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Timelapse Photography at Two Norwegian Reservoirs: Observations and Recommendations for Future Field Campaigns to Monitor Ice Stress

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Ice loads suggested in dam design regulations in Norway are based on a limited number of measurements. As design guidelines are tightened, there is a need to enhance understanding of the actual magnitude of ice loads and how they may vary based on location and local climate. To prepare for measurements in remote locations, timelapse cameras were deployed at two regulated reservoirs, Iptojávri and Tjårdavatnet, located near Skjomen, Norway from September 2013 to August 2015. The cameras monitored ice dynamics at the dam face from different angles. Photos revealed highly dynamic conditions of fluctuations in water level, resulting in ice fracture and surface flooding, and creating several layers of superimposed ice. In addition, weather events resulted in the substantial accumulation of snow, both fresh and through wind drift. Given the remote location of the two reservoirs, the severity of conditions for measurements was not previously known. Examples of weather and ice events at Iptojávri and Tjårdavatnet reservoirs are presented and discussed in the context of planning of field campaigns and interpretation of remote measurements. Recommendations are presented for the assessment of ice loads in remote reservoirs.

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1. Introduction

Norway is a hydropower nation with over 6000 dams installed across the country and reservoirs generating more than 95% of the electricity used in Norway. Most hydropower dams are of small height in Norway since the hydraulic head is generated by the high elevation of the reservoir. As a result, design loads due to ice exceed loads due to hydrostatic water pressure, rendering accurate knowledge of ice loads highly relevant for safe and economic dam design (Comfort et al., 2003; Gebre et al., 2013). In addition, retrofitting of dams is common since Norway performs periodic revisions of the safety of existing dams based on the latest design standards. Current Norwegian design rules stipulate line loads between 100 and 150 kN/m as default assumption. However, ice conditions, dam properties, operations, etc., should be taken into account when determining the actual design load for a particular dam (NVE, 2003).

The present study is part of a multi-year effort to understand ice loads on concrete gravity dams in Norway (Petrich et al., 2014, 2015; Sæther et al., 2016; O'Sadnick et al., 2016). Earlier, nine years of ice load measurements and analyses in Canadian reservoirs have been summarized by Comfort et al. (2003). They found that low ice loads are produced in reservoirs with constantly falling water level, after a large water level drop occurred (i.e., 2-3 m with ice thickness <1 m), or if water level changes are generally large and frequent. In all cases, the formation of strong bonds between ice and dam appears to be inhibited. The highest loads were measured during simultaneous occurrence of thermal loads and intermediate-size water level fluctuations. Measurement campaigns conducted since then (e.g., Morse et al., 2011; Taras et al., 2011; Petrich et al., 2014, 2015) illustrated for example spatial variability of loads along flat dams. All studies had to contend with inter-annual variability in weather and ice conditions.

In spite of its relevance to economics and safety there appears to be no generally accepted approach to determining maximum ice loads specific to individual sites. Advance knowledge of general ice conditions at a particular site is advantageous and at times necessary for planning of field experiments. Due to the remote locations of many reservoirs, access roads are often not maintained during winter however, making extended snowmobile excursions the most cost-effective method for site visits. To reduce the costs associated with site visits and to get a more-or-less continuous impression of ice conditions throughout the season, we tested the deployment of timelapse cameras at remote sites for extended periods of time.

Two timelapse cameras were deployed at Tjårdavatnet during the winter of 2013/2014 to test the feasibility of our approach. That deployment was successful and images demonstrated that challenging snow conditions existed. The following year, the monitoring program was expanded to include a dam of the neighboring Iptojávri. This study presents observations from the resultant photos obtained at both reservoirs gathered primarily over the 2014/2015 winter season.

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2. Methods

Timelapse cameras were installed at Tjårdavatnet and Iptojávri on 15 September 2014 (Fig. 1). Both dams are of small height and were chosen as they were deemed to require remedial action for ice loads under the revised design guidelines. Bordering Sweden, Tjårdavatnet has an area of approximately 3.6 km^2 with a straight-faced dam 440 m in length located along its northern edge. The regulated water level is 26 m. Lying 3.5 km to the west of Tjårdavatnet, Iptojávri has an area of approximately 2.4 km^2 and a dam 350 m in length along its north eastern edge. Since the regulated height is 10 m while the actual dam is only 6 m at its highest point at the bottom outlet, an ice cover may ground at the dam when water levels are low. Reliable car access to these reservoirs exists for only two to three months out of the year. UM562 digital scouting cameras were used at all locations and powered using twelve lithium batteries to ensure their operation throughout the season. Photos of 5.0 megapixels in resolution were taken at 30 minute intervals and saved to an SD card. Cameras were retrieved on 27 August 2015. At Tjårdavatnet, one of the two cameras installed stopped operating on 21 November 2014 likely due to a faulty battery contact. At Iptojávri all cameras worked throughout the season. At both dams, some images were found not to be useful due to snow, ice, or condensation obscuring the camera lens. Such periods lasted upwards of 3 days and typically came after events of heavy snowfall. Images were individually examined to determine the extent of water level fluctuations, ice fracturing, and snow accumulation. Timelapse videos were created to further capture slight variations in ice conditions (available at https://youtu.be/rDm2mD-VvQs, https://youtu.be/jpQ3PKKvJGw).

