23rd IAHR International Symposium on Ice
Ann Arbor, Michigan, USA, May 31 to June 3, 2016

Observations of Ice Stress at Taraldsvikfossen Reservoir, Narvik, Norway, 2014/15

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From October 2014 to June 2015, ice stress was measured at Taraldsvikfossen reservoir in Narvik, Norway. Three frames composed of five stress sensors placed vertically at 0.15 m intervals were attached to the dam 6.0 m apart. During this time, compressive and to a lesser degree tensile stresses were observed primarily in the range of ±100 kPa. However, measurements exceeded this range on several occasions. The magnitude and timing of the peaks in stress depended on vertical position with the upper three sensors often displaying opposite behavior of the lower two sensors. We analyze two main events of high stress to determine the likely cause and enhance our understanding of the ice dynamics exhibited. The influences of water pressure and ice temperature are examined in depth to delineate between mechanical and thermal stresses during each event. Our findings demonstrate the strong influence of loading due to mechanical processes with the fracture of ice and flooding of the ice surface represented clearly in the data. The challenges that exist in modeling and predicting ice loading are discussed alongside considerations to be taken into account for data interpretation and further measurements.

ISSN: 2414-6331

1. Introduction

With upwards of 95% of electricity in Norway coming from hydropower, the monitoring and maintenance of the many dams located across the country is necessary to ensure their structural integrity and longevity. A mountainous topography enables the hydraulic head of Norwegian dams to be generated from large drops in elevation over a short distance (NVE, 2003). Reservoirs are typically small in size having a low concrete dam less than 15 m in height. For low dams the governing load case when assessing stability, i.e. overturning and sliding, will almost always be highest regulated water level combined with ice pressure. This is because the latter represents a very high percentage of the total load in comparison to larger dams where water pressure, uplift and dam weight are the major loads.

Prior to the 1980s, technical standards and good engineering practice formed the basis of dam design and safety with no in situ field measurements of ice stress available to incorporate into regulations (ICOLD, 2015). In the years following, measurements were obtained largely at small dams in Canada with a few measurements of ice stresses also being gathered in northern Norway (Hoseth and Fransson, 1999; Petrich et al., 2014; 2015). With the newest update to Norwegian regulations concerning dam safety in 2010, greater focus is now being placed on ice stress and its impact on dams leading to a need to further add to these measurements (Gebre et al., 2013).

Since 2012, ice stresses have been measured at Taraldsvikfossen reservoir located in Narvik, Norway (Petrich et al., 2014; 2015). Similar to earlier observations in Canada (Comfort et al., 2003; Stander, 2006), it became evident from the first three years of data that various effects resulted in stresses, including thermal expansion and water level fluctuations, and that the relative dominance of the processes varied between seasons. The aim of 2014-2015 season was to obtain a detailed vertical stress profile at the dam to determine line loads. In this study, the origin of stresses is analyzed. Results reveal depth-dependent behavior in the ice and a non-trivial response to primarily mechanical loading.

2. Methods

Taraldsviksfossen Reservoir is a small reservoir of approximately 1650 m^2 located 212 meters above sea level in the town of Narvik, Norway. Confined by a straight sided concrete dam 6 m in height, it is maintained to provide a backup water supply and not regulated (Fig. 1a). The reservoir is fed by Taraldsvikelva, a creek which flows much of the year and keeps water levels in the reservoir at that of the spillway. In winter, the creek freezes limiting the flow into the reservoir significantly. Given its relatively stable water level and accessibility, ice stress measurements were performed at Taraldsviksfossen Reservoir.

We installed five frames with stress sensors along the eastern wall of the dam 6 m apart on 3 October 2014 (Fig. 1). Stress was recorded using custom modified GeoKon 4850 pressure cells consisting of two rectangular steel plates (100 mm x 200 mm) separated by de-aired oil. In addition to stress, each cell measured temperature. Three frames (B, C, D) held five cells placed 0.15 m vertically apart (center-to-center) with the center of the uppermost cell placed 0.075 m

ISSN: 2414-6331

above the nominal water line. The other two frames (A, E) held one cell each with the center placed 0.075 m below the surface. Cells are designed to measure normal compressive stresses up to 1 MPa. We also installed a weather station and water pressure sensor. A detailed description of the setup is given by Petrich et al. (2015). To provide photos of the reservoir at 30 minute intervals, we mounted two UM562 trail cameras at the locations indicated in Fig. 1. All instruments were connected to a CR1000 data logger stored inside the maintenance hut. The logger and both cameras transmitted data and photos through a GPRS link. Measurements of stress are available at http://www.ndat.no/dam while photos have been combined to create a timelapse video of Taraladsvikfossen Reservoir available online at https://www.youtube.com/watch?v=vdO74tNzyVw.

