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Time-dependent spatial distribution of thermal stresses in the ice cover of a small reservoir

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ABSTRACT

Static ice loads (ice actions) are a key design parameter for dams in cold climates. However, their theoretical description is still elusive, introducing uncertainty in design and hindering development of remediation measures. We present and analyze measurements of stresses due to thermal loads in a small reservoir in northern Norway. Several weeks of observations, including both cold and warm spells, were well-described by a simple equation that accounts for thermal expansion and temperature-dependent creep. One model parameter was found to depend systematically on the location of measurements within the reservoir. Biaxial stress measurements showed that the stress field was not homogeneous. Results suggest that the stress field in reservoirs should be predictable from first principles with numerical methods and point toward a promising, simple parameterization.

1. Introduction

Design rules and practices have been established in several countries to ensure the safety of hydropower dams. One design parameter is static ice load, resulting from thermal expansion of the ice cover or water level fluctuations (e.g. Comfort et al., 2003). Ice loads are variable actions whose intensity and/or points of application vary frequently and significantly over time (CFBR, 2013). Design standards are based on limited empirical measurements as current understanding of the magnitude of ice loads is still limited (Comfort et al., 2003; Gebre et al., 2013; Timco et al., 1996). Since field measurements of ice forces on dams have suggested that maximum static ice loads depend significantly on the location of the dam, climate and sudden temperature changes, increasing efforts to understand ice loads on dams has been called for (Gebre et al., 2013). Benefits could be two-fold: on the one hand, costs may be reduced during dam construction or maintenance. On the other hand, solutions for ice load reductions may be developed: a more profound understanding of the mechanisms involved in ice-structure interactions may lead to the development of more cost efficient strategies for reducing the actual ice-load on dams. This may be of particular interest for the design of dams for small-scale hydropower plants. The potential for cost reductions during the lifetime of dams is exemplified by a recent change in the Norwegian regulation to the Water Resources Act (Vannressursloven) with respect to safety at hydropower plants, implemented in 2010 (Ministry of Petroleum and Energy, 2009). The guidelines and design recommendations include new considerations regarding ice loads on dams (NVE, 2003), that cause a need for upgrading and strengthening of existing dams and infrastructure.

According to the Norwegian guidelines (NVE, 2003), thermal ice loads are assumed to be line loads between 100 and 150 kN/m near the top of the dam. However, during the most recent decades this has been verified in only one measurement campaign during a single season at Silvann dam in the northern part of Norway (Hoseth and Fransson, 1999).

This study focuses on thermal ice loads. Measurements were performed in a reservoir at a time of year when the ice level was kept steady by the balance of a small influx of water from a creek and outflow over the spillway beneath the ice over.

2. Methods

2.1. Installation

A weather station and stress cells were installed at Taraldsvikfossen Reservoir near Narvik, 68.4405° N, 17.471° E, 212 m above sea level in December 2012. The reservoir is small (1000 m^3), bound at the western side by a straight concrete gravity dam and extending approximately 30 m in North–South direction (Fig. 1). A concrete maintenance hut is situated half way along the dam. Water depth in the reservoir is approximately 6 m at the dam, reducing to 1 m at the eastern shore. The Taraldsvik creek enters the reservoir from the North-East. A weather station was mounted at the maintenance hut, and a 3 m long vertical string of temperature sensors was frozen into the ice to measure the temperature profile through water, ice, snow, and air.

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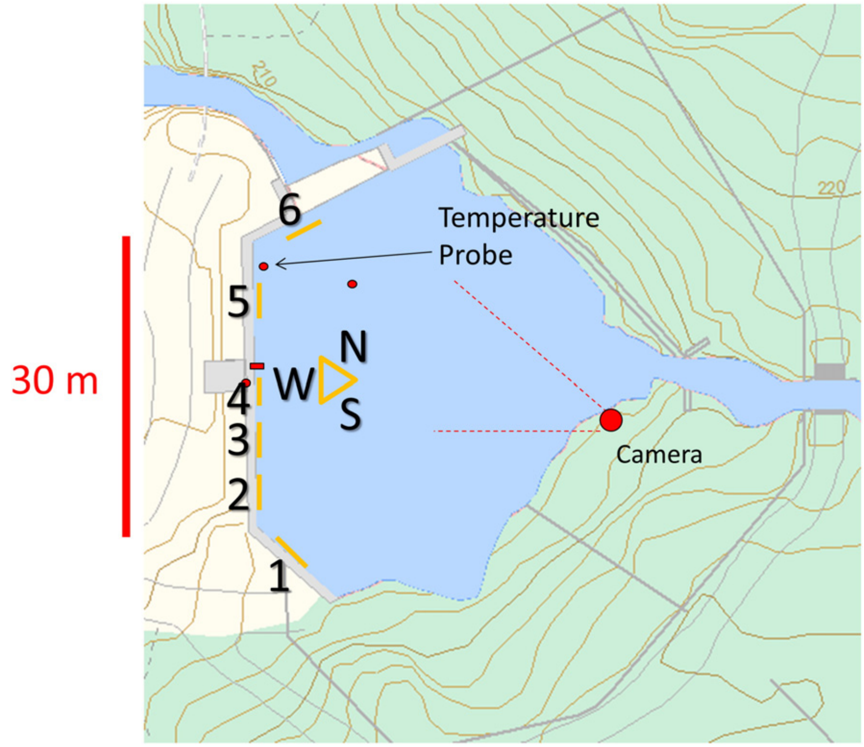

