidelines about the relative strength, the white ice is assumed to be equivalent to the clear ice.

In these two plots (Figure 7 and Figure 8), the height of each bar is the range – the minimum and the maximum 'A' values provided by the source. The sources are identified in Table 1 – they are ordered by publication year. In both figures, the recommended maximum weights are spread about equally around the average.

In Figure 7, the guidelines are relatively coherent. The observed variations in recommended values are caused by a different 'A' value, Source 5 (CRREL, 2006) is prescribing a relatively high value for 'A' (10 kg/cm^2) – it is not known why. One possibility is that this report was mostly aimed at a particular target readership – the U.S. Army Corps of Engineers – who likely has a higher risk tolerance. In Figure 8, a considerable discrepancy is noted between the various guidelines, which is attributed to how each is treating the presence of the white ice – whether or not it is considered 50% weaker than clear ice, or is included in the thickness measurements.

Discussion

This paper is addressing ice bearing capacity from the viewpoint of prospective guidelines users, typically, road builders wishing to gain additional insight as to how to go about determining the bearing capacity of an ice cover. The readership may be puzzled by the lack of agreement between how different guidelines deal with the white ice/clear ice dichotomy, and the consequences on recommended ice thickness. This is an important issue:

- If flooded white ice is assumed to have the same strength as clear ice, this assumption will increase the 'effective' thickness of the ice cover, which may imply a substantial increase in the ice road's operational lifespan.
- If natural white ice is altogether excluded from the ice thickness measurements, this will have the opposite effect.
- If white ice resulting from flooding operations is weaker than clear ice, then by assuming it is equivalent to clear ice, bearing capacity will be overestimated by an unknown amount.

Another point of interest is the range in 'A' values that is found in the guidelines when using Gold's formula. In the guidelines summarized in the present paper, these values vary from 2.5 to 10. In some of the most recent guidelines, the range is from 3.5 to 7.

A question may be raised as to how to go about establishing a better consensus for future guidelines editions in Canada, assuming such a consensus is desirable or achievable. A number of approaches could be used. One possibility is to repeat Gold's breakthrough analysis with more recent data, wherever they can be retrieved from. Another is to examine what has been done so far via numerical modeling and, if required, to conduct mechanical testing and pilot studies for validation and analytical purposes. This would also serve to generate information on the time factor, its effects on ice deflection and cracking development in the ice cover.

Conclusion

The response of an ice cover to a vertical load depends on the nature of the ice (thickness, temperature, internal structure, presence of fractures, etc.) and on what the loading event entails (total weight, load distribution, duration, etc.). The main challenge of any ice road operation is to ensure a breakthrough never happens. Gold's formula is a practical and robust guiding principle to estimate maximum loading, as long as it is used in conjunction with good judgment and takes into account all factors involved in the planning, maintenance, and usage of the ice road. It is suggested that a consensus be sought amongst stakeholders for its application and for factoring in the presence of white ice in the ice cover. In order to do so, some of the knowledge gaps would have to be filled in. This could be done with new empirical data, numerical and analytical modeling and physical testing, in consultation with the stakeholders.

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Figures

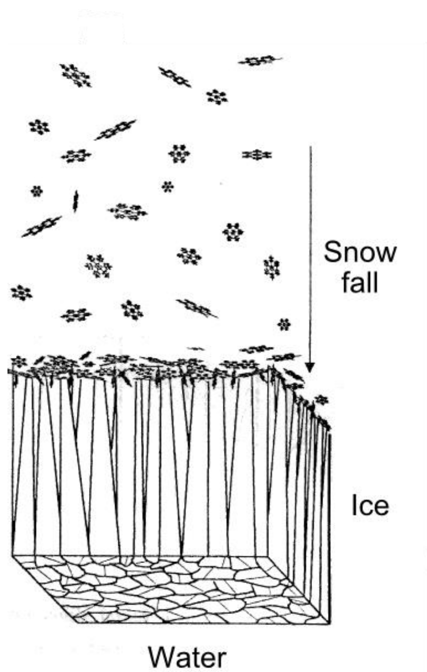

Figure 1: A common scenario for the initiation and downward growth of an ice cover. That ice is typically clear ice.

Figure 2: White ice (from flooding operations) on top of clear ice in a large block, collected from the Rideau Canal skateway, in Ottawa.