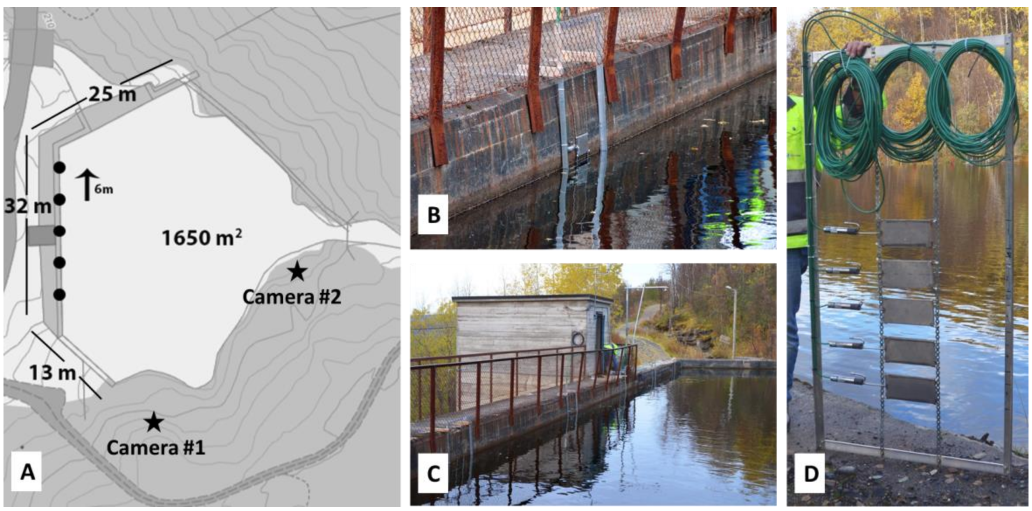

Figure 1. a) Diagram of reservoir including position of frames (circles) and cameras. The primary wall of the dam is 32 m in length while the spillway takes up most of the 25 m long wall. b) Placement of frame B showing position of uppermost sensor in relation to water line c) Position of all frames along dam face d) Frame before installation

To model thermal stresses in the ice, we used the approach of Bergdahl (1978). The relatively simple model predicts a change in ice stress (dσ) as function of a change in ice temperature (T) with time (t). We follow Petrich et al. (2015) and use

$$\frac{d\sigma}{dt} = A\left(\frac{dT}{dt}\right) - \mathrm{sign}(\sigma)\left(\frac{T_1}{T}\right)^m * Bk\left(\frac{|\sigma|}{\sigma_0}\right)^n \qquad [1]$$

where σ_0=100 kPa, T_1= -1 ^{0}C, m=1.92, k=2 , A=200 kPa/^{0}C, B=27 kPa/day and n=3.7. Compressive stresses are positive in this study.

3. Results

During the 2014-2015 season, five events occurred where stress rose quickly from values near to 0 kPa to above 100 kPa. Here we focus on the two largest events to analyze the influence of mechanical and thermal loading. Measurements from only one frame are presented for brevity.

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In most cases, stresses recorded at frames C and D were similar to the stresses at frame B but sometimes differing in magnitude.