Fig. 1. Sketch of the approximate locations of the load cells deployed on 12 February 2013. Markers indicate station name. North is up. Map source: NVE Atlas.

As summarized by Cox and Johnson (1983), sensors used for ice stress measurements fall into two categories: cylindrical sensors having an effective modulus much greater than ice, and thin, wide sensors (flat-jacks), preferably having an effective modulus close to that of ice. Flat-jacks and cylindrical stress gauges were found to compare well during a recent series of field measurements in ice-covered reservoirs in Canada (Morse et al., 2011; Taras et al., 2011). In this study, stresses in the ice were monitored with 15 custom designed oil-filled GeoKon 4850 stress cells (essentially the same as those used by Carter et al. (1998) and Taras et al. (2011)). The cells consisted of two rectangular steel plates (100 mm × 200 mm) welded together around the periphery with de-aired oil occupying the space between the plates. A short tube connected the cell to a vibrating wire pressure transducer that also measured temperature with a temperature-dependent resistor. The cells were calibrated by the manufacturer to an accuracy <0.5 kPa. Stress cells were mounted on steel tape at desired vertical separations and attached to wooden support (Figs. 2 and 3). In each case the center of the upper-most stress cell was 0.2 m below the ice surface at deployment. Two stations along the dam had three stress cells spaced 0.15 m (Stations 3 and 5) while the station toward the center of the reservoir measuring stress normal to the dam (Station W) had cells spaced 0.25 m. All instruments were connected to a CR1000 data logger recording stress data every 5 min. A timelapse camera overlooked the NW corner of the dam, including part of the spillway. The camera recorded images

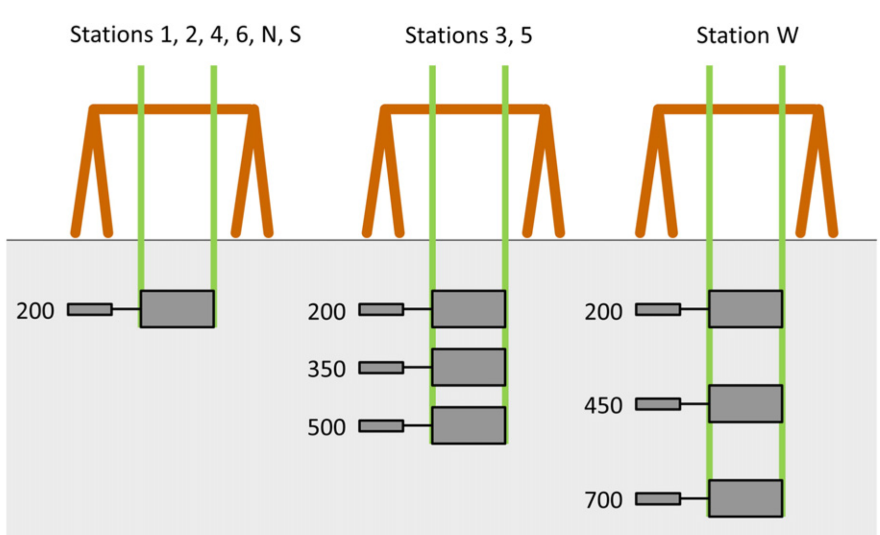

Fig. 2. Configuration of pressure cells (large rectangles) at 9 measurement stations. Depths of the centers of the vertical cells are given in mm below ice surface at the time of deployment.