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SPATIAL-TEMPORAL VARIABILITY OF STATIC ICE FORCES

Brian Morse [1], Edward Stander[2], Alain Coté[3], André Taras[3], Rock Santerre[1], Yann Prat[1]
[1]Laval University, Quebec, Canada
[2]State University of New York, Cobleskill, USA
[3]Institut de recherche d'Hydro-Québec, Varennes, Canada

ABSTRACT

The spatial and temporal variability of ice forces near dam faces have been studied over three winter seasons. This paper introduces the project and explores some of the preliminary results acquired to date.

Field measurements included ice deformations rates calculated using a robotic total station and image analyses. In-ice stresses were determined using in-situ stress gauges places at various locations and depths. Ice pressures against the wall were measured directly at four elevations and at up to 11 locations.

While ice displacement measurements followed a fairly regular pattern associated with thermal events and water level fluctuations, in-ice stresses behaved in a spatial-temporal chaotic manner – sometimes in phase with ice displacement and sometimes not. Measured pressures against wall face showed correlations with temperature changes and water level fluctuations but were also fairly chaotic. This article presents some reflections on the nature of the observed spatial-temporal variability.

CONTEXT

A collaborative research project has been set up between Laval University, Hydro-Québec and BMT-Fleet Technology to study static ice loads on dams. The project is in its fourth year. Taras et al. (2009) presented ice force measurements at two Quebec hydroelectric dams over the 2008 and 2009 winter field seasons, and attempted to relate measured force values to variations in air temperature and reservoir stage variations. Bisanswa (2011) presents a comprehensive overview of all data collected at these sites.

Prat (2010) and Prat et al. (2011) document measured ice sheet strains using a Leica TPS 1200 total station within one of the gauged reservoirs (Beaumont) in 2009 using a robotic total station (Figure 1). The figure shows that horizontal ice displacement is away from the perimeter (both shore and dam) and is greatest in magnitude nearest the dam.

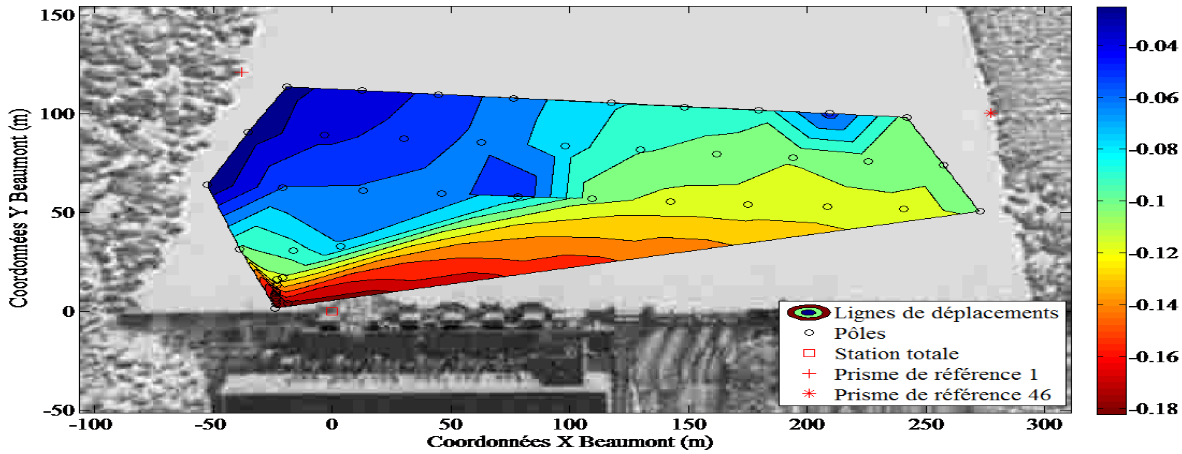


Figure 1. Measured ice displacement (m) from Jan. 21st to March 16th 2009 perpendicular to the dam. (Note that pole placement is indicated by open circles).

