Cold Regions Science and Technology 106–107 (2014) 194–206

Contents lists available at ScienceDirect

Cold Regions Science and Technology

journal homepage: www.elsevier.com/locate/coldregions

Inner structure of anchor ice and ice dams in steep channels

Mathieu Dubé *, Benoit Turcotte [1], Brian Morse [2]

Dept. of Civil and Water Engineering, Pavillon Pouliot, Laval University, 1065 ave. de la Médecine, Québec, QC, Canada, G1V 0A6

ARTICLE INFO

Article history:
Received 14 December 2013
Accepted 28 June 2014
Available online 3 July 2014

Keywords:
Steep channel
Freezeup processes
Ice dams
Anchor ice
In-situ growth
Frazil ice

ABSTRACT

Dynamic ice growth (composed primarily of anchor ice and ice dams) is the dominant process in steep (slope $> 0.3\%$) channels during winter. The ice growth (in all its manifestations) regulates water levels, flow resistance, bathymetry, flow rate, water quality and fish habitat. Empirical models of the processes are available but in order to develop more physically-based models, more knowledge about the nature of ice in these channels is required. This paper presents original data from two channels of the Montmorency River watershed known for their intense anchor ice and ice dam development activity. The data include time-lapse photographs, underwater photographs, water level records, and water and air temperatures collected during winter 2012–2013. Moreover, anchor ice and ice dam samples were analyzed with thin sections and using computed axial tomography (CAT) scan technology. This study aims at understanding the development processes of both anchor ice accumulations and ice dams by investigating their crystal types and sizes, their growth mechanisms, patterns, and orientation, and their porosity.

Two main types of ice crystals were observed: columnar ice crystals and fixed-frazil ice crystals. Relatively large columnar ice crystals grew upwards (away from the bed) perpendicularly to the local flow surface and were only observed in ice dam samples. Fixed-frazil crystals originated from the deposition and/or interception of drifting frazil particles that became “fixed” to the bed and to existing ice accumulations. The data suggest that in-situ growth of fixed-frazil ice crystals was the dominant process (accounted for the most ice development) for both anchor ice and ice dams. Fixed-frazil ice consists of a bonded mass of interlocking plate shaped crystals demonstrating a preference to be perpendicular to the bed and water surfaces. The mass displays some variability in porosity (mean value 41%). When analyzed using CAT scan slices, the interlocking plates appear as a tree-like or dendritic structure. The average size of resulting crystal segments and the maximum size of individual whole crystals within fixed-frazil ice structures were significantly more important for ice dam samples than for anchor ice samples.

1. Introduction

Anchor ice accumulations and ice dams are fascinating structures that form across steep channels during the freezeup period (Fig. 1). Anchor ice forms below the water surface on the channel bed material and it represents the most documented steep (slope $> 0.3\%$) channel ice type because of its important impact on flow conditions. It is indeed an ice process that is less dominant from a hydraulic point of view in low-gradient channels compared to the most documented floating ice cover. Anchor ice has been studied in the field (Hirayama et al., 1997; Kempema and Ettema, 2011; Parkinson, 1984; Terada et al., 1998; Yamazaki et al., 1996) and in the lab (Clark and Doering, 2004; 2006; Kerr et al., 2002; Qu and Doering, 2007). Northern Europe scientists such as Stickler and Alfredsen (2009) and Tesaker (1994) have presented anchor ice as a submerged ice type forming on the channel bed that generates backwater effects. Many published studies either reported anchor ice release at sunrise or that anchor ice accumulations were ephemeral (e.g. Parkinson, 1984). More recently, complex, stable, anchored ice features such as ice weirs and ice dams have been described in detail (Stickler et al., 2010; Tesaker, 1996; Turcotte et al., 2011) and their thermal and hydrological impacts were documented (Turcotte et al., 2012, 2013, 2014). Submerged anchor ice weirs form at natural steps made of stone clusters or between dominant boulders where anchor ice accumulations can link across the channel which can in turn substantially increase the water level upstream. As weirs continue to develop at variable spatial rates (Dubé et al., submitted for publication; Turcotte et al., 2013), parts of them can eventually emerge, thereby forming ‘ice dams’. They cause significant backwater effects that can even extend to the floodplain.

Any hydraulic structure (dam, bridge, culvert, water intake, bank protection, habitat creation, etc.) built in a winter-affected steep stream

---

* Corresponding author. Tel.: +1 418 730 5308; fax: +1 418 656 2928.
E-mail addresses: mathieu.dube.4@ulaval.ca, mate.dube@hotmail.com (M. Dubé), benoit.turcotte.1@ulaval.ca (B. Turcotte), brian.morse@gci.ulaval.ca (B. Morse).

[1] Tel.: +1 418 656 2131x7857; fax: +1 418 656 2928.

[2] Tel.: +1 418 656 2867; fax: +1 418 656 2928.

http://dx.doi.org/10.1016/j.coldregions.2014.06.013
0165-232X/© 2014 Elsevier B.V. All rights reserved.

