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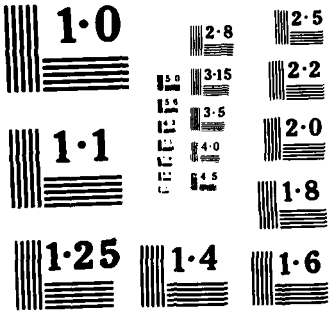
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Snow in the construction of ice bridges

Barry Coutermarsh and Gary Phetteplace

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Snow's contribution as a wearing surface, leveling material or reinforcement to ice bridges is discussed. It is shown that it has limited value as a reinforcement and then only by adding water and freezing the resulting slurry. Snow can be used effectively as either a leveling or wearing surface but natural ice thickening is inhibited by the insulating property of the snow. The snow should be of uniform depth and not mounded or windrowed to avoid deflecting the ice away from the water surface. This would substantially weaken the carrying capacity of the ice bridge.

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PREFACE

This report was prepared by Barry A. Coutermarsh, Research Civil Engineer, and Gary E. Phetteplace, Mechanical Engineer, of the Applied Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory.

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SNOW IN THE CONSTRUCTION OF ICE BRIDGES

Barry Coutermarsh and Gary Phetteplace

INTRODUCTION

The idea of using snow to help construct or reinforce ice bridges is appealing for several reasons. If the existing ice is too thin for the proposed loads, machine-made or natural snow could be used to build up the existing ice to the desired capacity. This could be much quicker than waiting for the ice to thicken naturally, thus allowing use of the bridge over a longer period. A snow layer might also be added as a buffer between the traffic and ice, preventing premature breakdown of the ice surface.

This report discusses the feasibility of using machine-made snow as a wearing surface, leveling material or reinforcement agent in the construction of ice bridges. Before looking at each of these applications, let's take a simplistic look at an ice layer and its characteristics when a load is applied. We can then compare ice and snow properties to see what is important in a bridging situation.

BACKGROUND

When a load is applied to the top of an ice sheet, the ice deflects downward. This builds up compressive stresses in the top part of the ice and tensile stresses in the bottom part, as illustrated in Figure 1. Since ice is weaker in tension than it is in compression, a loaded ice sheet will fail at its bottom surface first (Johnson 1980). The compressive and

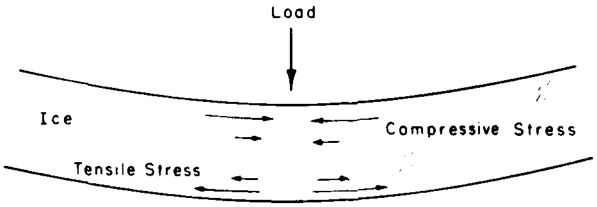

Figure 1. Stress buildup in a loaded ice sheet.

tensile strengths of ice depend on temperature as well as the physical composition of the ice. It is beyond the scope of this paper to present a detailed discussion of ice strength. Ice growth and strength characteristics vary between sea ice and freshwater ice. This paper will assume the use of fresh water and freshwater ice. Butkovich (1954) gives values of compressive strength for freshwater ice between approximately 15 kg/cm^2 at 0°C and almost 70 kg/cm^2 at -50°C and tensile strength (for clear ice only) between approximately 13 kg/cm^2 at 0°C and 25 kg/cm^2 at -50°C. Natural ice that is formed by water freezing around snow layers can contain air pockets, however, and be substantially weaker than clear ice.

Snow compressive strength depends mainly upon its density. Natural snow with densities, ρ_s, less than 0.4 g/cm^3 have low strengths of less than 1 kg/cm^2, with higher densities having strengths between 1 kg/cm^2 and about 35 kg/cm^2 at $\rho_s = 0.7$ g/cm^3 (Mellor 1964). Furthermore, snow that has been pulverized and redeposited has less strength at any given density than naturally compacted snow. Snow tensile strength is also predominantly affected by the density. Again, for densities less than 0.4 g/cm^3, tensile strength is less than 1 kg/cm^2 ranging to approximately 17 kg/cm^2 at a density of about 0.7 g/cm^3 (Mellor 1964).

In light of the above, we can look at the most effective use of snow in building ice bridges.

