Reinforcement of ice covers: A summary of previous full-scale scenarios and relevance to Canada's winter road infrastructure

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Abstract

Winter roads are seasonal routes that only exist in the winter – they run over land and over frozen water surfaces (lakes, rivers). The over-ice segments are particularly vulnerable to a warming climate. Ice reinforcement for the purpose of sustaining higher loads, and/or for a longer yearly operational lifespan, may be seen as an effective means to remediate weak links along a winter road, but that technique is not well known. A review of documented cases is presented in which reinforced ice was used in full-scale scenarios, with information on construction and deployment procedures. Retrieval of reinforcement, after the winter road season is over, is another aspect that warrants attention in a planning scheme. A distinction is made between the concepts of ice 'failure', linked with 'first crack', and 'breakthrough', which is a complex phenomenon involving a sequence of radial and circumferential cracks, when a vehicle breaks partly or completely through the ice. Determining the bearing capacity of reinforced ice is seen as an outstanding challenge in being able to implement a safe and effective reinforcement procedure. The solution would be to perform real-world, fully instrumented ice testing, and most importantly, allow for breakthrough to be achieved, so as to capture the full response and assess the ultimate resistance of the ice cover.

Introduction

As their name implies, winter roads are seasonal routes that only exist in the winter – they run over frozen land and frozen water surfaces (lakes, rivers)[1-3]. These roads cannot open if the segments crossing over ice covers (referred to herein as over-ice segments, ice bridges or ice roads) have not achieved a thickness deemed safe enough to accommodate the weight of the vehicles expected to travel on them. Various sources of information exist on building and maintaining winter roads and establishing what a safe ice thickness should be. They take the form of provincial and territorial guidelines, as well as reports from various organizations – for a brief review of these documents, the reader is referred to Proskin, Parry and Finlay [4] and Barrette [5].

Over-ice segments are particularly vulnerable to a warming climate [1, 6-8]. Ice reinforcement for the purpose of sustaining higher loads, and/or for a longer yearly operational lifespan may be seen as an effective means to remediate weak links along a winter road, i.e. ice bridges and shoreline crossings that are problematic because of a warming climate, and consequences thereof.

Ice cover reinforcement (Figure 1) is not a new concept – it has been explored by a number of investigators in the past. According to Michel, Drouin, Lefebvre, Rosenberg and Murray [9], however, *"[t]here is no known publication on their design as such, although much knowledge is available on bearing capacity of natural ice covers"* (p. 599). To this day, such guidance in reinforcing ice covers is still lacking. This may be due to the effectiveness of the existing flooding techniques to artificially increase ice thickness to the required level. However, we have reached a stage where the traditional modus operandi no longer suffices, and ice reinforcement strategies should be given due consideration. The first step is to be aware of what has been documented to date in terms of reinforcement procedures and outcome.

Objective

The main objective of this paper is to summarize full-scale ice reinforcement scenarios documented in the English literature. The relevance of this review may be best understood by considering that the winter road community in Canada may not be fully aware of the potential that ice reinforcement techniques represent. Where an ice road is problematic, other solutions are envisaged, such as re-routing of over-ice segments over land, which is expensive and not always feasible. Safe and effective reinforcement measures could be a valid alternative, at least for some locations and for relatively short segments.

Full-scale scenarios

From Vasiliev, Pronk, Shatalina, Janssen and Houben [10, p. 56]:

> *"[d]uring World War II in the USSR different ways of ice reinforcement using logs, branches and twigs were used to permit motor traffic on the ice of Ladoga Lake on the "Life Road" during the siege of Leningrad. The reinforcement of river ice roads on ice cover (ice ferries) with these materials was also used for heavy military transport in other areas of the military action (Bregman and Proskuryakov, 1943)."*

The cited 1943 document inside this quote is in Russian and was not consulted by the author of the present paper, but this would be one of the earliest source of information on an operational scenario. In this section, a review of ten documented case examples is presented in which reinforced ice was used for real scenarios, or for evaluation in full scale.

The Engineer [11]

In this source, a very short description is presented on a procedure to reinforce ice:

> *"According to two Soviet inventors, Alexei Ozherelyev and Vasili Chervyakov, reinforced ice only 200 mm thick can withstand convoys of loaded lorries while reinforced ice 500 mm thick can withstand railway trains. Even ice only 80 mm thick can be reinforced to withstand heavy loads. The proposed method of reinforcement consists in cutting 30 mm wide longitudinal and transverse grooves, using a circular saw, and laying cables made of fibreglass or other synthetic material in them. Holes are then drilled in the bottom of the grooves to admit water. When it freezes the cables in the ice play the same role as steel reinforcement in ferro-concrete."*

An idealized representation of this procedure is shown in Figure 2.

Carnes [12]

This source describes an ice bridge that was built in January 1963 (for military purposes) over the Imjin River in South Korea. At the time, the daily temperatures ranged from 10°C to -26°C. The aims were:

> *"[t]o determine if such a bridge could be successfully constructed on a tidal river in a temperate zone area with a relatively mild climate; to find out if an ice bridge could be constructed which could carry heavy wheeled and tracked vehicles; and if so to ascertain if an ice bridge have a true tactical value (p. 104).*

The crossing was 150 m in length – this was the narrowest point in the sector of interest. The construction began after the ice achieved about 150 mm in thickness, following these steps:

- After deciding on the route, wooden stakes 100 mm in diameter were frozen into the ice at a distance of about 3.8 m from a center line on both sides.
- Logs 100 to 150 mm in diameter were placed horizontally end to end all along both edges of the road, against the inside edge of the wooden stakes, and frozen in place. The gaps between them were filled with grass. The logs served two purposes: one was to delineate the road; the other was to retain flood water for the following step.
- Rice straw mats 100 mm in thickness were then laid inside that corridor, directly on top of the ice and in random orientation. These were flooded, and allowed to freeze.
- The subsequent layer was made from branches, brush and twigs varying in diameter from about 10 mm to 25 mm. The final thickness of that layer was about 100 mm.

- The previous step was repeated until a total thickness of about 250 mm of reinforced ice was achieved.

At the end of this procedure, which required at least one week, the total thickness of the ice bridge, including both natural and reinforced ice, was about 500 mm (Figure 3). Note that the reinforcement was above the center of the ice column, i.e. inside the compression zone (Figure 1). A treadway – a surface onto which vehicles drove on – was assembled from wood planks and laid on the reinforced ice surface. The joints between them was staggered, and the assembly was held together with narrow pieces of lumber (Figure 4). Information about the construction of shoreline ramps, which was said to be the "most involved", is also provided in the source. Controlled crossings were initially conducted with lighter vehicles, up to about 700 kg. This was followed by an armored ('SPAT') vehicle, whose weight is not mentioned in the source, but which is here estimated at about 6,500 kg. A final, ultimate test was done with a M-41 tank, here assumed to be 23,000 kg in weight. All trials were successful, and the bridge was then open for unlimited use by small vehicles and light trucks. No information is provided on the ice response, e.g. cracking and creep displacements over the bridge's operational time span. It was closed in late February, due to a warm spell.