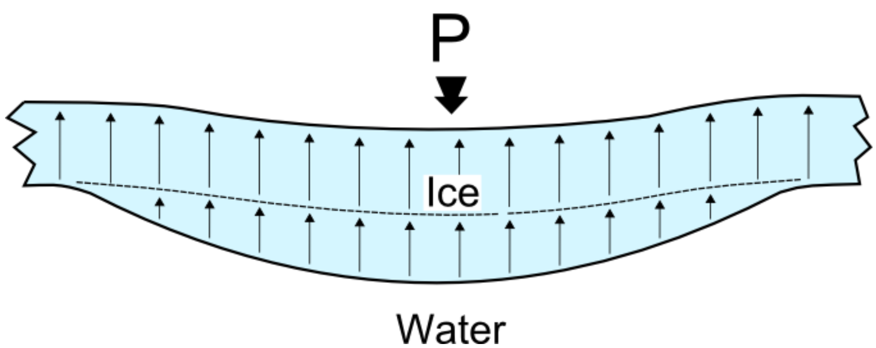

Figure 3: As an ice cover deflects under a given load, the initial pressure distribution under now load is increased by a certain amount due to the buoyancy of the water (after CRREL, 2006).

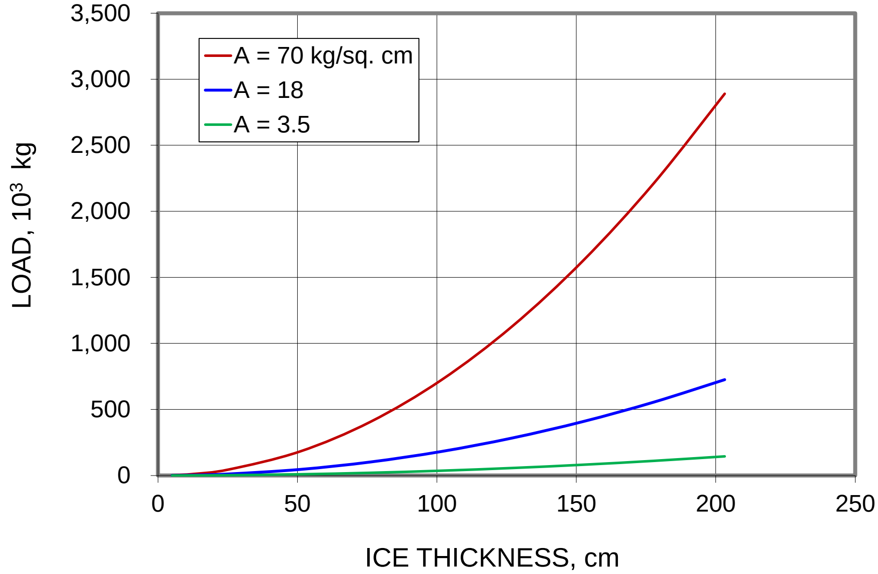

Figure 4: Maximum allowable load as a function of ice thickness for the three different A *values used by Gold (1971).*

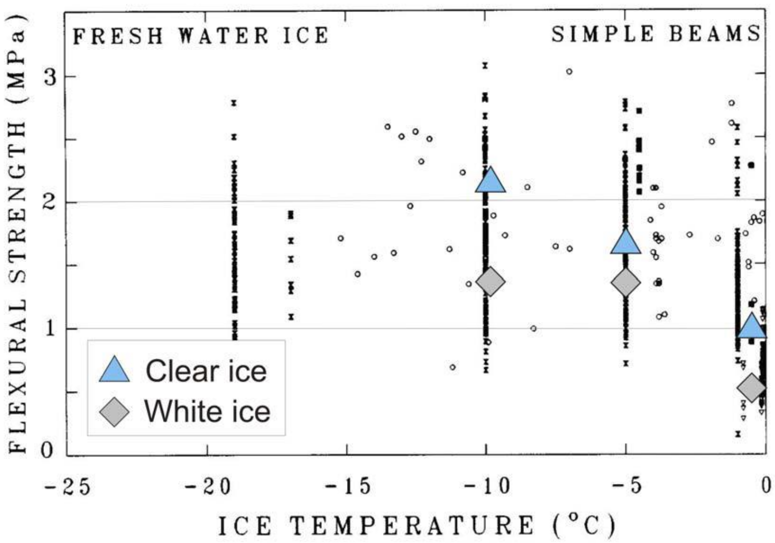

Figure 5: Flexural strength of white ice and clear ice from on the Rideau Canal Skateway in Ottawa (Barrette, 2011), plotted on a compilation by Timco and O'Brien (1994).

