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Ice interactions at a dam face

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A Laval University is co-operating with Hydro-Québec on a research project known as "Ice forces on dams: Harmonizing Design Criteria and Developing Means for Mitigation". This paper introduces the project and explores some of the preliminary results of the 2007-2008 field season.

Ice displacement, ice stresses and ice forces on the LaGabelle dam were measured at a number of locations. This paper presents the complex linkages between data sets and discusses the spatial-temporal variability of the ice forces and its impact on design criteria.

1. **Background**

Given the mature age of most Canadian hydraulic structures, many dams will be replaced or repaired over the next few decades. Ever since the 1995 Saguenay dam failures and resulting flood, there is an increased awareness of the need for safe design practices (Tchamen et al., 2007). Whereas recent studies (Carter et al. 1998 and Comfort et al. 2003) indicate that ice forces could be well above those recommended by the Canadian Dam Association (150kN/m), some public agencies have, in some cases, actually reduced their design values for smaller dams to 100 kN/m. If these dams are truly unsafe, mitigation measures should be defined and applied as soon as possible. On the other hand, should ice forces not present a safety risk (as is suggested by the fact that no known dam has failed in this manner), then investing in dam reinforcement may be a misuse of public funds. Thus, it is important to know what constitutes a safe, realistic and practical design value for ice thrust against linear structures. To respond to this need, Université Laval and Hydro-Québec have embarked on a 4 year project to determine reservoir ice forces on dams. This article presents some preliminary results from data obtained during the first year of observations (January – March 2008) at the LaGabelle.

2. Project Objectives

The objective is to develop design criteria for ice forces on dams and to provide a scientific basis for interpreting and harmonizing existing recommended criteria.

3. Methodology

The project is based on carrying out new field work using many instruments simultaneously:

- Different reservoirs have been monitored (one in 2008, two in 2008-2009 and more to come in the subsequent years).
- In situ strain within the ice sheet was measured using digital photography (successfully in 2008 & 2009 and using a robotic total station (successfully in 2009 only). These strain rates are then converted into potential in situ stresses.
- In situ stress within the ice sheet was measured using different gauges (two types of flat jack gauges and two sizes of biaxial gauges).
- Forces against the dam were measured using panel gauges.
- A series of time lapse photos of ice movement near the dam was obtained.

4. Site description

The 2008 site presented in this paper (Figure 1) is the LaGabelle dam located near Shawinigan, QC, Canada (46.4497°, -72.7385°). This is an ideal site since it is easily accessible, it maintains a constant average water level and there are water level fluctuations (due to hydro power peaking) that are about equal in range to the local ice thickness (0.5 m). The layout of the dam is detailed in previous studies : Starting from the right bank, there is a spillway (ungated (150 m wide) and gated (140 m wide) both having piers that retain the ice sheet); a hydro power section (130 m wide) with multiple water intakes located a significant depth below the ice cover; and a gravity dam section (80 m). The central part (42 m wide) of the gravity dam section was instrumented with 12 panel gauges.

The ice sheet was already about 20 cm thick on December 22nd (at 220 degree-days) when some 5 survey poles were inserted in the ice in a line perpendicular to the gravity dam (Figure 2) opposite gauge no. 12 (at X = 5 m in reference to Figure 7). At that time, there was virtually no snow on the ice. Over the next 40 days, 110 cm snow fell and on January 31st (at 520 deree-days), the ice sheet was 43 cm thick and was covered with very little snow. On February 1st, there was a severe snow fall (52 cm) that drowned the ice sheet and eventually led to the formation of 8 additional cm of snow ice. Then, after subsequent snow falls (total of 68 cm), a second 8-cm layer of snow ice formed and overlaid a slush layer about 8 cm thick (as measured on February 21st corresponding to 720 degree-days). Snow falls resumed starting on February 26th and an additional 26-cm layer of snow ice eventually formed over an additional 18-cm layer of slush as measured on March 18th when all instruments were finally retrieved.