Gold [13] – Case 1

Gold [13] describes a crossing that was built at a location where the river was 430 m in width, with a water depth of 2 m. There was a water current of 2-3 km/hour at that location. Following is the description provided in the source:

> *"A 75 m wide route was cleared across the river when the ice was 300 to 450 mm thick. A 45 m wide roadway was flooded to level out the surface. Small logs, 200 to 300 mm in diameter, were placed diagonally across the bridge at 0.6 m centers to form a 7.5 m wide road surface. The ice was built up by flooding until the average thickness of the roadway was about 1.5 m. […] The ice bridge was used for 8 weeks to transport about 17,000 tonnes of freight. The heaviest load was a truck and tractor weighing 118 tonnes. Regular checks were made on the condition of the bridge to ensure that no weak areas were present." (p. 180)*

An idealized representation of that construction is shown in Figure 5.

Gold [13] – Case 2

The second crossing described in Gold [13] was with steel cables and logs (Figure 6):

> *"When the ice was 700 mm thick, three 28.6 mm steel cables of 55-tonnes breaking strength were laid and anchored at each shore. Logs were placed across the three cables and frozen into position. The pumping of water onto the crossing was continued until the total thickness was about 1.30 m. Snow was removed from the adjacent cover over a width of 15 to 30 m on both sides. 1185 vehicles of gross weight less than 14 tonnes, 2034 of gross weight between 14 and 22.5 tonnes, and 52 of gross weight between 22.5 and 45 tonnes, used the crossing over the period 16 January to 15 April. The maximum load was 45 tonnes".* (p. 180-181)

Gold [13] – Case 3

The third crossing described in Gold [13] was with four layers of logs (Figure 7). At that location, the river was about 110 m in width and the water depth was from about 2 to 4.5 m. Following is the description provided in the source:

> *"Four layers of logs, 200-250 mm in diameter, were frozen into the ice. The first layer was placed crosswise, the second lengthwise, the third crosswise and the fourth lengthwise. The logs were*

> *frozen in as laid at a spacing of about 1.22 m between centers. The width of the reinforced area was about 9 m, and the total thickness about 1.5 m. Strips about 7.5 m on either side of the reinforced area were flooded so that the width of the built-up crossing was about 25 m. A hole drilled 7 m from the center line and fifty from shore indicated 1.25 m of solid ice and 0.13 m of weak ice near the surface. About 35 m from shore and 8.5 m from the center line there was 1.5 m of good ice. The water rose to the top of these test holes. The maximum thickness of the natural ice was about 0.61 m. A tower-erecting crawler crane weighing 90 tonnes was moved over the crossing. The crane was supported on four tracks about 4 m long and 1.4 m wide. The distance between the center lines of the tracks was 2.3 m along the width of the crane and 6.3 m along the length. Contact pressure under the tracks was 41 kPa. No cracking was heard as the crane traveled over the ice. The crossing was used regularly for carrying loads of up to about 45 tonnes"*. (p. 181)

Michel, Drouin, Lefebvre, Rosenberg and Murray [9]

The work described in Michel, Drouin, Lefebvre, Rosenberg and Murray [9] was to support development of large hydro-electric dams in Northern Quebec, east of James Bay. A winter road, about 600 km in length, was built for that purpose. It comprised eight major ice bridges and a number of smaller ones. The road was used over two winters (1971-72 and 1972-73). The source presents the theory for assessing bearing capacity of reinforced ice for those crossings; it also discusses the design, site selection, construction and testing of these structures. The load requirement was 70 tonnes, which was the weight of a "*D-9 bulldozer carried on a float*" (although higher loads have been achieved). Their design is depicted in Figure 8.

From the source:

> "*The bridges were reinforced with wood logs of aspen and black spruce averaging 150 mm in diameter. They were set a distance of 1.2 m center to center in the longitudinal direction with an overlap of 0.9-1.2 m. Two rows were first placed and a transversal layer was placed on top at distances of 12.2-24.4 m center to center, close to the surface of the ice bridge. […] The first row of logs was placed when the natural ice cover had a minimum thickness of 380 mm. It can be considered that this natural ice was a mixture of snow and columnar ice of poor quality. The second row was placed about 300 mm above the first one. The transversal row was set about 1270 mm from the bottom of the bridge.*" (p. 607)

The authors further commented that the logs were suspected to delay ice growth from below, especially if snow accumulated between them. The design assumed ice failure in tension, while the logs would take up the full load. In some cases, natural ice growth (at the base of the ice cover) caused the reinforcement to approach the neutral axis, thereby becoming less effective. It was also determined that the "*the type, quality and presence of wet cracks"* (p. 618) played an important role. For instance, although the crossings' design thickness was 1.6 m, that thickness was found to be insufficient at some locations – a more robust design was required (thickness of up to 2.54 m). This meant that the ice had to be monitored (in situ) on an on-going basis. Nonetheless, the conclusion was as following (p. 618): "*More than 3000 loads crossed safely the bridges during the two winters of 1972 and 1973 without delay*."

Fransson and Elfgren [14] – Three test cases

A field investigation was conducted by Fransson and Elfgren [14] to assess the effectiveness of laying the reinforcement at the top of the ice, then flooding it, in such a way it could resist compression (since it would be inside the compressive zone – see Figure 1). Three different materials were used for that purpose: sand, birch branches and lumber (Figure 9, Table 1). The site of that study was a lake in Sweden, about 40 km northwest of Luleå. Per the source:

> *"Initially the ice cover had a thickness of approximately 0.5 m. First, a 25 m wide surface across the lake (~ 120 m) was cleared from snow. Then the ice road was reinforced with:*
>
> *(a) a layer of 50 mm sand, and water on top of the original ice*
>
> *(b) branches of birch with a spacing of 0.3 m in two perpendicular directions*
>
> *(c) [lumber] (pine approx. 50x50 mm^2) with a spacing of 0.3 m in two perpendicular directions.*
>
> *The temperature was about -25°C during the flooding. In order to decrease the number of air pockets in the new ice, a light tracked vehicle was driven over it when it was partially frozen."* (p. 182)

A dump truck weighing 18.2 tonnes was used to load the reinforced ice (Figure 10). The variation – with time – in curvature of the ice surface was monitored with displacement gauges mounted below the vehicle. The loading event lasted 20 minutes. The truck was then removed and the deflection was monitored for another 10 minutes (as the ice rebounded). Deflection of the ice reinforced with sand and lumber was one tenth of that of the ice reinforced with the birch branches. As pointed out in the source:

> *"[...] the birch branch reinforcement hardly improved the ice load-curvature characteristics at all. This was probably due to the fact that the branches have low stiffness in compression. Thus they cannot help the ice to withstand the compressive forces but instead deform, when compressed, just as easily as the ice."* (p. 189)

What this study demonstrates here again is that reinforcement may be effective even if it is inside the compression zone, but it can also depend on the nature of the reinforcing material.