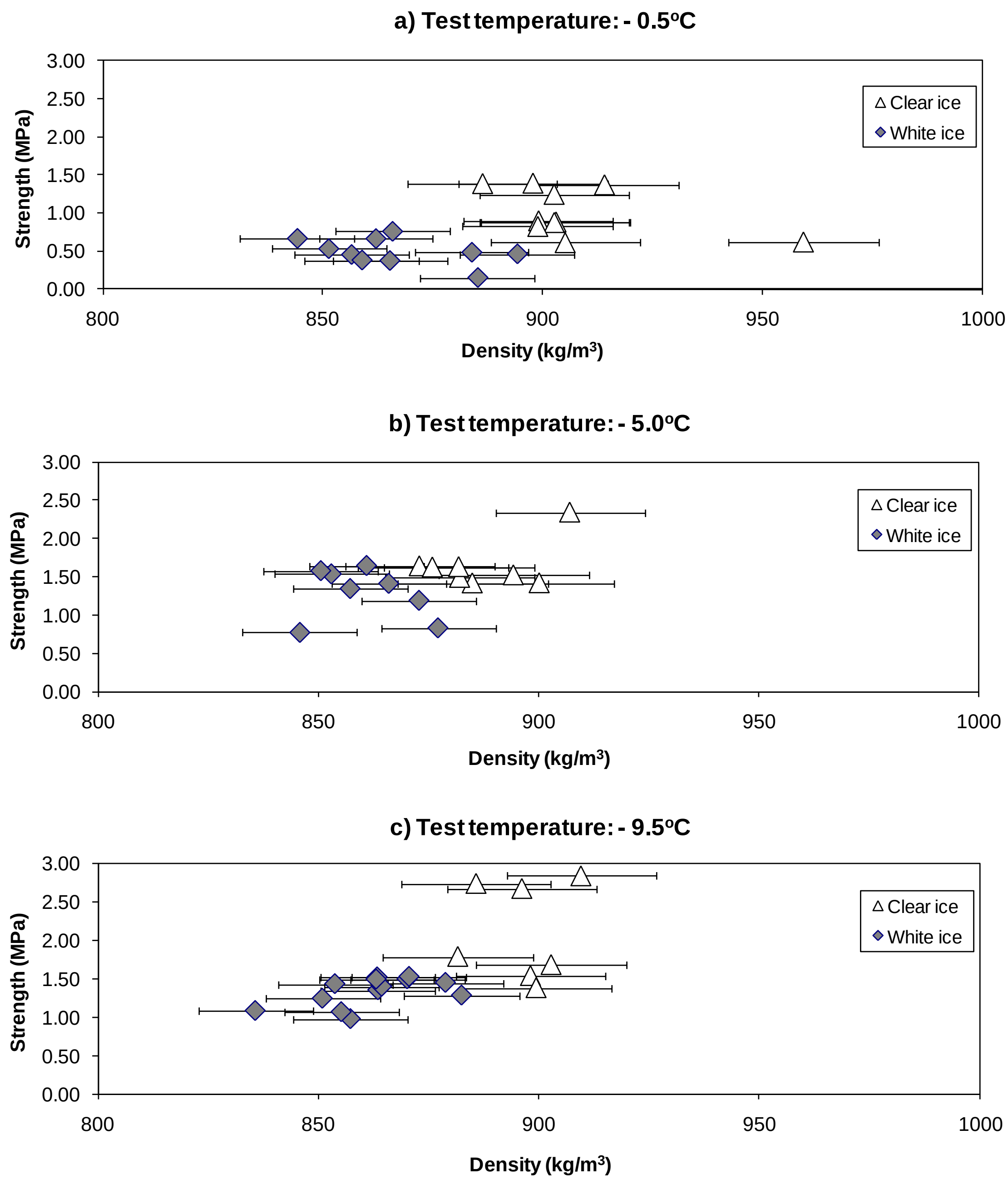

Figure 6: Flexural strength of white ice and clear ice from on the Rideau Canal Skateway in Ottawa (Barrette, 2011), plotted as a function of density.