Stresses in the ice sheet (kPa) were calculated using the strain rates (s^{-1}) in the ice cover and the Glen equation (1955):

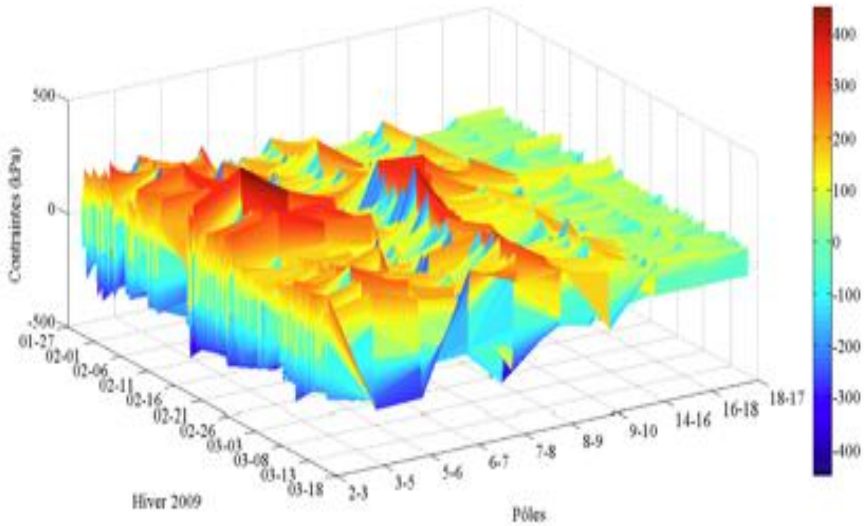
$$\text{Stress} = K\,(\text{strain rate})^{n'} \qquad (1)$$

The value of K is very sensitive to temperature. Prat used n' = 0.3045 and K = 89,000 for -2 °C falling to K = 44,000 for T = 0 °C. Morse et al. (2009) presented similar stress calculations for the 2008 data at another dam site (LaGabelle). Based on Barnes et al. (1971) in Hallam, (1986), Morse et al. estimated K = 73000 and for ice at T = -2 °C.

In calculating stresses using equation 1, Prat tried to minimize the effect of measurement uncertainty by taking a moving average through the points prior to calculating strain rates. There are still some residual effects in the data that create false stresses fluctuations but there is still some stress variability that is real. Note that it is greatest near the dam, tapering off as the distance from the dam increases.

Recent work by Song (2008) for T = -10 °C, shows that the type of creep at low stresses changes from that following the Glen expression to a Newtonian creep process with a corresponding value of n' = 1. A "low stress" is typically below 200 kPa but if there is some pre-stress loading, the transition can start at 1200 kPa (Song et al. 2006). This means that stresses can be many times lower than those that are predicted by the Glen equation. This may partially explain the over-prediction of stresses made by Morse et al. (2009).

We place some emphasis on the ice creep at the beginning of this paper because it may well be the process that limits ice forces on dams given that most strain rates on a reservoir are typically on the order of $10^{-9}\,s^{-1}$ to $10^{-7}\,s^{-1}$ and therefore stresses are very much dependent on the elasto-plastic properties of the reservoir ice.



Pole	D (m)
2	1.6
3	3.79
5	5.33
6	6.86
7	8.80
8	10.14
9	13.42
10	16.37
14	30.66
16	62.51
18	89.12
17	113.62

Figure 2. Calculated stresses (kPa) in the ice at Beaumont in 2009 perpendicular to the dam face as a function of time and distance (D) from the dam face.

OBJECTIVE

The purpose of this article is not to attempt to present all of our field data in a systematic manner. This would produce an unwieldy study, as more than 100 gauges of various forms were emplaced over the three winters seasons. Nor is it our purpose here to describe in detail any specific event or process. This was attempted in some detail by Taras et al. (2009) and by Morse et al. (2009), and the reader who wishes to explore exact relationships is referred to those articles among other ice force on dam studies made previously by others.