5. Results

5.1. Observation of vertical ice movement.

On December 22nd 2007, we vertically planted six florescent poles in the ice and marked them with a grey piece of duct tape at a distance of 1.4 m above the ice surface. We then installed a Canon 20D camera on the dam that took a photo of the poles every 10 minutes. We lost all photographic data taken prior to January 15th, 2008. By that time the 5th pole had disappeared through a crack in the ice that had opened up at exactly that spot. So, in fact, the camera tracked only 4 poles through March 11th 2008.

The time lapse photos were made into two AVI video files (that will be displayed during the conference). The first shows the movement of all four poles as the water level fluctuates over time. The poles can be seen to go up and down with the changes in water level and can also be seen to rotate as the ice the near the dam face is confined in its upward vertical movement by the presence of a ballicatter. The second video is a zoom of the first pole and the ice-structure interface dynamics. This video shows a solid fixed wedge of ice frozen to the dam (i.e. “ballicatter”) that is probably about 0.6 to 1.0 m deep at the dam face and 0.6 to 1.0 m wide at the ice surface. It also shows the ice sheet going up and down relative to the ballicater. As the sheet goes up and down, it rotates and flexes. At low water levels, a 10 cm fissure is present near the bellicater (at Y = 1.0 m). As the water level increases, so does the contact between the main ice sheet and the ballicater. At high water elevations, the fissure closes completely as the ice sheet rotates and forces against the dam increase (Figure 3). Also present on the photographs are the development of two other fissures (see Figure 2) although these were not as visible since the cracks were rarely visible.

In addition to the visual interpretation of the videos, the movement of each pole was digitized and rectified. Thus the angle of the pole with respect to the vertical was also obtained. This angle was then used to quantify the rotation of the ice sheet (Figure 3).

Figure 4 presents the water level and ice level fluctuations from the 20th to the 27th of February 2008 as related to a local datum (31.6 m above the permanent datum). The water level fluctuates between -0.3 m and -0.9 m. The fluctuations were due to hydro peaking operations and occurred over time periods as small as 5 hours. This is a value that is typically four times faster than thermal expansions within the ice sheet. Also included in figure 4 are the fluctuations of the four poles inserted in the ice sheet at various distances from the dam face. The poles are frozen into the ice cover and their vertical movement represents the vertical movement of the ice sheet. In general, poles B, C and D move up and down in sync with the vertical movement of the water level because the ice sheet floats on the water. However, they do not track the water level exactly because the ice is attached to the dam through a series of hinges. Although vertical fluctuation of the ice at pole A (situated only 1.5 m from the dam face) is obviously related to the changes in water levels, one can readily see that its vertical movement is confined to about 20 cm. This means that the ice sheet has some degree of vertical mobility but it is vertically limited. Therefore upward thrusts on the bellicatter can be developed resulting in compressive and tensile pressures of about 10 kPa. Also of interest, the tracking of the vertical motion of the poles shows the build up of snow and snow-ice over time. Between January 15th and March 9th, the ice at poles B, C and D got weighed down by about 90 cm whereas the ice at the dam (pole A) got weighed down by about 50 cm (Figure 5).

5.2 Horizontal ice movement

Figure 6 presents the lateral (horizontal) movement of the poles at their initial point of intersection with the ice. The image shows that there are hourly and daily fluctuations related to changes in water levels related to hydro peaking operations. In addition, there are long term movements of poles B, C and D that must be explained by the every increasing inclusion of water freezing within the cracks as they open and close. Note that most of the increase in distance from the dam occurs between poles B and the dam. From January 15th through February 18th, the movement was a mere 5 cm. On February 18th, a new crack seemed to have developed in the ice sheet between poles A and B. From that day to March 3rd, the ice sheet moved an additional 13 cm. This represents an average strain rate of 0.13m/(3.4-1.5m)/(14days*86400 s/day) = .05E-06s^{-1}. The following is relationship between stress and strain rate appropriate for the ductile range for ice at -2° C is (Barnes et al., 1971 as presented by Hallam, 1986):

$$\sigma(\text{kPa}) = 73000\left(\dot{\varepsilon}\right)^{0.3045} \quad (1)$$

This results in an average stress of 430 kPa and therefore an average push on the dam from the 0.5 m thick ice sheet of 210 kN/m. Figure 7 presents the strain rate calculated over a 6 hour period for the February 20th to 27th. The maximum value of 1.54 E-06 s^{-1} occurred between poles A and B at 5:00 on February 21st. The associated stress is 1200 kPa and the resulting force on the dam from a 0.5 m ice sheet is 600 kN/m. Between poles BC and CD, strains were 0.51 and 0.38E-06 s^{-1}. The associated stresses expected to see within the ice sheet are 890 and 810 kPa respectively corresponding to forces of 450 and 400 kN/m respectively . The actual maximum stresses observed against the dam at the panel no. 12 (situated in front of the poles) was 367 kPa.