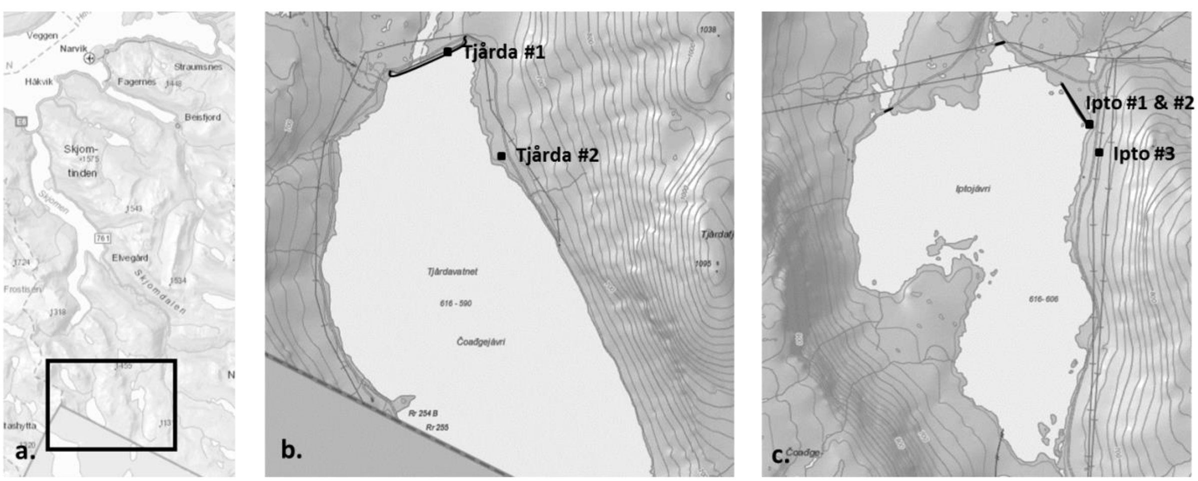

Figure 1. a) Location of Tjårdavatnet and Iptojávri (inside square); b) Map of Tjårdavatnet with approximate position of cameras marked; c) Map of Iptojávri with approximate position of cameras marked. Heavy black lines represent the location of dams.

3. Results and Discussion

In Table 1, dates of ice formation and ice breakup are listed for Tjårdavatnet and Iptojávri. Ice formation is defined as the day or span of days when a layer of ice is observed on the reservoir

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surface. Break up is defined as the period from the first appearance of open water until the reservoir is entirely ice free. The winter of 2014/2015 allows for a direct comparison between Tjårdavatnet and Iptojávri. For Tjårdavatnet, ice formation happened relatively suddenly when the portion of the reservoir in view transitioned from ice-free to ice-covered within one day. At Iptojávri, ice formation spanned a period of two weeks during which ice initially formed only in front of the bottom outlet of the dam. A longer amount of time was needed for the rest of reservoir to freeze. Similar to Tjårdavatnet, this area is more exposed to wind and of greater water depth. Break up conversely took a shorter amount of time at Iptojávri than at Tjårdavatnet. During the ice-covered part of the season, observations were made of significant fluctuations in water level revealing bed topography of the reservoir, the fracturing of ice and creation of superimposed ice, and the accumulation and wind drifting of snow along the dam face.

Table 1. Overview of ice formation and breakup

	Tjårdavatnet	**Iptojávri**
2013 Ice Formation	19 November	*not recorded*
2014 Break-Up	7 – 20 June	*not recorded*
2014 Ice Formation	5 November	10 – 27 October
2015 Break-Up	1 – 19 July	29 June – 5 July

3.1. Fluctuations in Water Level and Exposure of Bed Topography

While water and subsequently ice were in contact with a significant portion of the dam face at Tjårdvatnet throughout the recording period, at Iptojávri water was only consistently observed adjacent to the bottom outlet of the dam. During times of low water level, significant amounts of bed rock were exposed adjacent to both dams revealing the topography of portions of the reservoir bottom (Fig. 2a). Shallow water may lead to ice interacting with or even freezing to the bedrock, introducing new variables to consider when determining the cause and impact of stress placed directly on the dam. Additionally, large fluctuations in water level can lead to the exposure of stress sensors near the ice–water interface to the bedrock. Subsequently, sensors may undergo a period of refreezing during which measurements of stress are not accurate.