3.1. Event 1

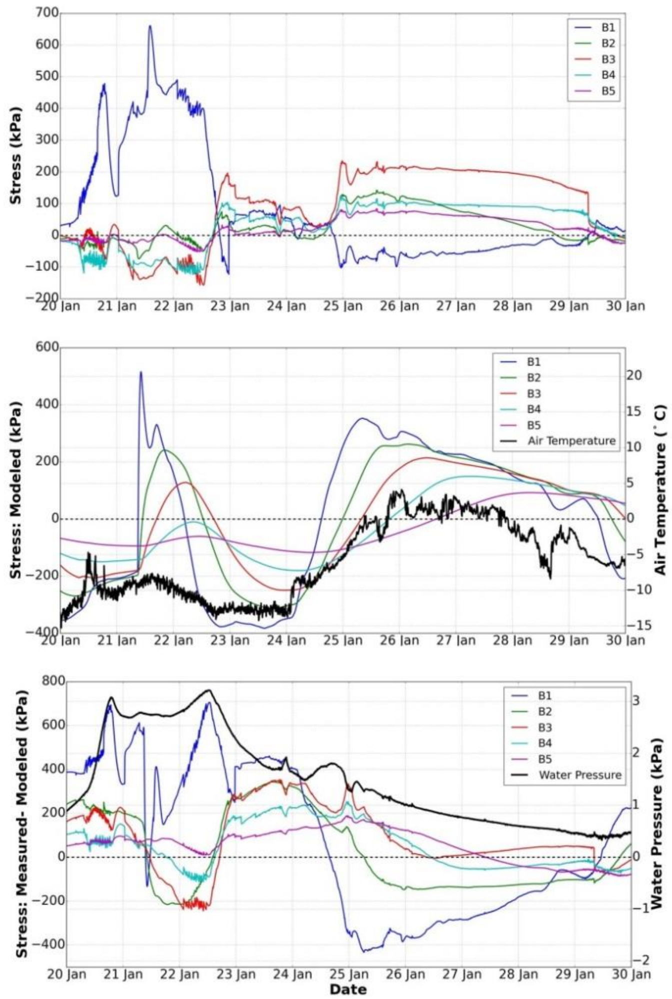

Figure 2. a) Stress measured in cells B1 through B5 from 20 – 30 Jan. b) Air temperature and predicted thermal stress using Equation 1 c) Water pressure and calculated difference between measured stress and modeled thermal stress.

Measurements are presented in Fig. 2. The fluctuations in stress observed between 20 and 30 Jan can be divided into three separate subevents:

20–22 Jan: Upward bending, fracture and partial flooding. Major stresses exceeding 700 kPa were recorded by cell B1 with a notable dip around midnight of 21 Jan (Fig. 2a). About 10 hours later, local ice temperatures increased toward 0 °C while air temperature remained around -10 °C (Fig 2b). This ice temperature increase resulted from surface flooding limited to the perimeter of the ice cover (cf. description by Petrich et al. (2014)) and is not representative for the entire ice cover. Peaks in the residual stress of cell B1, i.e. measured stress reduced by modeled thermal

 ISSN: 2414-6331

stress, line up in time with peaks registered by the water pressure sensor on 20 and 22 Jan (Fig 2c). Stresses recorded during this episode are most likely due to water level changes that induced bending stresses. Ice fracture may have resulted from tensile forces due to bending in the presence of low temperatures.

23–25 Jan: Insensitivity to temperature increase. The stresses registered in B1 disappear at about the same time the water pressure starts to decrease (Fig. 2a). Around midnight of 24 Jan, onset of snowfall and increased air temperatures led to higher ice temperatures and a predicted thermal stress (Fig. 2b) that has not been measured (Fig. 2a). However, on 24 Jan, cell B3 showed a temporary decrease in stress (Fig. 2a) that corresponds to a brief increase in water pressure (Fig. 2c). It appears the appearance of generally low stresses during this period is due to generally constant but slightly decreasing water pressure. At the same time, ice temperature increase did not result in thermal stresses at the dam, possibly due to cracks forming in subevent 1.

25–30 Jan: Downward bending. Shortly before midnight of 25 Jan, cell B1 started to register tensile stresses while all other cells, in particular B3, started to register increased compressive stresses (Fig. 2a). This is approximately the opposite of what had been observed from 20 to 22 Jan. Predicted thermal stresses (Fig. 2b) and observed water pressure (Fig. 2c) were gradually decreasing throughout this period, generally consistent with stresses relaxing toward 0 (Fig. 2a). The vertical stress profile in this period appears to correspond to ice bending downward due to decreasing water pressure. The highest ice stresses were recorded in the middle of the profile (cell B3).

3.2. Event 2

Measurements are presented in Fig. 3. Similar to Event 1, Event 2 can be divided into three subevents:

1 – 4 Feb: Upward bending, flooding, and rebound. B2 is the first cell to measure a response to an increase in water pressure with ice stress peaking at 450 kPa after water pressure reached 1kPa. As water pressure continued to rise, stress decreased in B2 while increasing in B1. Water pressure peaks at 3.9 kPa in parallel to a maximum in stress in B1 of 650 kPa and a sudden increase in ice temperature (reflected in a jump in modeled stress). This behavior is the result of bending of the ice cover upward as water level rose resulting in flooding around the edges of the reservoir by the time water pressure reached a maximum. Stress recorded in cells B3-B5 remains relatively stable during this time, maintaining values greater than predicted thermal stresses while showing only a slight decrease as B1 peaked. After water level decreased, the ice cover appears to rebound as displayed by the differing behavior of B1 and B2 in comparison to B3 through B5. The former decrease quickly with dropping water pressure, while the latter show a small increase in stress.

4 – 6 Feb: Upward bending and fracture. A second rise in water pressure led to stress increasing initially in B1 as the ice cover presumably bends upward. B2 through B5 recorded relatively

ISSN: 2414-6331

constant values of stress during this time. A sudden, short drop in water pressure resulted in all cells recording a peak in stress. As water pressure continued to increase, stress primarily decreased signifying the opening of a fracture in the ice and release of stress throughout its depth. This is supported by the sharp increase in thermal stress, signifying a local rise in ice temperature, the result of a sudden change in ice around the cells and not necessarily representative of the entire ice volume.