Haynes, Collins and Olson [15]

Field testing, conducted in Alaska, was designed to determine the bearing capacity of an ice cover reinforced with a geogrid [15]. This was done in a large pond (500 m x 400 m) inside a gravel pit. In October 1988, an opening was cut out from a 76 mm-thick ice cover, and a piece of geogrid was laid to float on the water inside the opening (Figure 11). The opening was then flooded, so as to increase thickness above the geogrid. In January 1989, the ice was 530 mm in thickness but the geogrid was only 76 mm below the top of the ice, which was also overlain by 460 mm of snow. A Small Unit Support Vehicle (SUSV) weighing 4364 kg was moved onto that surface so as to exert a load on it.

The progressive downward deflection of the ice was then recorded. It was found that, despite being so far up in the ice column, the geogrid contributed to reducing initial deflection (compared to an equivalent ice surface area devoid of reinforcement). Some reported advantages of using a geogrid are as follows:

- Increasing the bearing capacity of the ice cover
- Increasing the load-bearing after failure
- Low cost
- Light weight
- Relative ease of deployment
- Potential for recovery and re-use
- Excellent bonding characteristics
- Availability in light color

According to these same investigators:

> *"The greatest potential application for Geogrid for ice bridging may be in climatic areas that are marginal for growing ice and for relatively lightweight loads. It may have potential use on ice roads in critical areas that have thin or highly cracked ice".* (p. 11)

Summary

A compilation of the information provided in all sources is shown in Table 2. A distinction is made in that table between 'Operational', crossings that were used for transport operations, and 'Field study', which was testing under actual field conditions, but not an ice bridge per se. The former may be seen as 'proven' concepts'; the latter affords useful information on full-scale testing.

Deployment procedures

Based on the information from all available sources, deployment schemes are here divided into four different procedures: 1) laid on the ice surface, 2) laid below the water surface before freeze-up, 3) inserted through and below the ice surface, and 4) inserted into the ice surface.

Reinforcement laid on the ice surface

This procedure is the most common – a few cases were discussed earlier. Its main advantage is its relative simplicity. Material incorporation may also accelerate the ice thickening process, depending on how much and how it is used. The material is laid onto the ice cover as soon as it achieves a safe thickness to work on. It is then flooded, and that water allowed to freeze. The amount of labor and resources in the implementation of this procedure depends on the type and amount of reinforcement material, e.g. layers of logs are more involved than a geogrid or steel cables. Depending on how thick is the required ice build-up, snow banks may be required on each side of the road to contain water (e.g. Figure 8).

An important consideration is that, in real-case deployment scenarios, it can be difficult to achieve a given target depth (within the tensional zone) for the reinforcement, i.e. the material may end up being higher than anticipated. However, the outcome of some of the scenarios described in this paper is that, even if that is the case, reinforcement can still contribute in strengthening the ice cover. According to Fransson and Elfgren [14], the limiting factor for deflection, at least in a constant load scenario, and since "*ice creeps so easily in tension*" (p. 189), is actually within the compression zone, where the reinforcement has to be stiffer than the ice matrix.

Reinforcement laid below the water surface before freeze-up

This procedure can make use of cables or geogrid, but assumes that access to the site is possible outside the winter road operational timeframe (which is not always so in remote areas). In order to reach the target depth below the ice surface, due consideration must be given to the hydraulic conditions at the deployment site, i.e. it is best suited for calm waters. Also, weights or buoys (depending on material density) would have to be used so as to keep the reinforcement material at the target depth below the water surface. In the case of a geogrid, which usually comes in a roll, Haynes, Collins and Olson [15] observed that "*it unrolls in an undulating shape and does not lay flat up against the underside of the ice sheet*". So it would have to be sufficiently flattened prior to lay-out. Whatever precaution is taken, the reinforcement would likely vary, perhaps significantly, in depth below the ice surface. Downward growth of the ice-water interface is expected to fully incorporate the material, albeit possibly leading to the formation of a cleavage-prone ice-material interfaces [evidence of which is shown in 16].

Reinforcement inserted through and below the ice surface

This method has been used in the laboratory [15, 17] and is also described by Karpushko, Bartolomei, Karpushko, Zhidelev and Trapeznikov [18] – it is illustrated in Figure 12. It can be applied to cables or geogrid, and is done by cutting two slots across the width of the planned reinforced road segment – one slot at the beginning, the other at the end of the segment. If the material is denser than water (e.g. steel cables), buoys would have to be used in order to keep them against the canopy.

This procedure's main challenge is in being able to drive the material (below the ice) across the distance over which the ice cover is meant to be reinforced, which could range no more than a few 100's meters. An ice jigger[1], or similar device, could be used for pulling two lines attached to the material below the ice [19, see also 20]. Here again, a geogrid would have to be carefully flattened. An additional consideration (for very short segments) is to insert the material sideways along the length of the road [15], rather than from one end to the other, as shown in Figure 12.

Reinforcement inserted into the ice surface

This procedure, depicted in Figure 2, is an appealing alternative for cables (but not geogrids), and may be seen as the most practical and easiest option. There is no need for additional freeze-up time after deployment, i.e. the procedure is carried out once the target ice thickness (for road opening) is achieved. The deployment at a target depth below the ice surface ensures the material is initially within the tensile zone, close to the ice-water interface. The source mentions that a circular saw was used for installation purposes [11]. A hand-held chainsaw could also be used for short segments. Ideally, a better system would have to be devised for longer segments. It could take to the form of a walk-behind saw[2], modified to handle that particular application, e.g. with a thick saw blade.

Retrieval

Means of retrieving the reinforcement could play a pivotal role, but they are generally not discussed. Karpushko, Bartolomei, Karpushko, Zhidelev and Trapeznikov [18] is an exception – they allude to the challenge of extracting the reinforcement material from the water following the winter road season. Lack of access, until the ice has completely melted (so as to release the enclosed reinforcement material), is certainly an important consideration. A boat could be required if anchoring has been resorted to. A motor vehicle could also be needed to pull the material onto the shoreline. If dispensed on rolls, this would make retrieval (and transport) easier. The material could be stored on site, and await re-deployment the next winter.

The reason information on this topic is limited could be that retrieval was not seen as an issue by the few operators and engineers who documented ice reinforcement. That is so especially if logs were used. They would be abandoned at the end of the winter road season, and new logs would be harvested the following winter.

Avoiding breakthroughs

In practice, there are two responses of interest in assessing the ability of an ice cover to sustain a load. One, which is related with 'first crack', is when the strength of the ice has been mobilized (beyond the elastic response). This corresponds to a structural *failure*. It may happen for a number of reasons, namely the vehicle that caused the failure exceeded the allowable weight or the ice was thinner than expected.