Figure 8 plots the average stresses in the ice sheet between each of the adjacent poles (i.e., the average of the stresses between AB, BC and CD) based on strain rates calculated over a six hour period and using equation 1. Also plotted is the maximum registered ice stress on panel no. 12 situated in front of the poles. Maximum recorded stresses against the dam at panel no. 12 are typically 2.5 times less than the average nominal stress in the ice sheet.

Obviously, the nominal stresses calculated for the ice sheet are significantly higher than those measured at the dam face. There are many possible reasons for this including: (1) The strain rates are calculated over a 6 hour period. This period was chosen because water levels did fluctuate over a six hour period. However, the fastest strain rates certainly occurred when fissures are open and therefore were no stresses in the ice. (2) Considering the equilibrium of forces, the stresses ice in the bellicatter passed onto the dam are dependent on the contact area. (3) The ice temperature may have been higher than -2° C and therefore the constant in equation (1) could be over-estimated for actual field conditions; and (4) There is an indentation effect that may diffuse any peak loads.

To further show the connections between ice movement forces near the dam, Figure 9 presents the strain rates along with the data collected by a biaxial gauge no. 29273 placed at a depth of 31 cm from the ice surface. The gauge is located some 13 m from the dam face and some 12 m to the east of the poles (Figure 1). The cylindrical biaxial gauges are 10 cm long and 5 cm in diameter. They are placed vertically in the ice sheet in order to pick up lateral ice stresses (Stander 2006).

On February 20-21st, despite significant strain rates, the biaxial sensor picked up virtually no stresses in the ice sheet. At first this would seem unusual since the gauge is only 12 m further along the dam. However, one of the main findings of the field study is that stresses and strains vary very widely over very short distances. From noon to 16:00 on February 22nd, there is an event when data from different instruments are in sync. Stresses calculated from the pole movement using equation (1) rise up to 480 kPa, the mean stress observed at Panel no. 12 against the dam rises to 48 kPa and the biaxial gauge rises to a value of 28 kPa. The fact that the timing of the response from all the gauges is near-perfect shows the linkages in the ice processes. The fact that the biaxial gauge shows stresses 60% of those found against the dam is in general agreement with previous findings. The most important event occurred on February 25th when maximum average stress against the panel was 150 kPa and the maximum stress in the biaxial gauge was 100 kPa. On the surface, the average strain rate data did not show any significant stresses. However, when looking at the individual movement between the poles, the strain rates were very significant at that time.

5.3 Ice forces on the dam

There were 12 panel gauges placed against the dam. Each panel has four flatjack sensors welded to it where individual readings are taken. The panels are placed in the ice such that the top flatjack is just below the ice surface. Figure 3 shows the average force on the dam integrated over the four gauges and the12 panels. From February 20th until the 26th, the forces built up and reached a maximum of 92 kN/m. From that time, the maximum forces gradually fell until March 9th 2008. Of interest is the spatial heterogeneity of the ice forces on the dam wall. At any given time, some flatjacks will register stresses whereas others, only cm (vertically) meters (horizontally) away, will register none (Figure 10). In the figure, the top of the ice is at an elevation of 31.9 m. Stresses recorded on the flatjacks near the ice surface are the greatest. Very small stresses are recorded on the second and third flatjacks. Virtually no stresses are recorded on the fourth flatjack (that may have been in water). Horizontal variability is also present. Pressures are great at the panels situated at -10 and -30 m (from a local reference point) whereas virtually no stresses were recorded on the panels near -15 to -20 m. (Note that on the figure, flatjacks on panels are located at the intersection of each of the internal grid lines drawn). Note that Figure 10 shows that the water level is near its peak at this time.