SNOW AS A REINFORCING AGENT FOR ICE BRIDGES

It has been shown that snow, whether compacted or uncompacted, is weaker than ice. It is then obvious that simply spreading snow out on an ice layer will not add any strength to the ice, and in fact it will be a detriment. The ice will not only have to support the additional load of the snow but the snow will also insulate the ice, preventing further convective cooling to the atmosphere and inhibiting the natural thickening of the ice cover. To illustrate this let's assume we have a 25-cm-thick ice cover over 0°C water with an air temperature of -10°C (Fig. 2). The thermal conductivity, k, of ice is about 2.25 W/m°C. The thermal resistance, R, value of the ice layer is $0.25 \text{ m} \div 2.25 \text{ W/m°C} = 0.11 \text{ m}^2\text{°C/W}$. Figure 2 shows the situation when 10 cm of snow is added to the top of the ice. The thermal conductivity of snow depends upon its density, moisture content and grain structure. Thermal conductivity values of dry snow range between

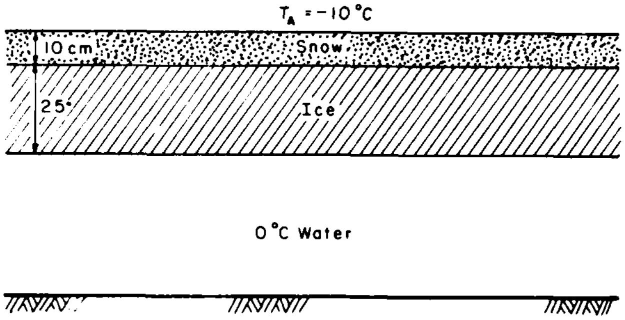

Figure 2. Physical situation with 0°C water and a 25-cm thick ice layer covered by 10 cm of snow with an air temperature of -10°C.

about 0.1 W/m°C to 1.3 W/m°C (Mellor 1964). The R-value of the 0.1-m layer of snow thus ranges between 0.08 and 1. Using the mean R-value of 0.54, we can see that the 10-cm snow layer results in a 400% increase in thermal resistance over that of the ice layer alone.

It is possible, however, to use snow to help thicken the ice by flooding it with water and allowing it to freeze. This procedure can be quite involved, depending upon the depth of the snow, air temperature, amount of area to be flooded and means of flooding. A look at the theory behind the freezing process will explain why this is so.

We will show the difference between heat loss from a water layer and heat loss from a snow-water mixture as we develop our examples. Since both examples have their lower boundary as ice, we will only concern ourselves with convective heat loss to the atmosphere. The situation will otherwise become complex with the inclusion of the heat transfer between the lower water boundary and the ice. This boundary condition will be the same for both examples. In order to freeze the flood water layer, energy transfer as heat must take place between the water layer and the atmosphere (since we are neglecting the lower ice layer).

The time to lower the temperature of the flood water to 0°C by removing its sensible heat can be calculated as follows. The enthalpy change of the water is defined by

$$dh = c_p \, dT_w \qquad (1)$$

where

h = specific enthalpy of water (a measure of the energy within the water volume)
dh = differential specific enthalpy change
c_p = specific heat of water (1.16 W hr/kg °C)
T_w = temperature of the water
dT_w = differential temperature change of the water.

The rate of enthalpy change of the water would then be

$$\frac{dh}{dt} = c_p \frac{dT_w}{dt} . \tag{2}$$

On a unit area basis,

$$\frac{dH}{dt} = \rho_w d_w \; c_p \frac{dT_w}{dt} \tag{3}$$

where

H = enthalpy of water
ρ_w = density of water (999.6 kg/cm^2)
d_w = depth of water = 10 cm
t = time.

Treating the water as a lumped system, an energy balance requires the rate of heat transfer from the water to the air to equal the rate of enthalpy change determined in eq 3. This again neglects heat transfer to the ice below.

The rate of heat transfer, ϕ_c, on a unit area basis from the water will be:

$$\frac{q_c}{A} = \phi_c = h_c \, (T_w - T_a) \tag{4}$$

where

q_c = rate of heat transfer from the water to the air
h_c = heat transfer coefficient from the water (25 w/m^2 °C [Calkins 1979])
A = unit area
T_a = air temperature.

The heat balance is then

$$-\frac{dH}{dt} = \phi_c . \tag{5}$$

It should be noted that positive heat transfer has been defined as heat transfer from the water. This transfer will decrease the enthalpy of the water, therefore dH/dt will be negative in sign.