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[1] https://www.youtube.com/watch?v=Q9vHIsDZ8_I

[2] https://en.wikipedia.org/wiki/Concrete_saw#/media/File:Concrete_saw2.jpg

Another is that the ice thickness was not sufficient. If the route crossed an area where a current existed, it could induce thermal erosion of the lower surface. Excessive speed can also promote ice failure. Any of these cases can be attributed to a lack of appropriate monitoring, i.e. the provincial or territorial guidelines were not adhered to.

After failure, water may make its way to the surface along a crack, an indication that this segment should be closed to traffic, until it is repaired (e.g. by flooding the surface) and freezes again. If a load that has caused failure is not removed, or if it significantly exceeds what is required for failure, or if the ice is not repaired before the next vehicle accesses that location, this can lead to a *breakthrough*. This is the second response that needs to be understood. It is the outcome of a process that is much more complex than the first one (failure), involving extensive crack development.

Added complexity to these two responses – failure and breakthrough – is the nature of the ice cover itself, which varies considerably in internal structure, the nature of the applied load (e.g. distribution, duration), and other factors, such as water depth and road characteristics (e.g. width, orientation).

Breakthrough with non-reinforced ice

A conservative approach to prevent breakthrough in a standard (non-reinforced) ice cover is to avoid failure (first crack) in the first place. In Canada, Gold's formula [13] is alluded to implicitly or explicitly in most guidelines, as a first-order approximation. This formula has the following form:

$$P = Ah^2 \quad \text{Eq. 1}$$

where

P: Design load, in kilograms
h: Ice thickness, in centimeters
A: Empirical parameter with pressure units, in kilograms per square centimeter

The thickness h is assumed to be representative of the ice road as a whole (or a segment thereof) with due consideration to variations, i.e. the thinnest area along the route should be used for the calculation. The coefficient A is related with the ice flexural stress. Values assigned to it vary [2, 21]. The most conservative value is 3.5 kg/cm^2, which has been used historically in several guidelines [e.g. 22, 23], presumably in keeping with Gold [13]'s empirical observations. That number is now at 4 kg/cm^2 in the latest guidelines [e.g. 24]. Higher values can be used under additional guidance from a professional engineer [e.g. 23, 24]. With this formula, a plot can be produced, as shown in Figure 13, where the load on the vertical axis is the maximum that should be allowed for the ice thickness on the horizontal axis. The 'A' values used in this plot are 3, 5 and 7 kg/cm^2, as examples. No physical or theoretical basis is provided in guidelines for the choice of the recommended value(s) – they are inherently considered a proxy for tolerance to risk.

What if loading is such that it does lead to a breakthrough? A sequence of events has been identified [25]. Here, we focus on short-term loading (less than a minute), and we overlook more elaborate scenarios, such as dynamic loading related with vehicle speed. We also assume an idealized, axisymmetric deformation in the elastic range (i.e. instantly and fully recoverable), with a concentrated load in the center (Figure 14).

- The maximum tensile stress (induced by loading) occurs directly below the load, along the lower surface of the ice. When that stress exceeds the tensile strength of the ice, radial cracks start forming. They may not be noticeable initially if they are hidden under the ice (and the snow cover, if there is one). The amount of load required to achieve this state is considerably lower than that required for a breakthrough.
- A further increase in load causes additional cracking, this time in circumferential patterns – the tensile stresses are then at the top of the ice cover. At this point, the amount of load reaches 40-60% of that required to produce a breakthrough.

- Once all tensile stresses have been relieved via fracturing, compressive stresses dominate. This is because of the interaction between individual pieces in the broken ice cover, *which restrains the fractured parts from expanding*” [25, p. 8].

While Sodhi [25] offers a model that approximates a breakthrough scenario, he states that *“[an] exact analysis is not available at [the time of writing]”* (p. 8). Note again that the ice is assumed to be uniform and devoid of structural flaws, which is rarely the case in a natural ice cover.

Breakthrough with reinforced ice

Reinforced ice may be considered a ‘composite’ [10] – its response to loading is more complex than that of ice only. The configuration of the material, its mechanical properties and how it binds to the ice matrix all factor in that response. Computational modeling to assess conditions required for failure (first crack) in reinforced ice, is able to provide some measure of guidance, conditional upon the validity of the simplifying assumptions [26]. This type of analysis can help decide what material to use, and how.

Methods to determine the ultimate bearing capacity of reinforced ice, i.e. beyond which a breakthrough can occur, have been provided in a few investigations.

- For the scenario illustrated in Figure 8, Michel, Drouin, Lefebvre, Rosenberg and Murray [9] first consider the layering, by factoring in non-dimensional parameters that take into account the ‘form of the load’ and the ‘width of the bridge’. According to this theory, which makes use of a modified ‘Gold formula’, the ‘state of plasticity’ of the ice, which refers to the mobilization of time-dependent deformation mechanisms (creep), would contribute to increasing the allowable load.
- Fransson and Elfgren [14]’s scenario (Figure 10) is mostly about the creep response, and is empirical, i.e. ‘creep constants’ were determined from the tests and incorporated into their formulations. One of these constants is presented as a means of anticipating loss of freeboard, when the water from wet cracks will flood the ice.
- Karpushko, Bartolomei, Karpushko, Zhidelev and Trapeznikov [18] follows Russian guidelines (“Industry Road Norms 218.010-98 Instructions for the design, construction and operation of ice crossings”). The source refers to a formulation equivalent to Gold’s formula, so as to determine the bearing capacity of the crossing. If it is deemed insufficient for the expected loads, the engineer then calculates the reinforcement required to accommodate the additional load (with a safety factor), using empirically-derived formulations.
- In Vasiliev and Gladkov [27], formulations are used for applications on reinforced concrete, also involving empirically-derived parameters.

Gold’s ‘A’ value and tolerance to risk

Table 2 summarizes the full-scale ice reinforcement scenarios. An ‘A’ value for the coefficient in Eq. 1 (Figure 13) was derived from the reported thickness (h) and maximum load (P) in each case. That value was applied to non-reinforced ice scenarios and may be seen as a proxy for tolerance to risk. It is used the same way here with reinforced ice, for the purpose of discussion.

In almost all scenarios, *A* was within a similar range as that recommended by recent guidelines for non-reinforced ice covers, i.e. from 3.5 to 5 kg/cm^2 [2, 23, 24]. One exception is the military scenario documented by Carnes [12], which had the highest tolerance. Interestingly, the Cold Regions Research and Engineering Laboratory (CRREL), a research organization supporting the U.S. Army, recommends an ‘A’ value of 10 kg/cm^2 [28], albeit for non-reinforced ice, consistent with that shown in Table 2 for Carnes [12]’s scenario.