This ever-changing spatial-temporal distribution has many implications since it demonstrates that ice connectivity is always shifting. As a result, the estimated maximum average unit force on the dam (92 kN/m estimated from our 12 panels) could be significantly over- or under-estimated if there are insufficient panels to know how the loads are distributed. For example, if only 1 panel was placed on the dam, depending on its location, it would have measured no force at all or it may have measured a peak value of 180 kN/m. Had 5 panels been placed on the dam, depending on their location, the estimated maximum force would have varied between 25 to 160 kN/m. For 9 panels, it would have been between 70 and 120 kN/m.

Conclusions

This study demonstrated that the ice processes in a reservoir near a dam face subject to water fluctuations are very complex. As such, in order to know the real average pressure on the dam, a significant amount of panels are required. This has important implications for determining safe design values. The study also demonstrated the linkages between strain rates and stresses in the ice measured and against the dam face. At times, there was an obvious strong correlation while at other times there was none. The research program is continuing and we look forward to validating the preliminary data presented here and providing results from subsequent field campaigns and from numerical modelling efforts.

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Figure 1. Location of LaGabelle dam on the St. Maurice River (Google Earth)

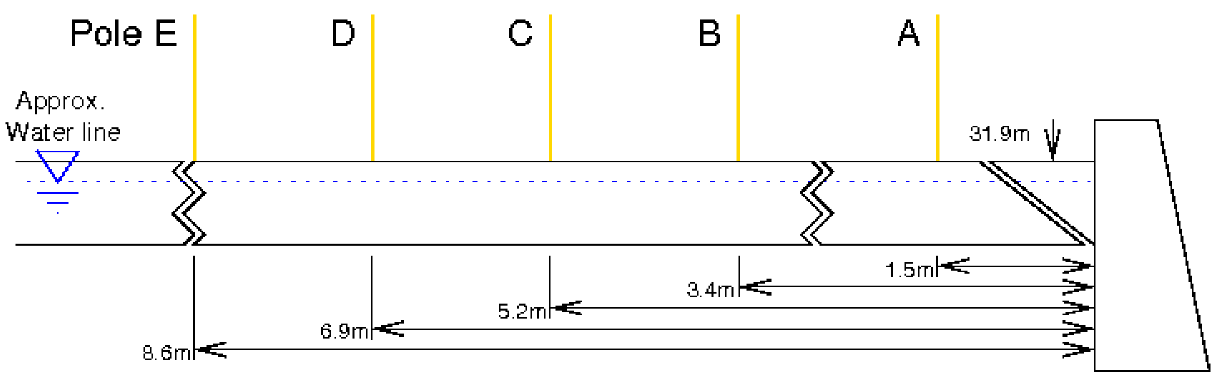

Figure 2. Location of poles placed in the ice perpendicular to dam face
(Note 1-m wide bellicatter frozen to the dam and separated from the ice sheet by a crack that could open as much as 10 cm. No major gaps were observed at the two other cracks that formed hinges in the ice sheet that facilitated its vertical movement.)