Equation 5 can also be written as

$$-\rho d_w c_p \frac{dT_w}{dt} = h_c (T_w - T_a) \tag{6}$$

or

$$-\frac{\rho d_w c_p}{h_c} \frac{dT_w}{dt} = T_w - T_a \quad . \tag{7}$$

Separating variables results in

$$dt = \left(-\frac{\rho d_w c_p}{h_c}\right) \frac{dT_w}{T_w - T_a} \quad . \tag{8}$$

Integrating eq 8 and evaluating from the start of heat transfer ($t=t_s$) to the finish ($t=t_f$), with the starting value for the water temperature being T_{ws} and ending value being T_{wf}, gives:

$$\int_{t=t_s=0}^{t=t_f} dt = \frac{\rho_w d_w c_p}{h_c} \int_{T_w=T_{ws}}^{T_{wf}=0} \frac{dT_w}{T_w - T_a} \tag{9}$$

or

$$t_f = \left(-\frac{\rho_w d_w c_p}{h_c}\right) \left[\ln\left(\frac{T_{wf} - T_a}{T_{ws} - T_a}\right)\right] + C_o \tag{10}$$

where C_o is a constant of integration. C_o is evaluated at the boundary conditions of $T_{ws} = T_{wf}$, which must result in $t_f = 0$, therefore $C_o = 0$. To illustrate the freezing of a water layer on ice, let's assume we have the following conditions:

- Air temperature -10°C.
- River water temperature 0°C.
- 25 cm of ice at 0°C.
- Flood water temperature 5°C.
- Flood water depth 10 cm.

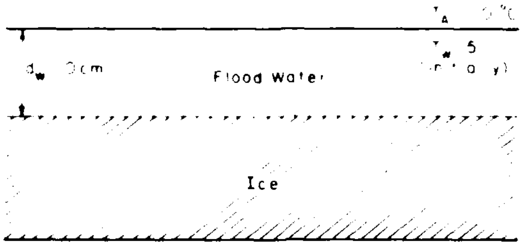

Figure 3. Initial conditions from the ice sheet up; 25 cm of ice flooded with 10 cm of 5°C water; air temperature of -10°C.

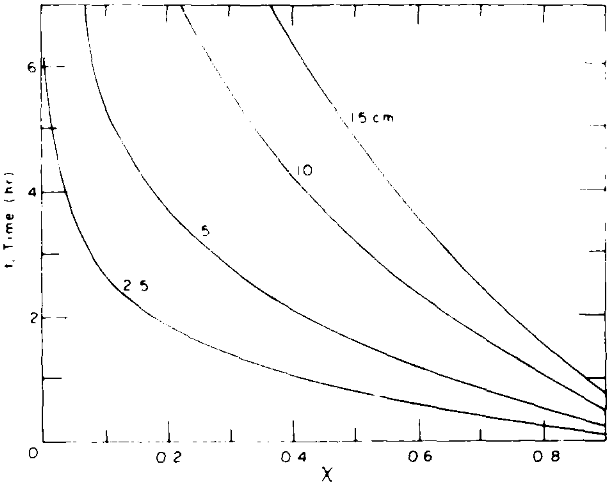

Figure 4. Time needed to remove the flood water's sensible heat versus χ for different flood water depths. χ is a nondimensional parameter of water temperature and air temperature.

Figure 3 illustrates the assumed conditions. Using eq 10, we arrive at an elapsed time (t_f) of 1.9 hours to lower the flood water temperature from 5°C to 0°C.

Figure 4 is a graph of time to remove sensible heat versus χ (a nondimensional parameter of water temperature and air temperature) where

$$\chi = \frac{T_{wf} - T_a}{T_{ws} - T_a}$$

with four water depths illustrated.

Water at 0°C must still lose energy, in the form of latent heat, before it will freeze. The latent heat of solidification of water is 3.34 x 10^5 J/kg. The volumetric latent heat of solidification, L, of water is 3.34×10^5 J/kg (999.6 kg/m^3) = 333,866,400 J/m^3. This latent heat is lost by convective heat transfer to the ambient air, allowing ice to form at the top of the water surface and to grow downward. This will consequently slow the rate of heat loss from the water because of the insulating effect of the ice.

The time required to remove this latent heat, which is also the time required to grow the ice, is given by (Lunardini 1981):

$$t = \frac{L\, k_i \left[\left(1 + \frac{h_c}{k_i} d_w \right)^2 - 1 \right]}{2(T_w - T_a)\, h_c^2} \qquad (11)$$

with t, the time, in seconds. In our example

$$t = \frac{(333{,}866{,}400 \text{ J})(2.25 \text{ W/m°C})\left[\left(1 + \left(\frac{25 \text{ W/m}^2 \text{°C}}{2.25 \text{ W/m°C}} \right) (0.1 \text{ m}) \right)^2 - 1 \right]}{2\left(0\text{°C} - (-10\text{°C}) \right) (25 \text{ W/m}^2 \text{°C})^2} \qquad (12)$$

$$\simeq 207739 \text{ seconds} \simeq 58 \text{ hours.}$$

Figure 5 is a graph of time required to remove the latent heat or grow the ice sheet from 0°C water versus air temperature for four different water depths.