For the other scenarios, according to current guidelines, the thickness achieved could have carried the required loads *without reinforcement.* So why was reinforcement used in the first place? One reason is that, as mentioned earlier, reinforcement is a source of resistance to breakthrough. Another is thought to be the difficulty in being able to assess its effectiveness. As stated elsewhere [9, p. 618], "*It was indeed not feasible to fail one bridge to test its bearing capacity and thus verify theory with measurements*." Without verification, any theory or assessment aimed at determining bearing capacity of these complex structures is of limited value. Overall, the designers' prudence was warranted. But this underscores the need for controlled breakthrough testing, so as to validate theory.

Conclusion

Winter road operators in Canada do not use ice reinforcement techniques, at least not on a systematic basis. Or if they do, it is not well documented. This may be seen as a missed opportunity because not only can the ice be made stronger, it will also resist breakthrough. In order to raise awareness that ice reinforcement has been used successfully in the past, and in various ways, several full-scale scenarios are presented – all are for short (key) segments. Four deployment schemes are also described. As for retrieval, conceivably also a decisive factor in determining feasibility of an ice reinforcement scheme, almost no information is available on it.

Given the increasing amount of uncertainty regarding winter road safety and effectiveness in the context of a warming climate, it is desirable at this time to build on the experience acquired to date, and develop a knowledge-base about reinforced ice. Gaining sufficient confidence is key – it will help avoid over-conservativism while devising safe and cost-effective solutions. This can be best accomplished by performing more full-scale, fully instrumented testing on reinforced ice covers, as shown herein. But achieving breakthrough in those tests is essential: we need to capture the full response history, so as to validate theory. (This could be done, for instance, by loading the ice cover with a crane stationed on land or on a bridge.) In addition, factors such as environmental compatibility and stakeholder acceptability in selecting an appropriate reinforcement scheme need to be addressed, along with deployment and retrieval methods. This would lead the way toward guidelines on implementation and alignment with relevant regulations. It is further proposed that this endeavor be undertaken and/or coordinated at the federal level, so as to address Canada's winter road infrastructure as a whole.

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Figures

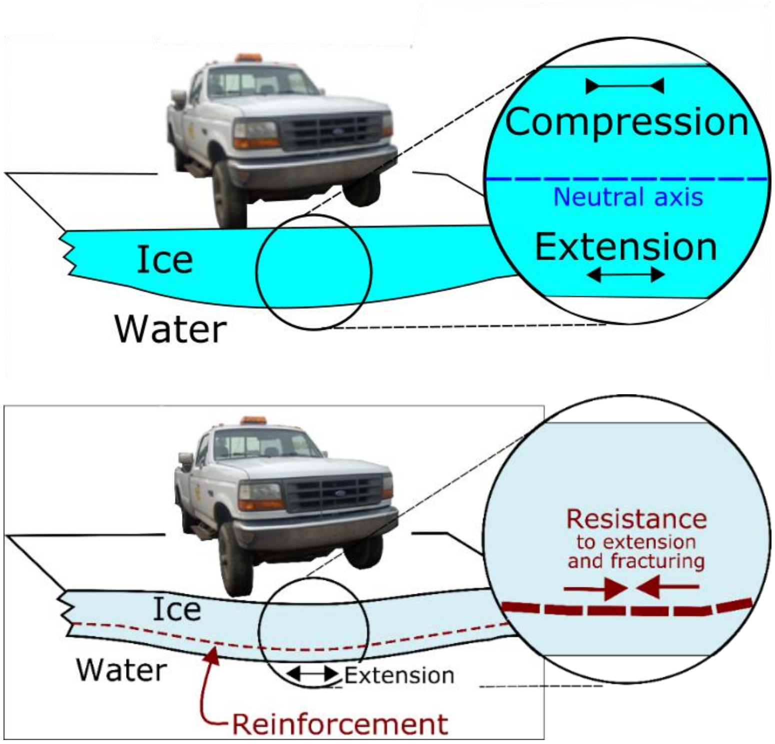

Figure 1: The principle of ice cover reinforcement. Top) State of stress in the ice – the compression and extension zones are, respectively, above and below the neutral axis. Bottom) Action of reinforcement. In this case, a geomembrane is shown, but there are many alternatives.

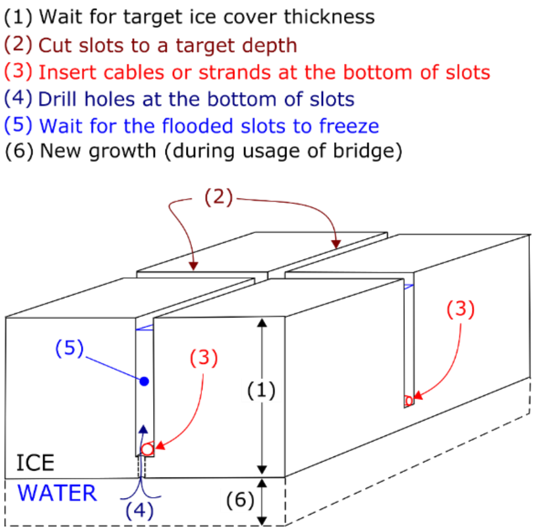

Figure 2: Procedure to reinforce an ice cover, based on the description in The Engineer [11]. For the purpose of this illustration, it is divided into six steps. The reinforcement is labeled (3).

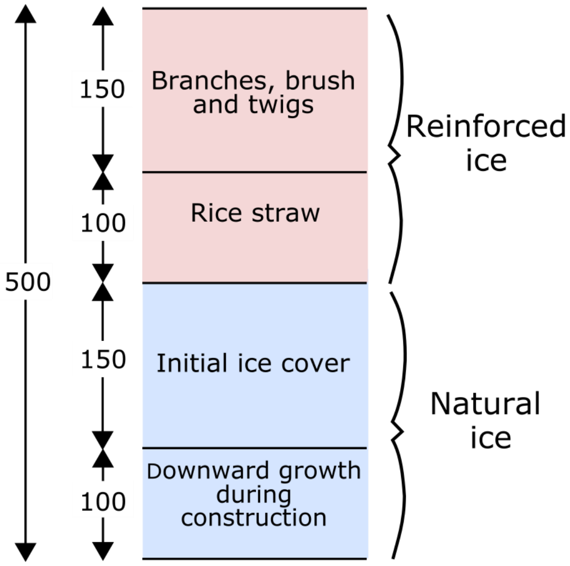

Figure 3: Simplified cross-section of a reinforced ice bridge in South Korea [12]. Downward growth is assumed, based on the information provided in the source. Dimensions are in millimeters.

Figure 4: Top) Passage of the first vehicle across the Imjin River, in Korea. Bottom) Passage of the largest load across that river – a M-41 tank. From Carnes [12]. Reprinted with permission of the Society of American Military Engineers.