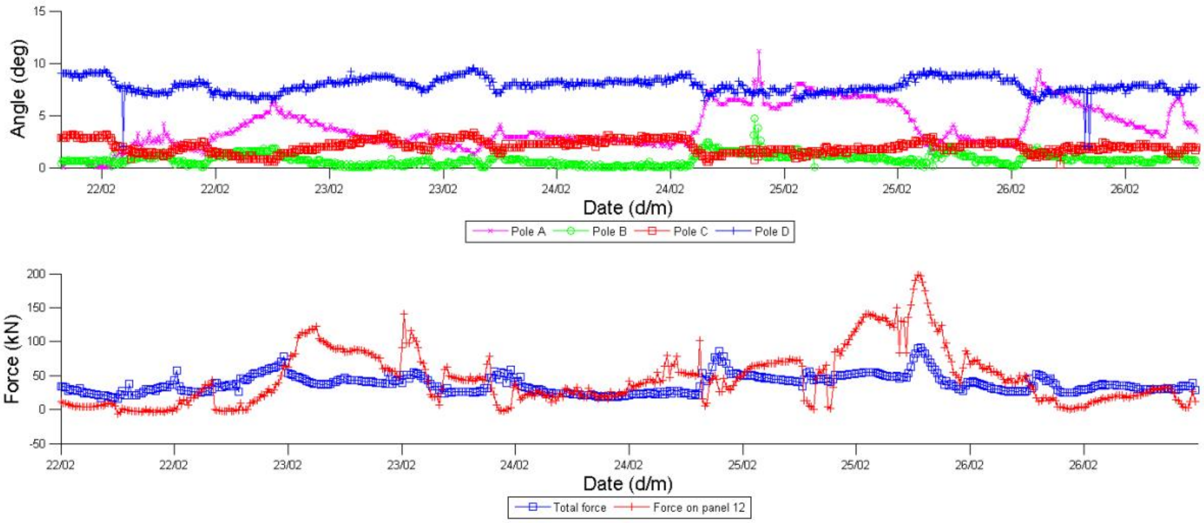

Figure 3. Rotation of poles and resulting force on dam (opposite poles at panel no. 12 at X = 5 m) and total average force from 12 panels (from X = -5 to 37 m)