The total time required to freeze our water layer is therefore

1.9 hours + 58 hours = 59.9 hours or 60 hours.

What advantages are there from a snow layer on the ice during flooding? The most obvious advantage is that the snow will displace a volume normally filled by the flood water. In this way a smaller amount of flood water is required to make the necessary thickness of ice. The snow will also help remove sensible heat from the flood water. As the flood water flows through the snow layer it will contact a large snow crystal surface area, melting snow until the sensible heat of the flood water is removed. This transfer will take place nearly instantaneously. The desired situation is to ensure that enough snow is present to remove all of the flood water's sensible heat, leaving water or a water-snow slurry at 0°C. The

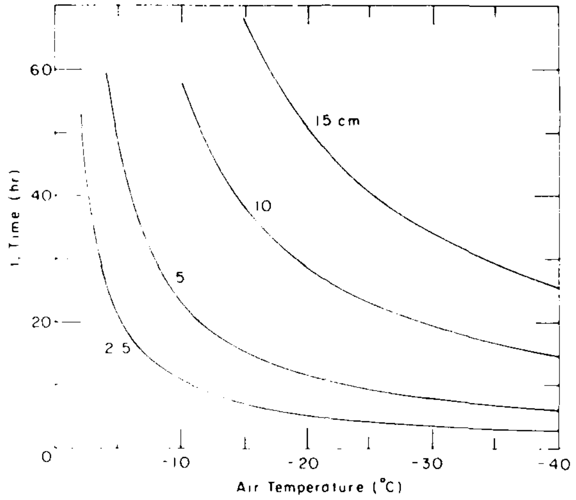

Figure 5. Time needed to grow an ice sheet (latent heat removal) versus air temperature for four flood water depths.

mass of snow necessary depends on its temperature, density, volume, specific heat and both the temperature and volume of the water flooding the snow mixture.

The heat sink capacity available in 0°C snow to lower the flood water temperature will be the product of its latent heat, λ_s, and density, ρ_s. With the sensible heat available in the flood water, we can use the heat sink capacity value for the snow to determine how much snow and water to mix to get 0°C water.

The energy balance between the snow and water will be

$$V_s \rho_s \lambda_s = V_w \rho_w c_p (T_w - T_s) \tag{13}$$

where V_s, V_w are the volumes at snow and water respectively and T_s is snow temperature. This balance equation can be written in the form

$$V_w = C_t V_s \tag{14}$$

where

$$C_t = \frac{\rho_s \lambda_s}{\rho_w c_p (T_w - T_s)} .$$

C_t is a coefficient relating water volume to snow volume that is based on the temperature difference between the water, T_w, and snow,

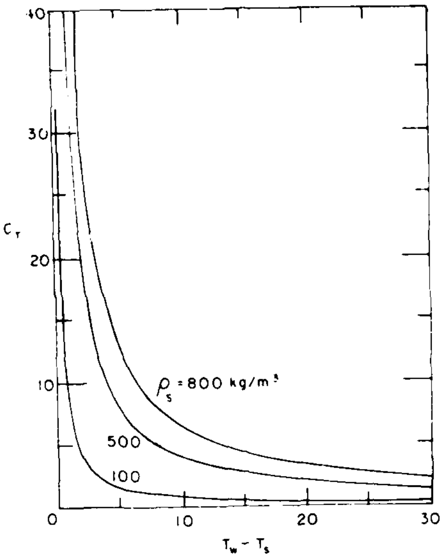

Figure 6. Coefficient C_T that relates flood water volume to snow volume versus temperature difference between the flood water and snow layer for three possible snow densities.

T_s. Figure 6 is a graph of C_t versus different values of $(T_w - T_s)$ for three snow densities and $c_p = 4176$ W s/kg °C.

To illustrate this, let's assume that we have 10 cm of man-made, uncompacted snow on our ice, and we wish to thicken the ice by 10 cm. The snow has a density ρ_s of 500 kg/m³ at a temperature of 0°C. The water density is again 999.6 kg/m³. The latent heat of solidification of snow is 3.34×10^5 J/kg. From eq 13

$$V_s \left(500 \frac{\text{kg}}{\text{m}^3}\right) (3.34 \times 10^5 \text{ J/kg}) = V_w \left(999.6 \frac{\text{kg}}{\text{m}^3}\right) \left(1.16 \frac{\text{W hr}}{\text{kg °C}}\right) (5\text{°C} - 0\text{°C})$$