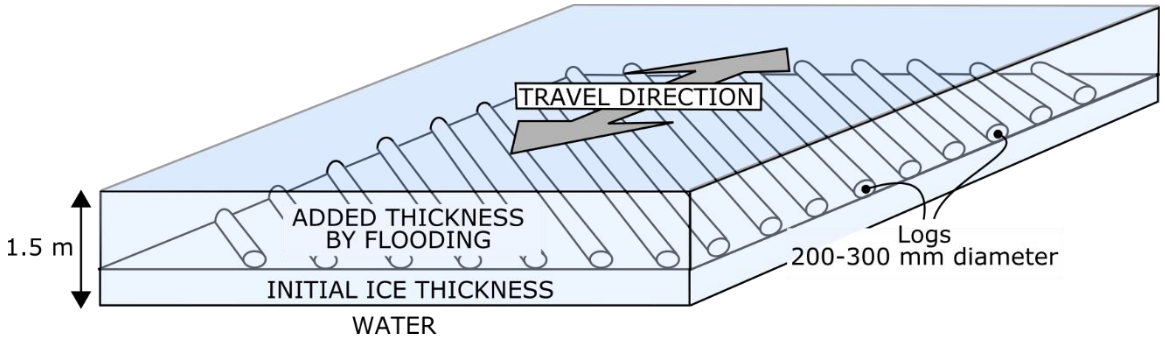

Figure 5: Ice bridge reinforced with logs placed diagonally on the ice surface [drawn following the description provided in reference 13]. Not to scale.

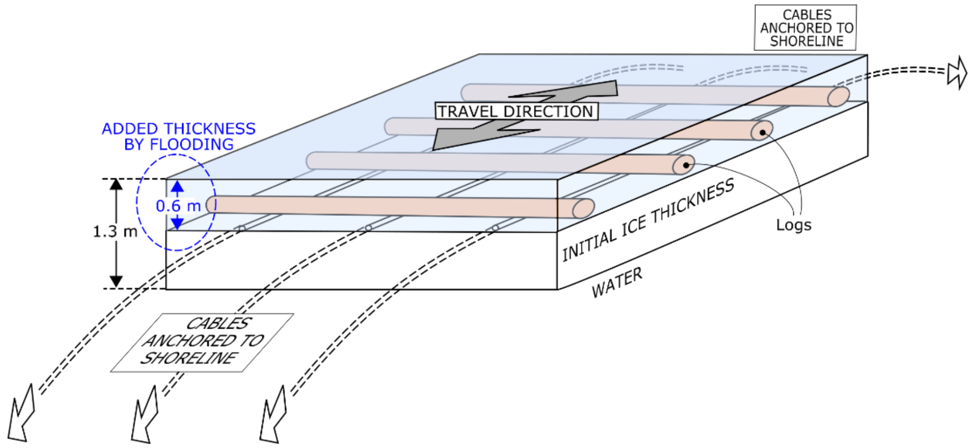

Figure 6: Ice bridge built from logs laid on top of steel cables that were anchored to both shorelines [drawn following the description provided in reference 13]. Not to scale.

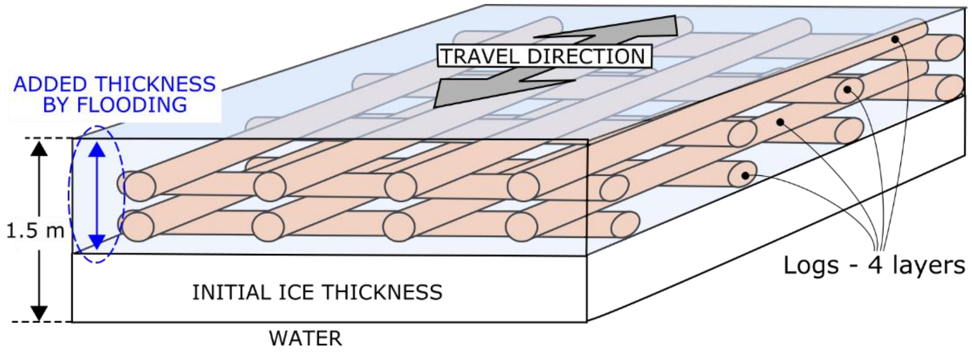

Figure 7: Ice bridge built from four layers of logs [drawn following the description provided in reference 13]. Not to scale.

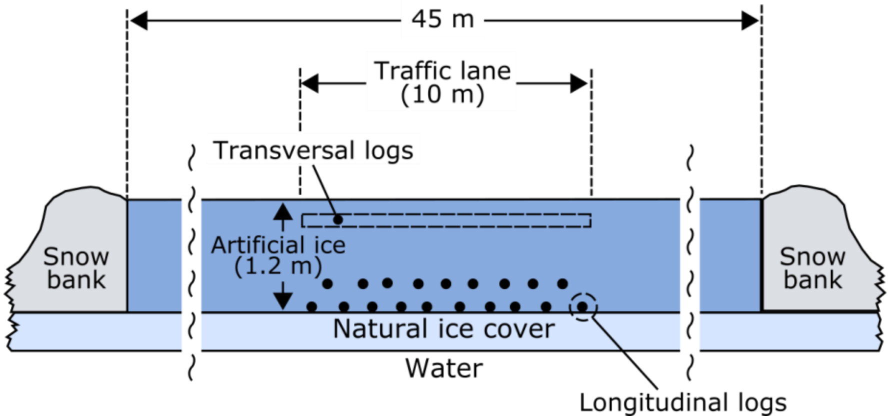

Figure 8: A "typical design" for the ice bridges described in Michel, Drouin, Lefebvre, Rosenberg and Murray [9, Fig. 8, p. 609]. Reinforcement comprises two longitudinal rows of logs and one transversal row of logs. Not to scale.