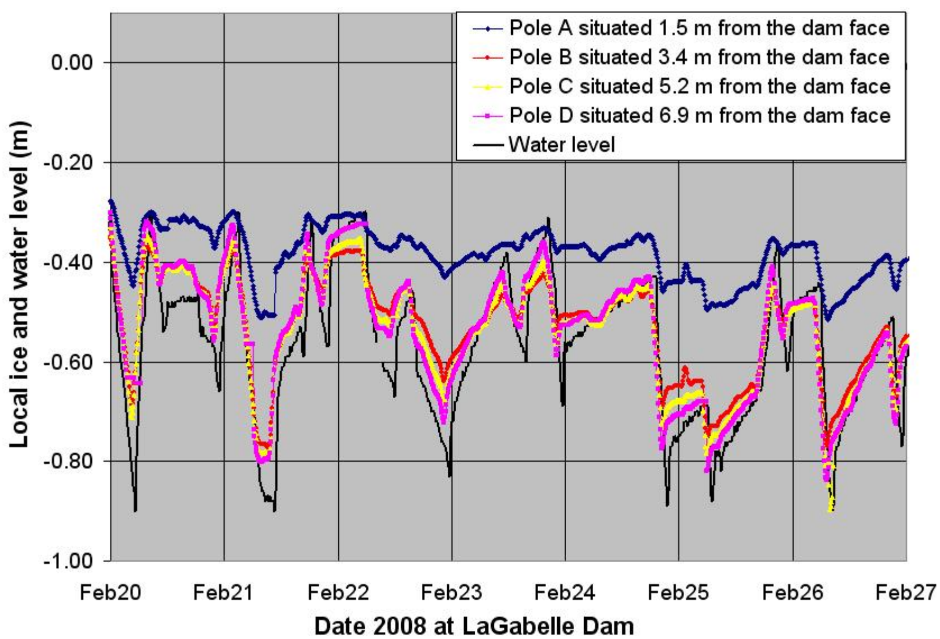

Figure 4 - Poles vertical displacement and water level fluctuation

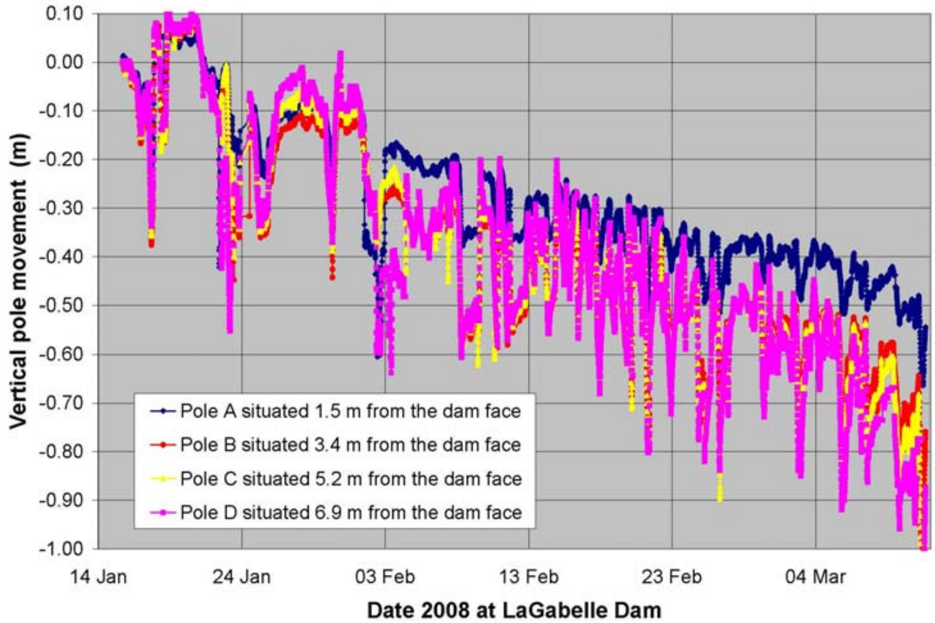

Figure 5. Vertical movement of poles from January to March 2008

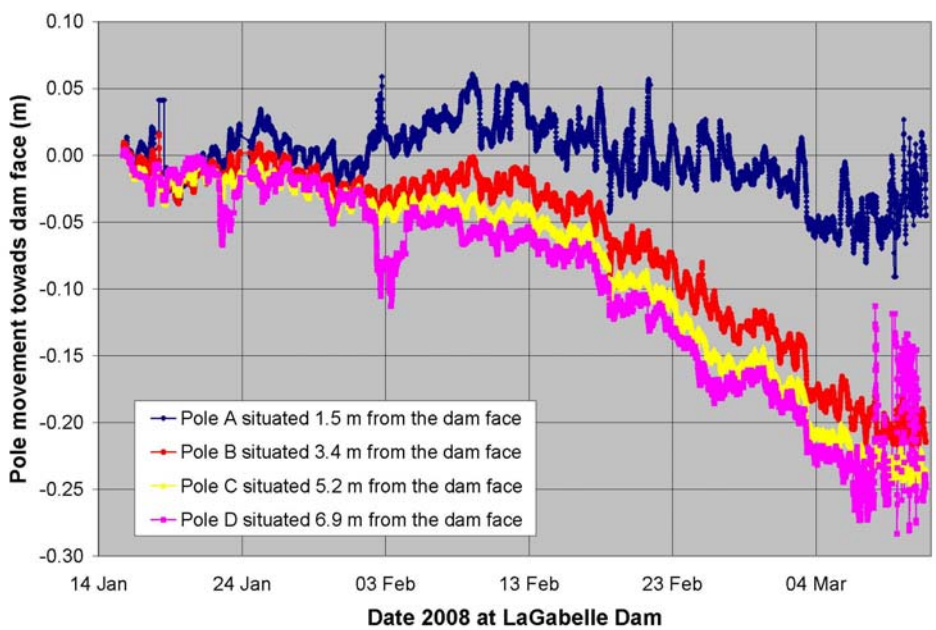