Rather, the purpose of this paper is to present some examples of various types of acquired data and to provide a general reflection on processes that might explain the extreme spatial and temporal variability that we observed year after year (regardless of the gauge type or measurement technique applied). In so doing, we are attempting to impart some knowledge about the spatial-temporal variability of static ice stresses and strains in ice sheets on reservoirs while inviting comments in order for us to better understand what is actually occurring.

INTRODUCTION

An in-depth understanding of freshwater ice forces on dams and other hydraulic structures is important for design purposes. Traditionally, dam stability is based on a unit width (i.e., calculations at each meter of dam width must pass the stability tests). This ensures a safe design and generally works well for most ambient forces (e.g., hydrostatic force, dam weight, etc.) as these vary in a systematic and continuous manner along the dam face and dam foundation. However, ice unit forces (i.e., “line loads”) are known to vary as a function of width: the applied unit force (kN/m) over a 30 m width (i.e., a typical concrete pour width) is less than the unit force applied over smaller widths of say 1 m. This phenomenon is referred to as a scale effect or as an ‘indentation’ effect (e.g., Saunderson, 1988).

Initial estimates made in the early 1900s (Barnes, 1928) were about 700 kN/m and were based on the observation of rubble ice formation events on lakes and the calculation of thermal expansion and a compressive ice strength of 2500 kPa for a one foot thick ice sheet as this was thought to be the most critical thickness. In the 20th century, dam design engineers have generally been using an ice load of 150 kN/m (10 kips/ft).

Since most recent experiments (1990s to today) have been based largely on point load measurements only, the question becomes whether it is realistic to use those values “as is” or whether a more integrated pressure value (calculated over a larger width) should be used for design purposes. For example, the peak load at LaGabelle in 2008 at one location was 130 kN/m whereas the peak load measured over 40 m (based on averaging data from 11 locations) was only 80 kN/m.

Forming a scientific opinion of how to interpret historical ice load data needs to be based on some understanding of the spatial temporal distribution of these loads and on some understanding of what is actually going on at the ice/dam interface.

Loads can be generated by several known mechanisms and can be either additive or subtractive, dynamic or static. Dynamic loads are characterized by impulse and momentum terms describing the deceleration of ice floes as they come into contact with a structure and are often crushed there. For example, dynamic forces can be caused by individual floes moving with a river current and driven into bridge piers (Johnston et al. 1999). Rubble ice may build up against piers forming an ice jam (Beltaos et al. 2003). Wind may combine with or without currents and force an ice sheet to climb over ice booms (Morse, 2001). However, in the case of dam interactions, most forces are static where the impulse and momentum terms are negligible.

STATIC LOAD GENERATION MECHANISMS

Static forces behind retaining structures fall generally under two headings. Static loads are generated primarily by thermal changes in the ice sheet as well as by ice jacking due to water level changes in the reservoir.

Thermal forces develop when the floating ice cover expands and forces itself upon a reservoir’s perimeter. Generally speaking, the forces are omni-directional as the expansion occurs in all horizontal directions at once. Thermal expansion is generated primarily in the upper layer of the ice sheet where ice temperatures may vary as environmental conditions change.

The bottom of the ice sheet is always close to the point of fusion given that it is floating on water whose temperature is near zero degrees and therefore variations in temperatures there are minimal.

When the surface of the sheet increases in temperature, the cover’s expansion is somewhat restrained by the bottom half of the ice sheet that does not suffer thermal effects. However, once stresses in the sheet reach values exceeding the ultimate tensile stress (i.e., about 700 kPa), greater movement may occur if the basal portion of the ice sheet fails in tension. The interplay between expansion, restraint and the development of tensile fissures is described by Ashton (1986) and by Barnes (1928). He describes an experiment to observe these cracks in an ice sheet grown on a Montreal warehouse floor.

Barnes notes that water going into the open fissures may subsequently freeze causing expansion as the ice cycles through events. Ashton also notes that as pieces of ice rotate relative to one another, there is insufficient space because of the extra length required along the element diagonals. This can also produce compressive forces in the sheet.