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Figure 2. Approximate minimum (left column) and maximum (right column) water levels at Iptojávri (a & b, from camera labeled Ipto #3) and Tjårdavatnet (c & d, from Tjårda #2). Photos taken in September 2014 before ice formation.

3.2. The Fracture of Ice and Creation of Superimposed Ice

Fig. 3 presents photos captured by the camera labeled Ipto #1 located adjacent to the bottom outlet of the dam (Fig. 1c). From this viewpoint, the magnitude and impact of water level fluctuations in Iptojávri are particularly apparent. Through comparison of photos to water level data of Statkraft AS, it was found that during the recording period 13 cycles in water level occurred. One cycle being defined at Iptojàvri as a decrease in water level of 5-6 m followed shortly by an increase of equal magnitude. Smaller fluctuations during these cycles were also observed. Once temperatures dipped below freezing, major decreases in water level led to fracturing of the ice cover. Subsequently, layers of superimposed ice formed as the reservoir refilled. In relationship to stress measurements, such layers may cause ice thickness to vary greatly throughout the reservoir further complicating analysis of measurements. In addition, these layers themselves will have differing mechanical properties, making the force they exert on the dam face less predictable. Based on prior work one would expect ice forces of the fractured ice found at Iptojávri to not be very high (Comfort et al., 2003). However, to the extent of our knowledge, no measurements have been performed in the presence of non-trivial bathymetry like that found at the Iptojávri dam.

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As illustrated in Fig. 4b, at Iptojávri fractured, jumbled ice was often pushed towards the face when water level increased. At Tjårdavatnet (Fig. 4a), low water levels and comparatively more consistent bathymetry lead to no evidence of ice floes fracturing and accumulating at the dam wall. The impact of such differences on the amount of stress eventually placed on the dam would be a potential focus of future field campaigns.

Figure 3. Photos from the Ipto #1 camera displaying a decrease and subsequent increase in water level. a) 26 Oct. 2014; b) 28 Oct. 2014; c) 4 Nov. 2014; d)13 Nov. 2014; e) 18 Nov. 2014; f) 26 Nov. 2014; g) 29 Nov. 2014; h) 2 Dec. 2014.

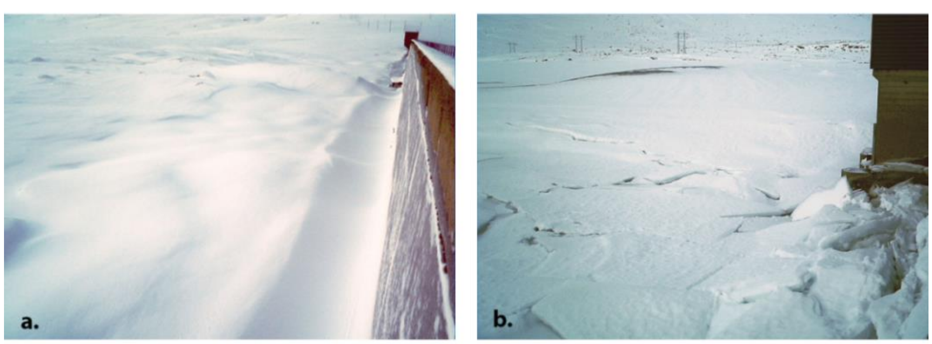

Figure 4. Variations in ice conditions at the dam face of a) Snow-covered ice at Tjårdavatnet on 12 December 2013 and b) snow-free ice at Iptojávri on 3 January 2015.

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3.3. Variable Weather Conditions and the Accumulation of Snow

Fig. 5 provides an example of the significant snow accumulation at both Tjårdavatnet and Iptojávri. As displayed in Fig.2, much of the dam face is often not in contact with water. Throughout the season however, snow fall combined with wind drifting is seen to cover nearly the majority of both dam faces. A snow cover of 10 m height would have the potential to depress a free-floating ice surface by up to 3 m. This would lead to flooding of the interface between ice and snow and potentially snow-ice formation, introducing more variables to consider when interpreting measurements of stress. Given that current models of ice stress assume a layer of homogeneous freshwater ice, such processes should be considered to further understand the possible variations in stress observed over a season. In addition, the direct impact of large amounts of snow on loads at the dam should be considered. The weather conditions that result in the accumulation of snow at the dam face may also impact both the stress sensors and other instrumentation used for measurements. Creation of a system resilient to the environmental elements at both dams is therefore necessary.