Figure 6 - Lateral displacement of ice sheet

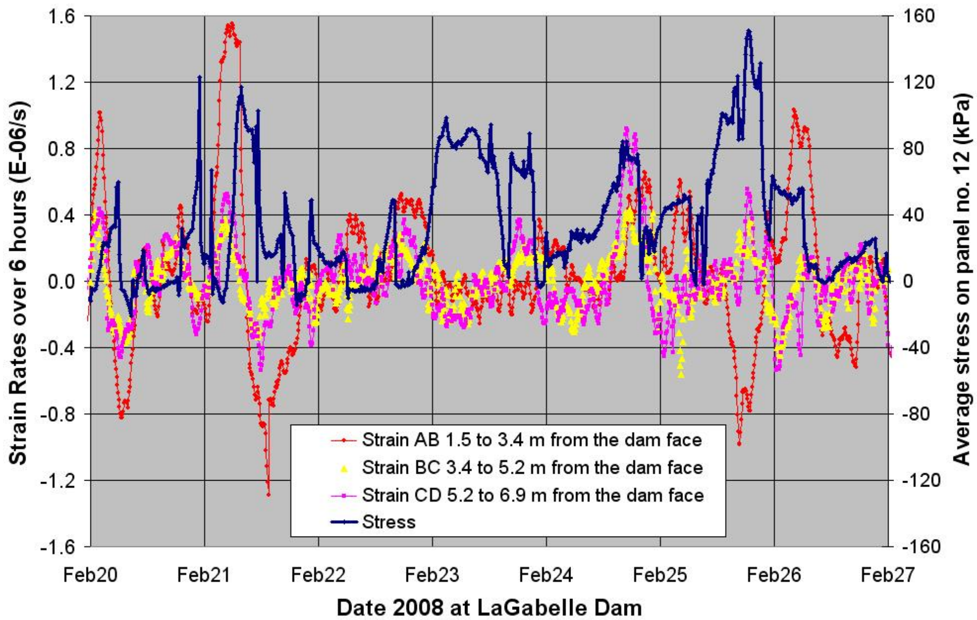

Figure 7 – Strain rate between poles and measured maximum stress against dam face

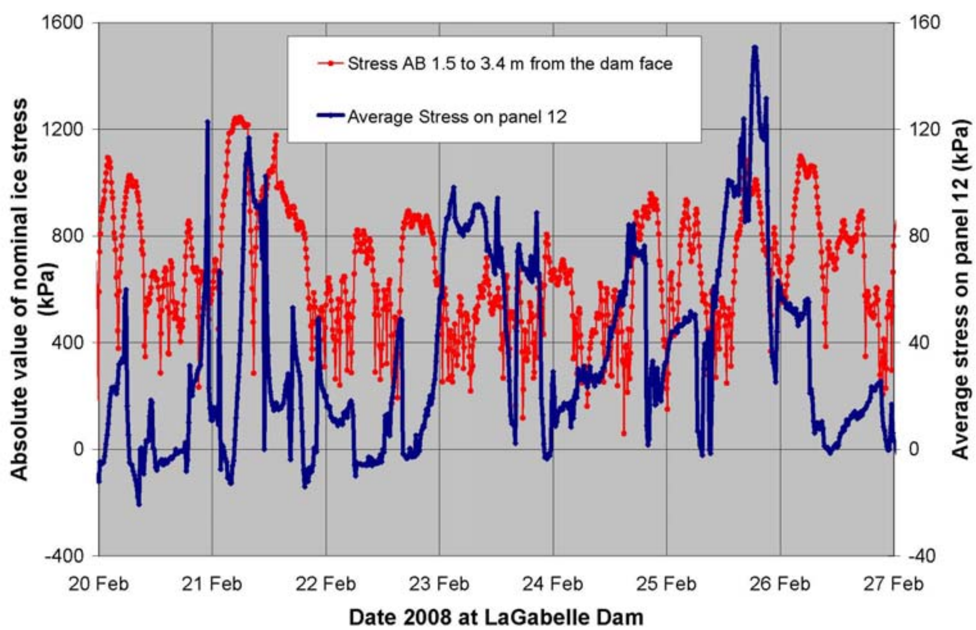

Figure 8 – Stress between adjacent poles and average stress measured at Panel no. 12