Ice sheets may also force themselves upon the reservoir perimeter through ice jacking (Carter, et al., 1998, Stander, 2006). The idea here is that the ever-present fissure that is found close to the reservoir's edges opens and closes due to level fluctuations. This is an old idea that Barnes refers to and that has received more attention recently. When the fissure opens with falling stage height, water intrudes and freezes within the crack, leading to a slight increase in the size of the ice cover, and subsequently to ice thrust with rising water levels Generally speaking, these forces are compressive and perpendicular to the perimeter of the reservoir.

Comfort et al. (1992) presents a statistical model to account for the load generated by thermal effects as well as those generated by ice jacking. They suggest that the greatest loads are generated when water level fluctuates around a mean value by an amplitude of approximately one ice sheet thickness.

ICE FORCE PROCESSES

Prior to this study, we believed that static forces would be fairly homogeneous over most of the dam face. For example, we imagined that global changes in ice temperature would lead to global variations in ice force. However, sensors placed in various locations over the last three winters suggest that the stresses can vary significantly from one location to the next. Two sensors can be in phase while a third is entirely out of phase. One sensor can see large stresses while a nearby sensor sees nothing. We are beginning to ask why this might occur. In particular, we wonder: are the sensors reliable? Are there contact issues between the ice and the sensor? Is the very placing of the sensors causing local stress points or thermal piping? Are variations between sensors caused by variations in the depth of emplacement? Is thermal erosion at the ice/water interface locally affecting sensor measurements? Are tension cracks in the ice sheet creating local stress distributions in the ice cover? Is the inherent variability in the values of K (equation 1) and Young's modulus creating stress variability and/or distorting our analyses? Does the ice's structural variability create non-linear vertical stress distributions in space and time? Is reservoir geometry important?

With respect to forces generated by ice jacking, what controls the amount of ice that can freeze in the shore-perimeter cracks? Do thermodynamic processes (sublimation, condensation, etc.) cause the water in the fissures to freeze at different rates on different surfaces at different times of the day and night? Are local variations in bank slope controlling fissure opening? Does the fact that the fissure is not perfectly straight lead to unevenly distributed forces at the dam face?

Questions also arise as to load redistribution and/or load transfer mechanisms. We have already alluded to the fact that the bottom of the ice sheet may be in tension while the top is in compression (or vice versa). We have also alluded to the fact that loads may be transferred differently once tension cracks form. Here, one must really think in three dimensions. It is quite easy for a beam to bend because of a change in thermal gradient over its thickness. It is quite another thing for a plate to hump up because of a local increase in thermal gradient. The beam has so much freedom to adjust to the differential expansion over its thickness whereas the plate has virtually none. (Try bending a book in two dimensions at once.).

Carter et al. (1998) points out that the maximum load on a structure depends upon (1) the load generating mechanism (e.g., wind, currents, thermal expansion, tidal jacking etc.) and (2) the capacity of the medium (i.e., ice sheet) to transfer that load without failure. As such he investigated the maximum load that can be transferred from the sheet to the dam wall before the sheet fails through *flexure* and through *buckling*. Their ultimate force equations are based on these values because he reasons that it is very difficult to foresee all the load generation mechanisms that could conspire to create all the possible load frequencies and intensities. Their calculations take into account the presence of multiple parallel fissures in the ice sheet running along dam face. The resulting loads are shown to be proportional to ice thickness (to some power depending on the type of failure). However, one could ask of this: what ice thickness is most important? Is it the ice thickness at the time that the cracks form, or the ultimate thickness that the ice cover attains by the end of the winter? Furthermore, ice thickness has a marked gradient with respect to distance from the dam face. For example, the ice thickness at Beaumont in late February are of 105 cm at 0,5 m from the dam face, 62 cm at 2 m and 37 cm at 20 m. In addition to this gradient in thickness, there is also a marked gradient in ice type that would cause the ice to buckle and flex at different stress levels as a function of distance from the dam face.