6 – 9 Feb : Downward Bending and Recovery. Ice appears to rebound from its previous upward bending resulting in the largest measurements of compression being recorded near the bottom of the ice (B5, 500 kPa). After water pressures reached a minimum and began to stabilize, stress in all sensors decreased and began to trend towards zero.

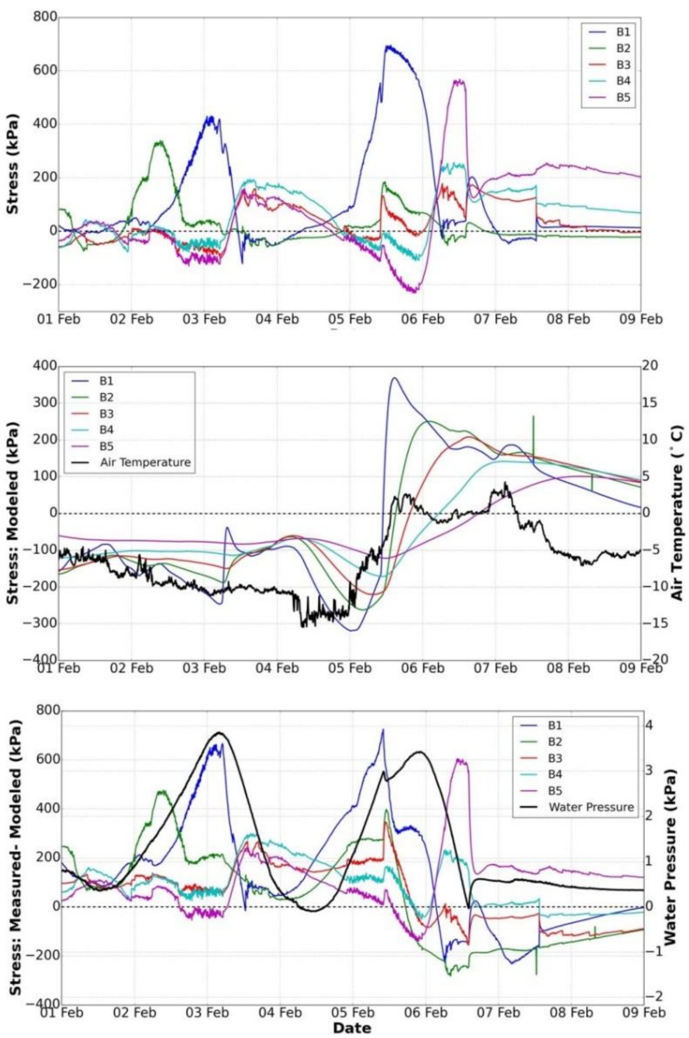

Figure 3. a) Stress measured in cells B1 through B5 from 1 – 9 Feb. b) Predicted stress based off of variations in ice temperature compared to air temperature c) Calculated difference between measured and modeled stress compared to water pressure.

ISSN: 2414-6331

4. Discussion and Conclusions

Measurements of ice stress gathered in the 2012/2013 season agree well with predicted values of thermal stress calculated using the Bergdahl model (Petrich et al., 2015). When we apply a similar approach to the 2014/2015 data however, predicted and measured values of stress show little relation particularly during periods where stress peaks in magnitude. Through comparing measurements to those made of water pressure a distinct correlation becomes apparent leading to the conclusion that major stress events in 2014/2015 were mechanical in origin. This relationship is non-trivial and will require further investigation in the future. In particular, discontinuous events such as the development of cracks and surface flooding should be examined further to determine the magnitude and duration of their impact on measurements of stress. Also of note is the low air temperature (between -15 and -10 ^{0}C) during measurements of high mechanical stresses. It can be assumed that ice was frozen securely to the dam wall during these periods of time thus resisting movement up or down. In addition the spillway was likely frozen over. These two factors may have contributed to higher stress on the dam than during times of warmer temperatures. As presented above, the ice did eventually show signs of fracture leading to a release of stress. The point at which this occurs would be a useful focus for future research.

The data presented here support earlier studies that showed non-linear distribution of stress through the thickness of the ice (e.g. Taras et al, 2009; Fransson, 1988). During the mechanical loading events summarized in this study, maximum stresses were recorded near the upper surface of the ice during times of increasing water pressure while decreasing water pressure corresponded to highest stresses near the center (Event 1) or at the bottom of the ice (Event 2). These findings as well as the other fluctuations in ice stress observed in the 2014/2015 season reveal the dynamic behavior of the ice cover throughout the winter. With additional measurements including those gathered during the 2015/16 season, our understanding of the stress place on dams by ice will continue to increase thus improving our ability to both predict and mitigate resulting impacts.

Acknowledgments

This work was supported by the Research Council of Norway, project number 195153 (ColdTech) and industry partners. Tore Pettersen of Norut Narvik provided excellent field support.

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 ISSN: 2414-6331