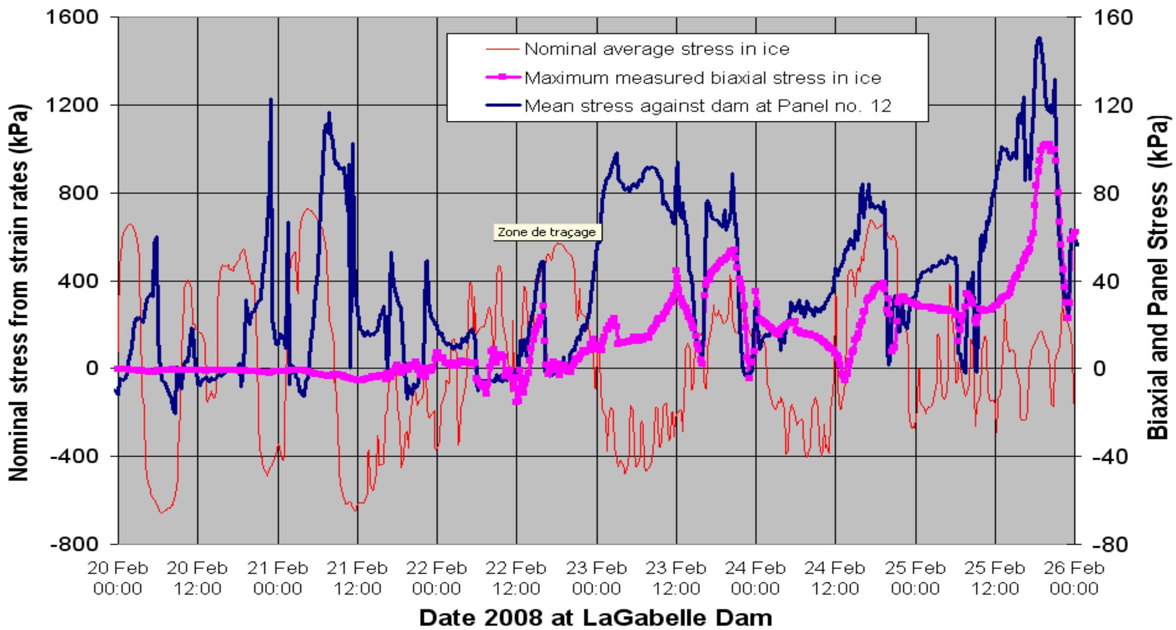

Figure 9. Comparison of stresses in the ice (from strain rates and biaxial gauges) and against dam face (at panel no. 12)

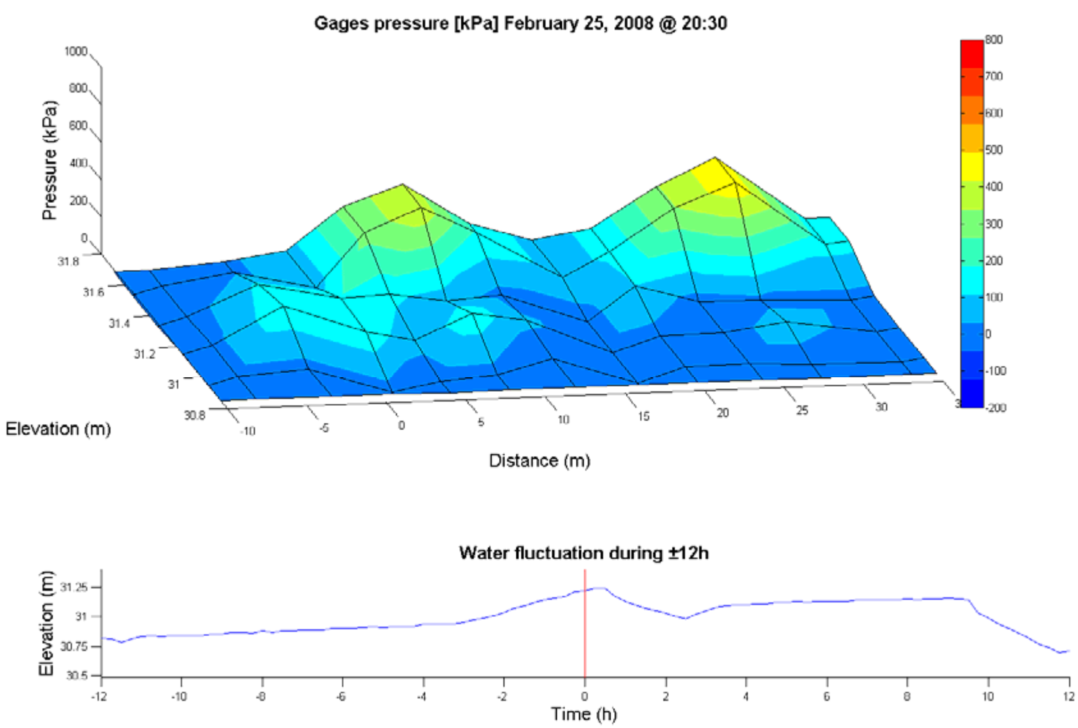

Figure 10 - Three dimensional snapshot of ice stress on dam