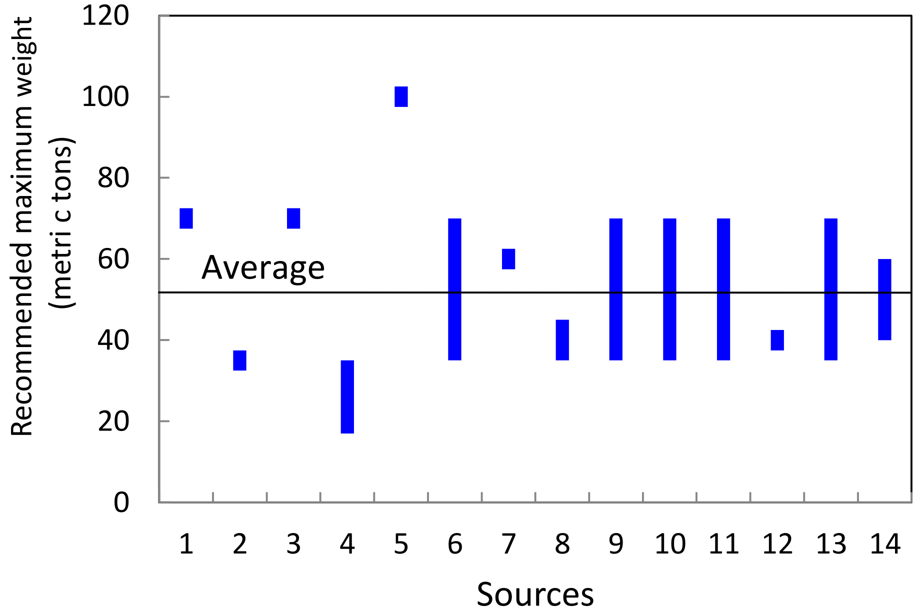

Figure 7: Recommendations from various sources, assuming a total ice thickness of 100 cm made entirely of clear ice.

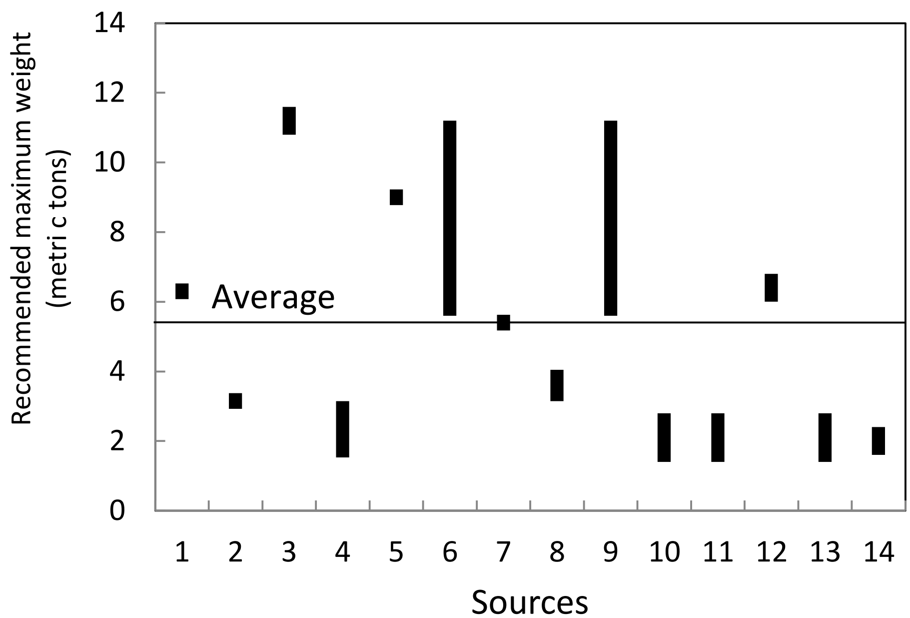

Figure 8: Recommendations from various sources, assuming a total ice thickness of 40 cm made of clear ice and natural white ice in equal proportion and of questionable quality.

Tables

Table 1: Sources in Figure 7 and Figure 8.

Source	Target readership	Reference
1	None	Gold (1971)
2	Quebec	CSST (1996)
3	Manitoba	Kuryk and Domaratzki (1999)
4	Canada	Treasury Board of Canada (2002)
5	USA	CRREL (2006)
6	None	Masterson (2009)
7	Saskatchewan	Government of Saskatchewan (2010)
8	Rideau Canal	BMT Fleet Technology (2011)
9	None	CSA-ISO 19906 (2011)
10	Canada	Proskin et al. (2011)
11	Alberta	Government of Alberta (2013)
12	Manitoba	Government of Manitoba (2014)
13	Ontario	IHSA (2014)
14	NWT	GNWT (2015)