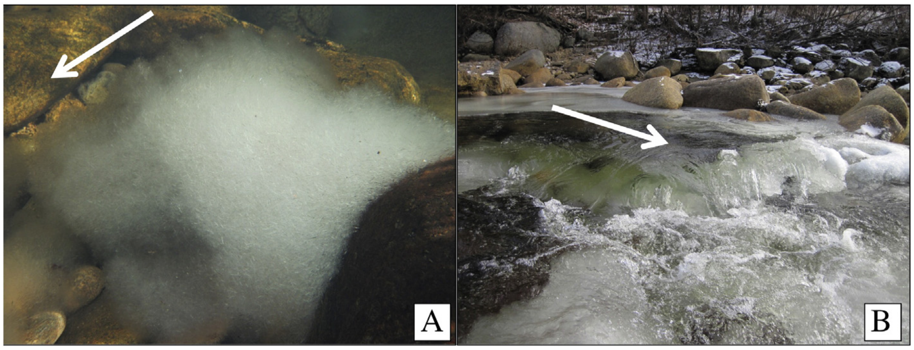

Fig. 1. (A) Underwater photograph of an anchor ice accumulation in a pool section of the Stream and (B) photograph of a partially emergent ice dam in the Stream. White arrows indicate the flow direction.

must account for dynamic ice growth. Previous studies have shown that anchor ice and ice dams (especially during the freezeup period) may produce the highest water levels, the lowest flow rates (because of increased hydraulic storage caused by ice), a completely changed river morphology (as rapid sections can become step-pool sections), a change in water current patterns (slower water at some places, concentrated jets at others), a completely different global resistance to flow and a regulated change in water temperature and water conductivity. The impact on local fish (e.g. Bradford and Heinonen, 2008) and flora habitat is self evident as the ice can cover the bed, flood the banks, and insulate water from the cold. As such, the study and modeling of those ice processes are of interest as steep streams are very abundant in nature. Generally, models, based on heat budgets and field observations have been empirical in nature. However, the recent observations and work are beginning to document the very structure of those ice features. This will open the doors to a more physically-based understanding and modeling of the processes and it is the intention of this paper to contribute to this initiative by presenting some new field data and ice structure analyses.

The first objective of this study is to describe the inner structure and crystal arrangements in anchor ice and ice dams as well as to identify their respective dominant growth mechanism. To do so, ice samples were collected during winter 2012–2013 from two channels known for their anchor ice and ice dam development (e.g., Turcotte et al., 2013). Computed axial tomography (CAT) scan analyses were performed on all samples while traditional thin section analyses were performed on selected ice structures of interest. The second objective of the study is to identify structural characteristics specific to anchor ice and ice dams. The results presented throughout this paper improve our understanding of 1) crystal types and sizes found in anchor ice and ice dams, 2) their growth mechanisms, patterns, and orientation, and 3) their porosity. One should note that the term “size” is used here to describe the crystal dimension in the a-axis (Michel, 1978).

The link between hydraulic conditions (e.g., Froude and Reynolds numbers) and anchor ice and ice dam development has received some attention in the literature. This paper adopts a different approach to explain the development of steep channel ice features by presenting and analyzing their complex crystallographic arrangements. Building on the work presented by Kempema and Ettema (2009) and Dubé et al. (2013), this paper attempts to establish a linkage between crystal characteristics and their development mechanisms.

Kempema and Ettema (2009) investigated the composition of anchor ice accumulations and suggested that variations in anchor ice crystal morphology are primarily caused by their in situ growth. This process would directly account for the internal strength of the anchor ice mass and the bonding between anchor ice and the substrate. Most of their 72 anchor ice samples did not reveal the presence of disk-shaped frazil crystals as it is often reported to be found in the water column (e.g. Tsang, 1982). Moreover Kempema and Ettema did not find any link between hydraulic conditions and ice crystal morphology. In fact, crystal shape and size could vary significantly within the same sample.

The characterization of ice structures is usually performed by analyzing thin sections of ice under crossed polarizers. Through these crystallographic analyses, one can determine the growth properties of ice samples as well as their deformational history. A detailed description of the thin-section technique can be found in Michel (1978), who separated low gradient freshwater ice into seven classes based on microstructure interpretation. More recently, ice structures have been characterized through the use of non-invasive techniques such as computed axial tomography (CAT). In a recent study, Gherboudj et al. (2007) used CAT scans to characterize air inclusions in floating river ice covers. The technology allows for the visualization of the shape and size of air inclusions, and provides a method to quantify ice porosity. Dubé et al. (2013) applied CAT and thin section techniques to non-floating steep channel ice samples collected in 2011–2012. The porosities of different ice structures were quantified and ice crystal structures were presented.

2. Sampled sites, sample categories and methods

2.1. Sampled sites

Anchor ice and ice dam samples were collected during winter 2012–2013 in the 1100 km^2 Montmorency River watershed located in a hilly-forested area north of Quebec City, Canada (Fig. 2). Samples were collected (location shown in Fig. 3) from two different instrumented channels: the *De l'Île* Stream (watershed of 80 km^2) and the smaller *Lépine* Creek (watershed of 8 km^2). Fig. 3 shows the location of all the instruments used in the study including water pressure and temperature probes, air pressure and temperature probes, and fixed automated cameras oriented in the upstream direction. Throughout this paper, these two channels will be referred to as the *Stream* and the *Creek*.

The Stream's width is relatively constant at 18 m and its slope in the 500 m-long reach of interest is 1.5%. Based on the Montgomery and Buffington (1997) channel morphology classification, this reach consists of rapids with numerous emergent boulders locally forming incomplete steps. At freezeup, ice dams develop in the alignment of dominant emerging boulders. Some dams develop at faster rates resulting in the upstream drowning of slower developing dams. Six samples were collected along this reach. Four of them (S1, S2, S3 and S4) were retrieved before (Nov. 27th, Nov. 30th, and Dec. 12th, 2012) a mid-winter breakup that took place on Jan. 31st 2013. This event cleared the Stream from all its ice and was immediately followed by a new freezeup period. The two other samples (S5 and S6) were collected from a new ice dam on Feb. 7th 2013.

The Creek width is about 4 m and its average slope along a 700 m reach is 2%. It presents a well-defined step-pool morphology and, at freezeup, ice dams form on every step. Five anchor ice and ice dam