Cold Regions Science and Technology 55 (2009) 86–102

Contents lists available at ScienceDirect

Cold Regions Science and Technology

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

A field study of suspended frazil ice particles

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ARTICLE INFO

Article history:
Received 1 October 2007
Accepted 19 March 2008

Keywords:
Suspended frazil ice
Anchor ice
Surface ice
Supercooling
Rouse equation
Rise velocity
Tidal river

ABSTRACT

This study presents comprehensive hydraulic, meteorological and ice data during a full winter period at a tidal river site situated on the St. Lawrence River at Quebec City, Canada. After briefly presenting surface ice floe and anchor ice characteristics, the article makes in-depth analyses of over 26 470 suspended frazil ice concentration profiles. Three distribution models are evaluated and the model that performed the best in describing the data was the Rouse suspended sediment model (modified for ice particles). It was found that the Rouse number (Z) had a mean, a median and a standard deviation of 0.48, 0.39 and 0.36 respectively. The corresponding computed frazil ice particles rise velocity (w_r) distribution had a mean, a median and a standard deviation of respectively 0.92 cm/s, 0.76 cm/s and 0.73 cm/s. The dependency of w_r on local turbulence was quantified. A literature review of rise velocity equations, as a function of ice particle diameter, was carried out and a specific relationship is recommended as the most promising candidate for further study. Based on this relationship, the mean frazil ice particle diameter was found to be 3.15 mm.

The paper explores fundamental relationships between air temperature, water temperature including supercooling, wind, water depth and velocity, surface ice floe concentration and thickness, mean suspended frazil concentration and anchor ice thickness. The paper ends with a discussion of the fundamental inter-dependency between the size of frazil ice particles and the Rouse number. This leads to the hypothesis that the dominant Rouse number of most river flows will normally be close to $Z\approx 0.4$. Furthermore, it proposes that the size of the frazil ice particles in a water body is controlled, at its lower end, by its basic size distribution during formation and, at the upper end, by the limiting rise velocity corresponding to $Z\approx 0.8$. Finally, it suggests that the size distribution of frazil particles situated under the surface floes, and therefore available for entrainment, depends on the time-history of turbulent conditions encountered during the ice floe's voyage.

1. Introduction

This paper is the concluding presentation of data, collected during the winter of 2005–2006 using various instruments deployed in the St. Lawrence River, at Quebec City. The original aim was to determine why the municipal intake kept getting blocked by frazil ice. An initial paper (Richard and Morse, 2007) focussed on how active frazil blocks the local municipal water intake and the reader requiring additional site information is referred to it.

This paper really focuses on frazil ice. It quantifies computed rise velocities and demonstrates how the distribution can be predicted for any river site. Furthermore, it reviews a number of rise velocity equations and make a strong recommendation regarding the use of one that may be new to river ice researchers. Putting the two together, the paper can also be used to predict frazil ice diameters at any site.

However, before presenting frazil ice, the reader is presented with data related to local hydraulic and meteorological conditions, and local surface ice and anchor ice conditions. Although this information could be considered a separate topic, it is presented to show the linkage between frazil ice processes, local hydraulic conditions and other ice forms.

2. Study objective

The most comprehensive general overview and theoretical development of frazil ice dynamics equations is given by Daly (1984, 1994). A number of researchers have conducted laboratory experiments that focussed mainly on water temperature and fluid turbulence interaction and their effect on frazil ice dynamics and frazil ice particles size distribution (e.g., Michel, 1963; Carstens, 1966; Mueller, 1978; Ettema et al., 1984; Hanley and Tsang, 1984; Daly and Axelson, 1989; Tsang and Cui, 1994; Clark and Doering, 2006). There are also studies on particle rise velocities (e.g., Wueben, 1984; Reimnitz et al., 1993). Some key references to field work include Gosink and Osterkamp (1983), Osterkamp and Gosink (1983), Tsang (1986), Jasek and Marko (2007). Quantitative results from field work are very rare because it is extremely difficult to measure frazil ice in nature. For example, to the best of the authors' knowledge, the only freshwater frazil ice concentration profile measured in nature was made by Tsang (1986).

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doi:10.1016/j.coldregions.2008.03.004

Although many instruments to measure frazil ice in nature have been developed over the years (e.g., Tsang, 1985; Daly and Rand, 1990; Pegau et al., 1996; Yankielun and Gagnon, 1999), there is still no definitive instrument available for field work.

Given the field data collected in the St. Lawrence River, the objective of this study is to use them, nevertheless, to build on the previous body of work examining frazil ice in the natural environment. Therefore, the objectives are to describe and quantify frazil ice suspended concentration profiles, particle diameters and rise velocity characteristics. It is also the objective to explore the relationship between all forms of ice encountered at the study site, including suspended frazil, surface ice floes and the anchor ice, as a function of many variables including local hydraulic and meteorological conditions.

In the paper, Section 3 presents a concise synthesis and selected references about the current understanding of frazil ice, its formation and transformations. Section 4 presents the field data. Section 5 presents an analysis of the measured frazil ice concentration profiles. Section 6 present an analysis of the computed frazil ice rise velocities and a review of the knowledge on that matter. Section 7 is a discussion on frazil ice processes; and Section 8 presents the major conclusions.