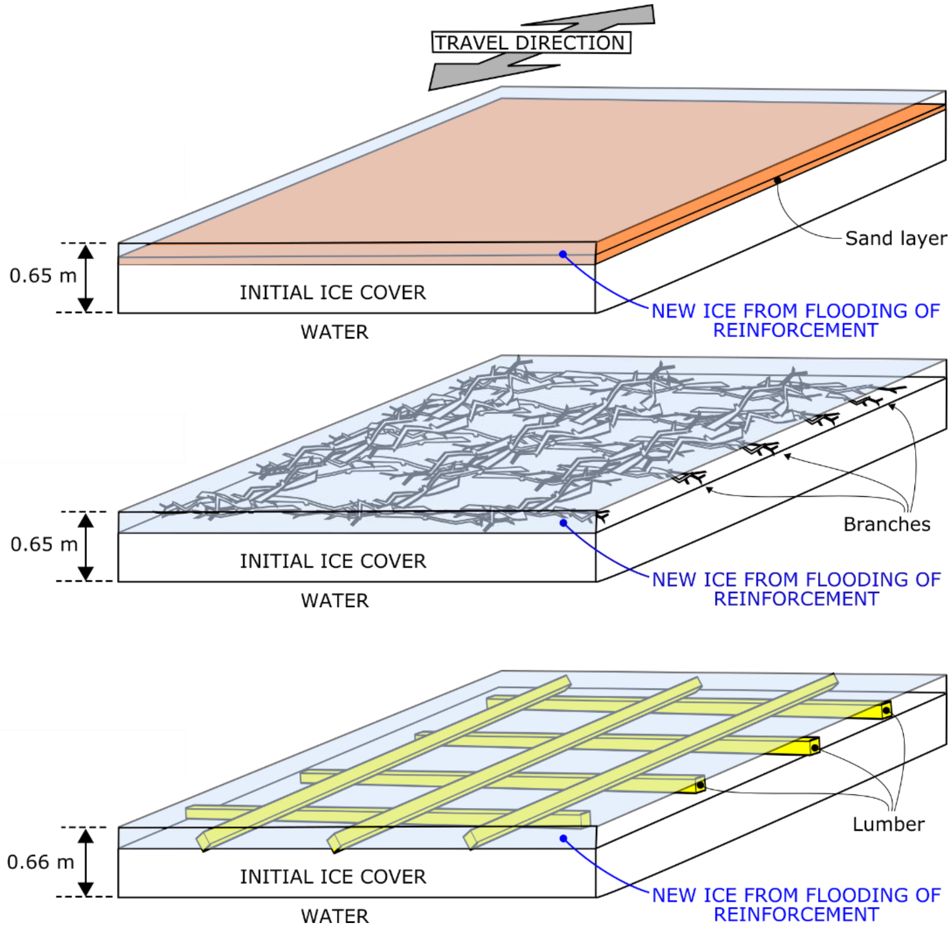

Figure 9: Three types of reinforcement reported in Fransson and Elfgren [14]: Top) A sand layer. Middle) Birch branches. Bottom) Lumber. Note that all are near the top of the ice cover. Not to scale.

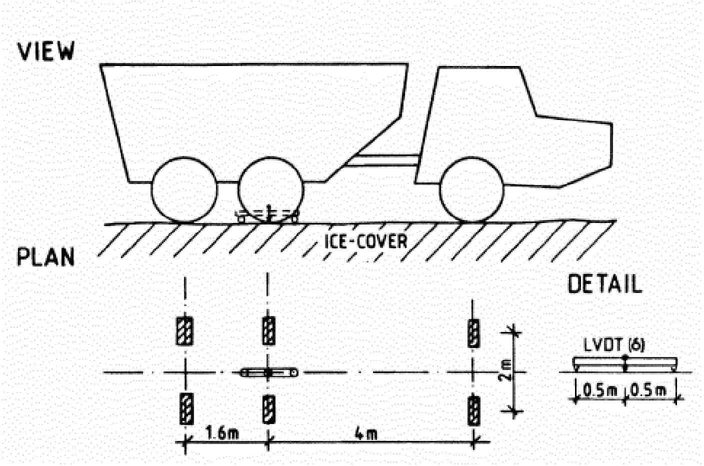

Figure 10: Vehicle and loading configuration for the reinforced ice covers shown in Figure 9 – from Fransson and Elfgren [14, Fig. 4.1]. The footprint is depicted, including distance between the wheels and the axles, and the location of displacement gauges ('LVDT') below the vehicle.

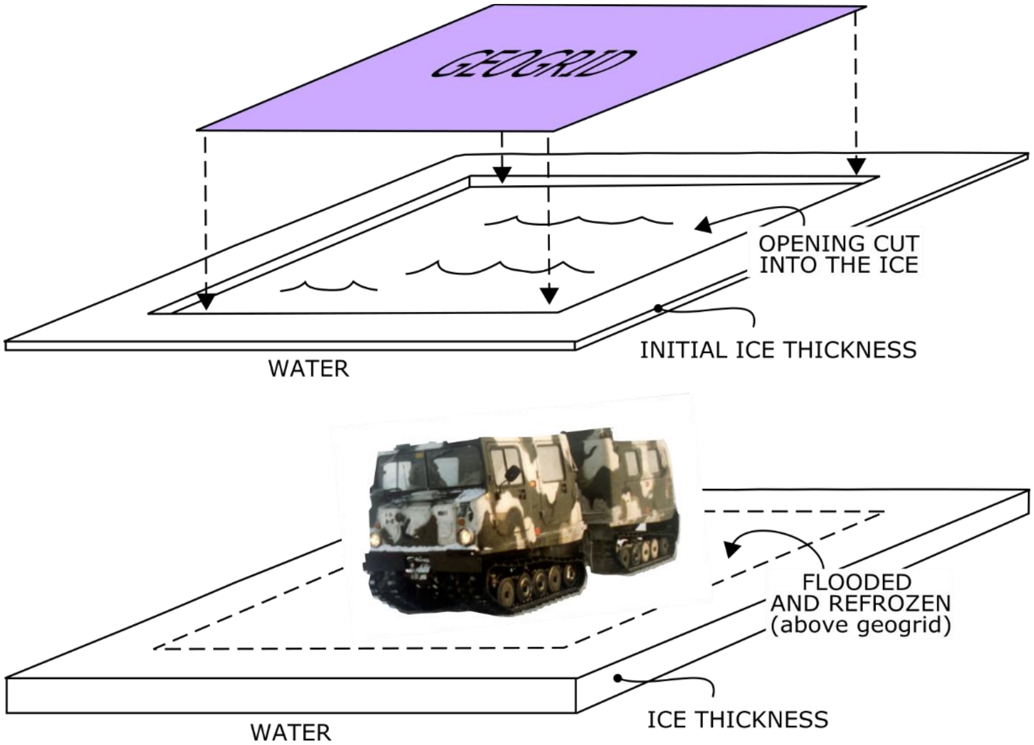

Figure 11: Schematic description illustrating the procedures used by Haynes, Collins and Olson [15] to study the effectiveness of an ice cover reinforced with a geogrid. Top) A geogrid was laid floating inside an opening that was cut out of an existing ice cover. Bottom) After flooding and refreezing, the bearing capacity of the reinforced ice was tested using a small military vehicle. Snow layer not shown. Not to scale.