Given that Carter et al.'s analyses are one dimensional (i.e., a beam analysis), Carter states (personal communication, 2007) that there is the indentation phenomenon that could be taken into account when designing for wider areas. What is causing the variability of pressures at the dam face? There may be sensor placement related issues (e.g., sensors causing non-straight fissures – see figure 3); there may be thermal piping issues that provide false readings and there may be ice contact issues. However, if the data is representative of real processes taking place at the interface between the ice and the dam, one can only wonder what the processes might be. Why will one gauge record pressures of 200 kPa while those 4 meters to the left and right register pressures half or a quarter of that value? Surely it must have something to do with how stresses are transferred through the fissures near the dam – a phenomenon which is extremely hard to qualify. Perhaps there exist points of contact which are more competent than others, leading to variations in the contact area or crushing strength of ice in front of some gauges. Perhaps the low strain rate of most contact events leads to variations in how the ice sheet accommodates stress. Perhaps that portion of the ice sheet which adheres to the dam face applies a moment arm to the gauge, thereby increasing load as a function of ice width (figure 3).

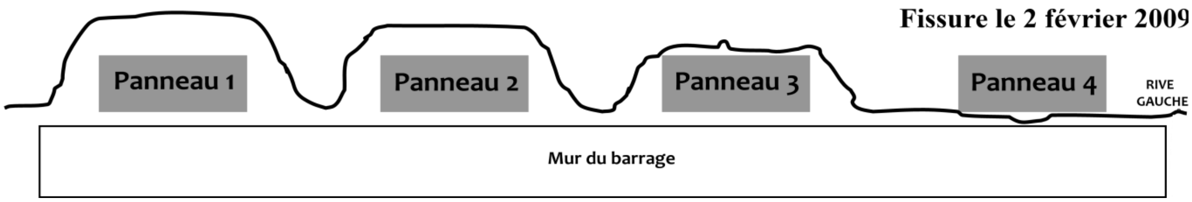


Figure 3. Fissure in front of four measurement panels hung along the LaGabelle dam 2nd Feb. 2009.

Consider the profile of fissures described in figure 4. As ice interacts with the opening and closing crack, they tend to develop a rounded and tapered shape. In this geometry, the force of the entire ice sheet must pass through a small area limited horizontally by points of contact depicted in figure 3 but also limited vertically by the reduced area caused by the tapering and rounding at the contact surface (figure 4).

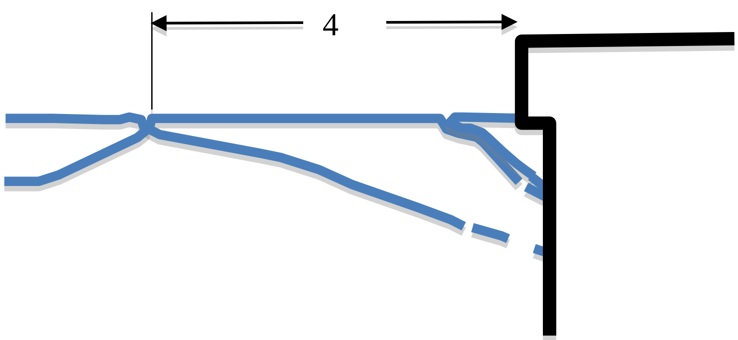


Figure 4. Profile of ice sheet in front of the Beaumont dam 2010. (The ice was 61 cm thick at a distance of 2 m from the dam face.)

Consider also that the stresses may well be limited by the rates of displacement in the ice sheet because changes in strain are relatively slow and at those strain rates, the Glen and Newton creep equations (1) suggest that stress is proportional to the strain rate (to a power – about 0.33 according to Glen and about 1 according to Newtonian creep observed by Song). A high local stress at the hinge would accommodate a very significant strain rate when compared with the rest of the sheet that is at a lower stress. Note too that the hinge would undergo significant pre-stressing and therefore the Newtonian creep may govern more than Glen-type creep.