3. Frazil ice: formation and transformations

Research into frazil ice studied in the laboratory has tended to concentrate on the formation of frazil ice, including how the water temperature and turbulence characteristics of the flow affect frazil ice formation, and how these may lead to different types of frazil ice crystals and different size distribution of crystals. Frazil particle diameters measured in the laboratory typically vary from 0.035 mm to 4.5 mm (Daly, 1984, 1994; Ettema et al., 1984; Daly and Colbeck, 1986; Clark and Doering, 2006).

In a natural environment, as they progress downstream, these particles grow, transform and evolve into other forms of ice (Table 1). They can deposit on the river bed forming anchor ice, or can proceed downstream where they can multiply and flocculate depending on water temperature, water depth and turbulence. Shen et al. (1995) present a spatio-temporal numerical model of this growth process wherein, for the early stages of development, frazil ice particles characteristic length is typically 1 to 100 mm. As particles grow in size, the relative importance of the buoyancy increases, thus permitting sufficiently large particles to float on the water as surface slush, while smaller particles remain in suspension. On the other hand, if turbulence intensity becomes too strong downstream, e.g., rapids, the surface slush may break up, and the frazil particles can then temporarily return to suspension. Eventually, surface slush can either attach itself to existing border ice, deposit under a fast ice cover, or, as the slush develops a crust at the surface, form into pans. The pans will grow in size and thickness as they float downstream. On the St. Lawrence River, these floes are initially about 1 m in diameter downstream of the Montreal rapids. Once they reach the present study area, 300 km downstream, they can typically attain 10 to 200 m in diameter. A key note to the analyses presented in this paper is what exists just below a surface floe's crust: a submerged transitory deposit of frazil ice particles and slush that have left suspension to either freeze into the crust or re-entrain into the flow. At the Quebec study site, the crust thickness was not measured. Only total keel ice floe thickness data was available but for information on crust thickness at a neighbouring site on the St. Lawrence River, please refer to Morse et al. (2003).

Table 1
Evolution of frazil ice in natural water bodies (based on Daly, 1994)

Phase	Ice type	Process	Length scales
Formation	Seed crystals	Seeding	4 to 300 µm
	Disk crystals	Frazil ice dynamics	0.1 to 4.0 mm
Transformation and transport	Flocs	Flocculation	0.1 to 10.0 cm
	Anchor ice	Deposition	0.1 mm to 40 m
	Surface slush and suspension	Transport and mixing	–
	Surface floes	Floe formation	0.1 to 100.0 m
Stationary ice cover	Fine grained, accumulation and suspension	Ice cover formation and under ice transport	0.01 to 100.00 km

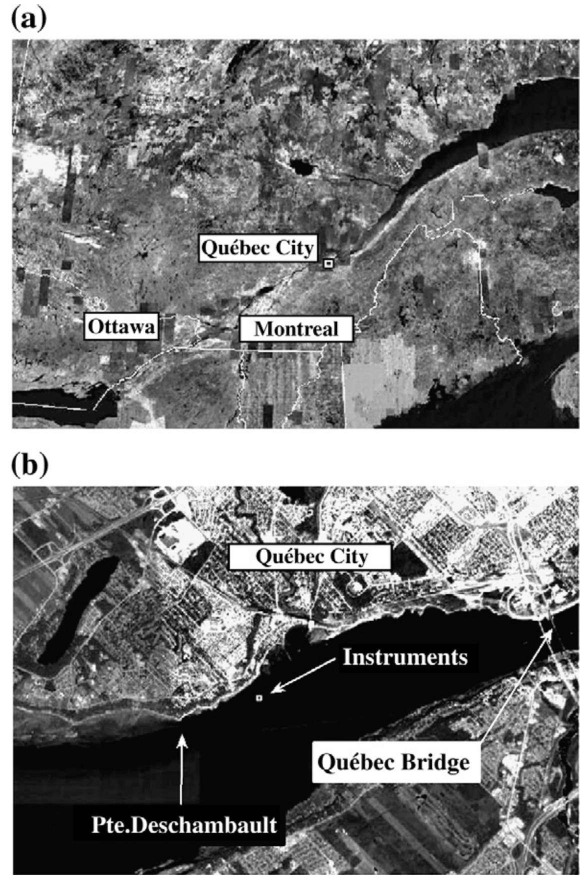

Fig. 1. Study site localisation (from Google Earth™).

4. Field data

The St. Lawrence River was instrumented at Quebec City, Canada, (Fig. 1) at 450 m from the left bank (north shore — Fig. 2) with an IPS4 (Ice Profiling Sonar) operating at 420 kHz (Birch et al., 2000). This relatively high operating frequency allows the detection of suspended particles (Jasek and Marko, 2007) in addition to the traditionally detected air/water ice/water interfaces. The study reach is tidal in nature. Water currents regularly change directions at each semi-diurnal tidal cycle. All the environmental, surface ice and anchor ice data for the full 2005–2006 field study period are presented in Richard and Morse (2007). A typical week of data is selected for presentation (Fig. 3) and is described in Sections 4.1–4.6.

4.1. Local water depths and velocities

At high tide, the local water depth (D) was typically 12 m and the local water current (U) reached −1.9 m/s. At low tide, the local depth was typically 8 m and the local water current reached 1.5 m/s. Because local velocities play an important role in the subsequent analyses, it is important to note that the values used in this study contain some uncertainty that will be discussed here. Fig. 4 presents local calculated