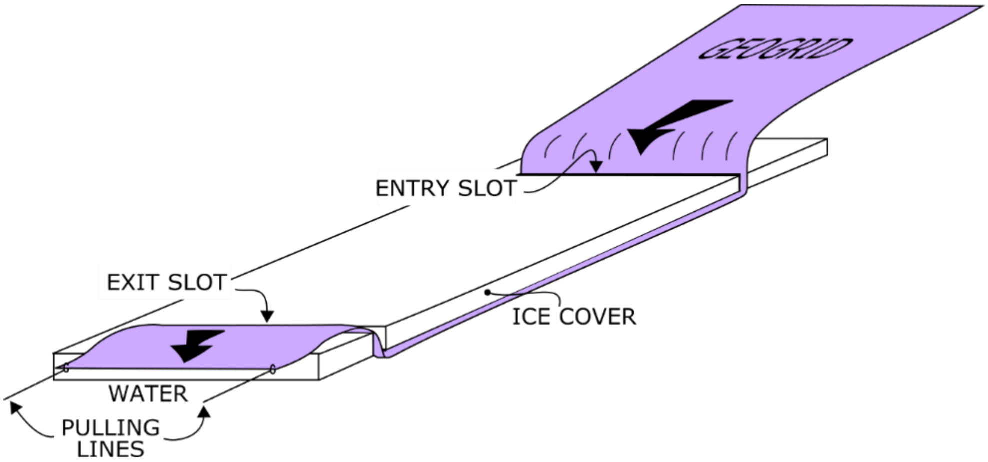

Figure 12: Schematic diagram illustrating a deployment procedure, here used for a geogrid, whereby the material is inserted below the ice through an 'entry' slot, and retrieved through an 'exit' slot.

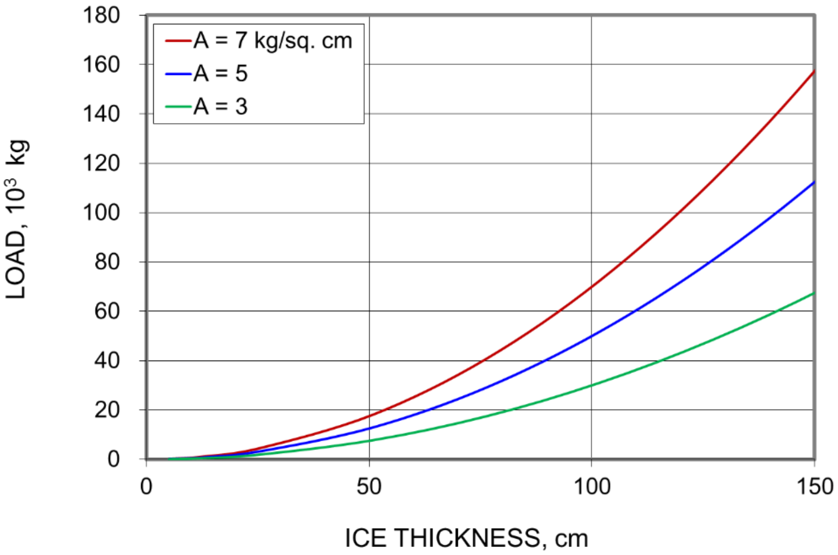

Figure 13: Load as a function of ice thickness for three different 'A' values, using the equation of Gold [13]. A higher value translates into a higher tolerance to risk.

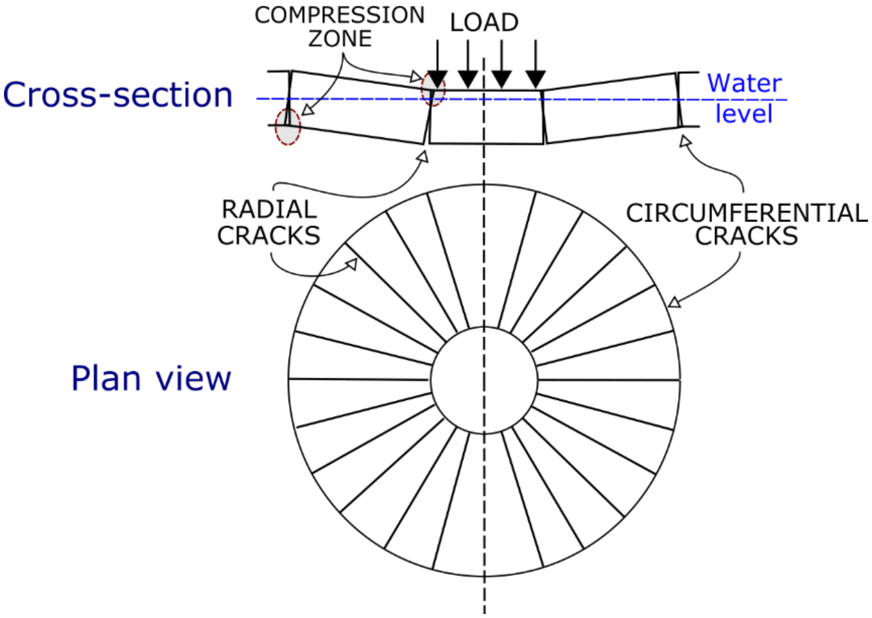

Figure 14: Idealized representation of cracking patterns in a vertically loaded ice cover [from 25].

Tables

Table 1: Thickness and surface area of the different reinforcement materials used in the trials reported in Fransson and Elfgren [14].

Type of reinforcement	Thickness of reinforcement (m)	Total ice thickness (m)	Area (m) x (m)
Sand	*0.10*	*0.65*	*10 x 30*
Birch branches	*0.20*	*0.65*	*10 x 31*
Lumber	*0.13*	*0.66*	*10 x 40*

Table 2: Summary of full-scale scenarios in which reinforcement ice was used. Imperial tons in the sources were converted to metric tonnes. The 'A' value is the coefficient in Gold's formula for non-reinforced ice covers, derived from the ice thickness and the maximum loads – a higher number may be seen as a proxy for a higher tolerance to risk.

Source	Purpose	Length (m)	Reinforcement material	Total thickness h (cm)	Maximum load P achieved	'A' value (kg/cm^2)
The Engineer [11]	Operational	Not mentioned	Fiberglass cables	20	Not mentioned ("convoy of loaded lorries")	-
				50	Not mentioned ("railway trains")	-
Carnes [12]	Operational	150	Branches, brush, twigs, rice straws	50	23 tonnes (M41 tank)	9.2
Gold [13]	Operational	430	Logs	150	118 tonnes ("truck and tractor")	5.2
Gold [13]	Operational	Not mentioned	Logs over steel cables	130	45 tonnes	2.7
Gold [13]	Operational	110	Logs	150	90 tonnes ("crawler crane")	4.0
Michel, Drouin, Lefebvre, Rosenberg and Murray [9] – *Waswanipi crossing*	Operational	640	Logs	173	90 tonnes	3.0
Michel, Drouin, Lefebvre, Rosenberg and Murray [9] – *Pontax 1 crossing*	Operational	90	Logs	160	90 tonnes	3.5
Michel, Drouin, Lefebvre, Rosenberg and Murray [9] – *Rupert crossing*	Operational	550	Logs	223	118 tonnes	2.4
Fransson and Elfgren [14]	Field study	30 – 40	Sand, birch branches, lumber	65	18.2 tonnes	4.3
Haynes, Collins and Olson [15]	Field study	50	Geogrid (polymer mesh)	53	4.4 tonnes	1.6