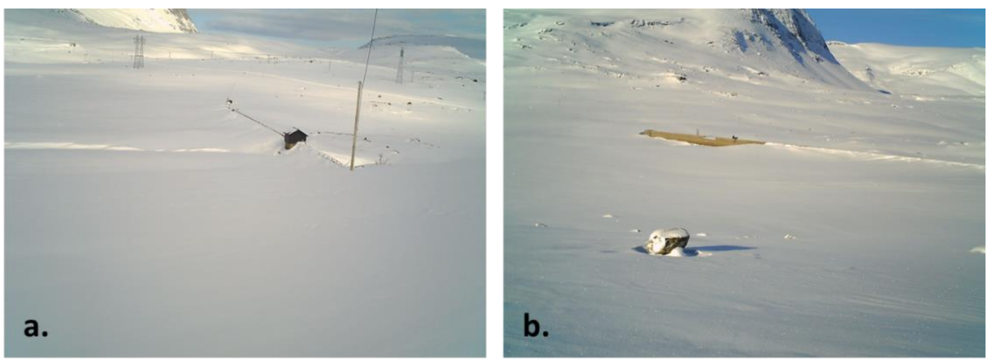

Figure 5. Photos displaying the approximate maximum snow accumulation at a) Iptojávri, 14 April 2015 and b) Tjårdavatnet, 21 March 2015. The northern end of the Tjårdavatnet dam is completely covered by snow drift (right hand side in the photo). The same situation had been observed during winter 2013/14.

4. Conclusions and Future Work

While there is a track record of successful ice load field campaigns (e.g., Fransson, 1988; Comfort et al, 2003; Morse et al., 2011; Petrich et al., 2015), we have shown examples in this paper of situations under which there is limited practical experience to draw from. Future work should therefore be guided by careful and realistic consideration of exactly what should be assessed. Given the current state, there are at least two different motivations for future work: (A) Determination of design loads, and (B) Design of mitigating measures. Approaches can be split into

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A. Determination of design loads
    A.1. Documentation of loads in challenging ice conditions
    A.2. Determination of maximum expected loads throughout Norway
B. Design of mitigating measures
    B.1. Baseline studies
    B.2. Full-scale tests

Comfort et al. (2003) concluded that maximum loads are to be expected in reservoirs that experience thermal loads and water level fluctuations covering a range similar to ice thickness. Using this as hypothesis for A.2., future work should include measurements and modeling of ice conditions in indicator reservoirs that can be reasonably expected to experience those conditions. This would take earlier work further, including recent progress in modeling of these processes (Comfort et al, 2003; Morse et al., 2011; Taras et al., 2011; Petrich et al., 2014, 2015; O’Sadnick et al., 2016). However, the impact of challenging ice conditions on loads has not been assessed for all cases (A.1.). In this paper we described observations of ice rubble attached to the dam, ice thickness increase close to the dam, a hypothetical potential for jammed-up ice to push into the dam, superimposed ice layers of different mechanical properties, significant regulation height, and loads due to snow pile-ups at the dam. Individual processes could be assessed separately at suitable indicator reservoirs. In addition to measurement, modeling of the corresponding processes would allow for generalizations (cf. Comfort et al., 2003). However, measurements in challenging ice conditions are met with needs for possibly unprecedented engineering solutions, for example with regards to sensor location in the presence of heavily fractured ice, sensors impacted by bedrock during low water, upward ice growth due to superimposed ice, questions regarding measurements beneath deep snow drifts, and access to remote locations. Load reducing measures require a decision on what load-generating mechanism to reduce for, a baseline understanding of magnitude and processes leading to the loads (B.1.) and field test (B.2.). This work can be performed at indicator reservoirs of relevant ice and operational characteristics. Baseline work (B.1.) should provide information about the magnitudes and procedures for predictions (cf. A.1. and A.2.) in order to facilitate the assessment of the mitigating measures (B.2.).

Using time series of photos, we were able to observe the extent of variations in water level, ice, and weather conditions at Tjårdavatnet and Iptojávri. While timelapse photos revealed a number of interesting dynamics at both dams, many challenges exist to create a successful field campaign that is both economically viable and yields useful, interpretable, and actionable data. Tight coordination between research, dam owners, operators, and regulating authorities is therefore necessary.

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