Is this the governing ultimate unit force mechanism? Consider further that the hinge is surrounded by water and that its temperature must therefore be close to zero degrees. Pfaff (1985) and others have shown that ice flows readily near its point of fusion. Add all these effects up, integrate over a small thickness and forces don't add up to much.

Ice stresses fluctuate much more near the dam (within the first few meters) than they do at distance from the dam (Stander, 2006 and figure 2 above). This observation supports the view that stresses are generated by the interplay of local boundary conditions at ice fissures under the influence of water level fluctuations. Far from the dam, the ice moves freely with changes in water level (Morse et al. 2009), while near the dam its movement is constrained by the presence of ice adhering to the dam face (“bellycatter”). As the ice sheet is so constrained, it develops stresses that vary at the same frequency as the changes in water levels.

What is not as easily explained is the general decrease in the maximum (horizontal) unit forces in the ice sheet as a function of distance from the dam. For example, at the Beaumont dam in the winter of 2009, the peak maximum stress measured by 12” biaxial ‘Geokon’ gauges (Cox and Johnson, 1984, Stander 2006) placed at 0.2 m from the dam was 630 kPa whereas the maximum measured stresses (measured by 4” biaxial gauges) at 3 m, 15 m and 29 m were 290 kPa, 330 kPa and 200 kPa respectively.

When integrated over the ice thickness, the maximum unit forces calculated at 0.2 m, 3 m and 29 m distances (no integration was possible at 15 m) were 550 kN/m, 160 kN/m and 70 kN/m respectively for biaxial gauges (Bisanswa, 2011). Similar differences between ice load near the dam and far away were observed in 2008 using measurement panels at the dam face and at 20 m (Taras et al., 2009). Ice load obtained by BP gauges were small in amplitude (30 kN/m) and showed smaller variations between measurements taken at 5 m and 20 m from the dam. These measurements were taken for winter with heavy snowfall and small ice temperature changes.

How can one explain this tendency of a diminished line load as a function of distance from the dam? It seems to recur every year at all locations. Does Newton’s law not imply that there must be an equilibrium of forces (given that there is virtually no acceleration)? Is the difference in force values transferred (through shear) to the reservoir banks? Preliminary calculations suggest that the ice is not stiff enough for this explanation to be valid (Lupien, personal communication, 2008). So where is the force going? Is this due to a plastic accommodation of stress within the ice structure, or a failure of basic physical laws?

DISCUSSION

Harmonizing design criteria based on historical measurements made by Carter, Stander and Comfort (among others) is not as easily as we imagined it would be. We must, in the end, answer the following questions:

1. How reliable and accurate are each of the sensors and under what operating conditions are they so (e.g., ice temperature, ice type, stress directions, etc.)?
2. What kinds of fissures exist, and where and when does each geometry appear? What kinds of hinges result and what are their properties (e.g., dimensions, vertical roundness and shape, horizontal uniformity, presence of stress points, temperature, elastic and plastic moduli)?
3. How are stress and strain related in different ice types at different temperatures, stresses, time histories and loading rates?
4. Regarding ice jacking, how fast do fissures freeze in with ice? How thick is the freezing-in process?
5. What are the optimal conditions whereby ice expands (causing a compressive load) but still remains cold enough to support large forces without too much plastic deformation?

6. What is ultimately, the governing process that limits the ultimate forces? Is it environmental? Mechanical failure? Plastic deformation at stress point locations? Speed and amplitude of water level changes in the reservoir? Ice flooding and thickening near the dam face?
7. From the measured data, what methodology should be used by extrapolation (statistical as Comfort et al. or deterministic failure analysis as Carter 1998) to obtain design load conditions?
8. How should one incorporate indentation effects along the dam face in the design criteria?

CONCLUSION

There is still more work to be done. We have deployed a number of gauges at two dams in Ontario this winter (2011) at Barrett Chute and Arnprior. We are also continuing laboratory measurements of the plastic properties of ice at high temperatures and the modelling of inclusion effects of gauges in the ice. Hopefully, this additional work will allow us to make further progress towards answering some of these questions.

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