$$V_s \left(1.67 \times 10^8 \frac{\text{J}}{\text{m}^3}\right) = V_w \left(5.81445 \times 10^3 \frac{\text{J hr}}{\text{s m}^3} 3600 \frac{\text{s}}{\text{hr}}\right)$$

$$V_s \left(1.67 \times 10^8 \frac{\text{J}}{\text{m}^3}\right) = V_w \left(2.0932 \times 10^7 \frac{\text{J}}{\text{m}^3}\right) \tag{15}$$

$$V_w = 7.98 V_s \quad .$$

This is approximately a 1 to 8 ratio of snow volume to water volume. In our example with 10 cm of snow, $V_s = 0.1$ m³. The largest volume of water at 5°C that could be added to this snow to result in 0°C water is, therefore,

$$V_w = (7.98)\ (0.1\ m^3) = 0.8\ m^3$$

or on a square metre basis, 80 cm of water.

This calculation shows that .. volume of snow sufficient to remove the sensible heat from any practical depth of flood water would be relatively easy to obtain. In our example 8.76 cm of water and 1.11 cm of snow would result in approximately 10 cm of 0°C water. This procedure would save us about 1.9 hours of the 60 hours required to freeze a 10-cm water layer as determined from our previous example where no snow was used. The time saving is a result of the instant removal of the sensible heat.

Any volume of snow less than 1/8 V_w would mean that the flood water would have sensible heat remaining. This would have to be transferred by convective heat loss to the atmosphere. Any volume of snow greater than 1/8 V_w would result in a 0°C snow-water slurry on the ice with only latent heat remaining in the water. This remaining latent heat would be transferred to the atmosphere by convective heat loss.

In order to remove the latent heat from the 0°C flood water faster than by convective cooling to the atmosphere, three conditions would have to be met.

1. A snow temperature substantially less than 0°C.
2. A volume of snow sufficiently large enough to remove both sensible and latent heat.
3. Application of the flood water in such a manner as to ensure the maximum surface area contact between the snow and water.

In theory, the above three conditions are all possible to obtain. From a practical standpoint, however, condition 3 causes some problems. If the flood water is sprayed over a cold snow surface under very low temperatures, premature freezing of the water droplets in the air becomes a problem, preventing a cohesive ice layer from forming. If the flood water does make it into the snow layer, some water will undoubtedly freeze as it trickles down into the snow layer. These frozen areas can stop other water from entering, thus creating voids. These air pockets can dramatically reduce the strength of the ice layer. If the flood water is applied in one step, however, a frozen mixture called "snow ice" is produced. The strength of snow ice is temperature-dependent, but is in all cases lower than clear lake ice (Butkovich 1954), from roughly 20% at 0°C to 50% at -50°C.

Snow has very little value as a reinforcing agent in ice bridges. It could, however, prove useful in a different context.

SNOW AS SACRIFICIAL WEARING AND LEVELING MATERIAL

If the ice at a bridging site is of adequate thickness to support all of the anticipated loads, it might be useful to have a sacrificial layer of snow applied as a wearing surface. This would prevent deterioration and the subsequent weakening of the ice itself, especially if tracked vehicles are using the bridge.

Snow could also be used as a leveling agent to smooth uneven ice or to ease the transition from shore onto the ice. If this is done, it is important not to concentrate mounds or windrows of snow on the ice surface (Fig. 7). This can cause the ice to deflect, leaving air gaps between the ice and water surface. These air pockets drastically reduce the strength of the ice layer and should be avoided.

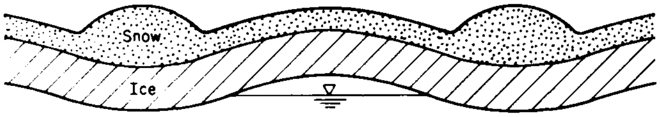

Figure 7. Snow mounds or windrows can deflect the ice away from the water creating a void that will substantially lessen the capacity of the ice.

CONCLUSIONS AND RECOMMENDATIONS

Snow itself is not a useful reinforcing agent for ice bridges. It may, however, be useful to leave a layer of snow on the ice during flooding operations. The snow will help to reduce the time needed to freeze the water, but will complicate the flooding procedure because care must be taken to minimize the occurrence of voids and air pockets, something that is extremely difficult to control.

Flooding with small layers of water (under 10 cm) and allowing freezing to take place between layers is probably the best method. If snow ice is formed during the flooding process a thicker layer of ice for any given load is required because of the reduced strength of this ice.

Using snow as a wearing or leveling surface makes sense but care must be exercised when doing so. Realize also that this snow layer will insulate against natural ice thickening if the temperatures are favorable for it.

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