Cold Regions Science and Technology 155 (2018) 280–288

Contents lists available at ScienceDirect

Cold Regions Science and Technology

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

Flow characteristics of a partially-covered trapezoidal channel

Navid Kimiaghalam[a,*], Shawn P. Clark[b], Karen Dow[b]

[a] GHD, 455 Phillip St., Waterloo, ON N2L 3X2, Canada
[b] University of Manitoba, 15 Gillson St., Winnipeg, MB R3T 5V6, Canada

ARTICLE INFO

Keywords:
Border ice
Partial ice cover
Shear stress distribution
Velocity distribution
Hydraulics

ABSTRACT

Partial ice covers alter the hydraulic regime of rivers in cold regions. Border ice is a type of partial ice cover that forms on the river banks and grows toward the centre of the channel to form a full ice cover; thereby impacting freeze-up processes. Many studies have been conducted to understand flow characteristics under open channel and full ice cover conditions; however, only a few studies have focused on the effects of partial ice covers on flow characteristics in a rectangular channel. This study goes even further by investigating stream-wise velocity and shear stress distributions in a trapezoidal channel with simulated border ice. This is the very first study to investigate the effects of different border ice coverage ratios and roughness conditions on flow characteristics in a trapezoidal channel. Experiments were conducted under seven different roughness and coverage conditions. High-resolution velocity data were collected using acoustic Doppler velocimeters within the fully-developed region of the flume. The magnitude and shape of the stream-wise velocity contours were significantly altered by the presence of the partial ice and rough boundaries. Moreover, local boundary shear stress distributions were significantly impacted by the coverage and roughness conditions. Generally, stream-wise velocity and local boundary shear stress increased within the open section and decreased within the covered section. For practical purposes, depth-averaged velocity and discharge distributions were investigated for each experiment. Results from this study will improve the current knowledge of the flow in partially covered channels and can be used for design and modelling purposes.

1. Introduction

Ice formation and growth on rivers is common in cold regions and can alter the hydraulic regime of the rivers. Understanding river ice formation processes is essential to design and operate hydraulic structures, operate hydroelectric generating stations, flood control, and understand morphodynamic changes in cold regions (Miles, 1993). Border ice is often the first type of surface ice that begins to grow on a river, starting from the channel banks and growing inwards toward the centre (Clark, 2013). A handful of field studies have found that the border ice growth rate can be a function of flow conditions, meteorological conditions, channel morphology and the presence or absence of frazil ice (Matousek, 1984; Miles, 1993; Michel et al., 1982). This type of partial ice alters the hydraulic regime of the river as well as the rate of heat loss from the river, thereby affecting ice growth and formation. It is therefore essential to understand the effects of partial ice covers on flow characteristics in order to accurately model the hydraulics and ice formation during this dynamic portion of river freeze-up.

The flow conditions become more complicated in the presence of an ice cover, in particular beneath a partial ice cover (Chen et al., 2015; Majewski, 2007). An ice cover changes the flow regime by adding an extra boundary layer to the flow and thereby alters the flow characteristics beneath the ice cover (Shen and Wang, 1995; Sui et al., 2010). More specifically, the boundary shear stress distribution, velocity profiles, Reynolds stress, and turbulent kinetic energy are among those important flow characteristics that can be impacted by the presence of a partial ice cover. Several studies have shown that the velocity profile under an ice cover consists of two layers separated at the maximum velocity plane (Chen et al., 2015; Lau and Krishnappan, 1981; Sukhodolov et al., 1999).

Many researchers have conducted experimental and field studies to understand flow characteristics in fully ice covered channels (Attar and Li, 2012; Lau and Krishnappan, 1981; Shen and Harden, 1978; Sukhodolov et al., 1999; Teal et al., 1994; Aghaji Zare et al., 2016); however, a few studies have focused on flow characteristics in partially covered channels. Most of the previous field studies focused on border ice formation and growth processes at specific field sites (Calkins and Gooch, 1982; Hirayama, 1986; Matousek, 1984; Miles, 1993; Michel et al., 1982; Newbury, 1968). Majewski (1992) and Peters et al. (2017 and 2018) conducted experimental studies to investigate flow

---

[*] Corresponding author.
E-mail addresses: Navid.Kimiaghalam@ghd.com (N. Kimiaghalam), Shawn.Clark@umanitoba.ca (S.P. Clark), Karen.Dow@umanitoba.ca (K. Dow).

https://doi.org/10.1016/j.coldregions.2018.08.016
Received 6 November 2017; Received in revised form 12 August 2018; Accepted 13 August 2018

characteristics in partially covered rectangular channels with different ice coverage ratios and boundary conditions. These studies showed that stream-wise velocity and boundary shear stress distributions in a rectangular channel were significantly impacted by the presence of partial ice covers and rough boundaries. Generally, stream-wise velocity and local boundary shear stress increased within the open section and decreased within the covered sections. Bed and cover roughness had more effects than the coverage ratio on the magnitude of local and average boundary shear stress in a rectangular channel (Peters et al., 2018). Kimiaghalam et al. (2017) investigated the applicability of available shear stress estimation methods on partially-covered rectangular channels with smooth boundaries. They concluded that due to the considerable inaccuracy of the available estimation methods, new methods are required to estimate local boundary shear stress in partially-covered channels, in particular under circumstances where local boundary shear stress would play an important role such as estimating local scour.

The present study focused on investigating stream-wise velocity, boundary shear stress, and discharge distributions in a partially covered trapezoidal channel under different coverage ratios and boundary roughness conditions. The trapezoidal geometry of the channel cross section provided a more realistic representation of certain field sites. Results from these tests should be useful for practical purposes such as channel design, erosion protection, river morphodynamic studies, ice formation and growth, sediment transport, and hydraulic structures design and operation. The present paper provides novel findings to fill the knowledge gap in understanding flow behaviour in partially covered trapezoidal channels.

2. Experimental set-up and measurement procedure

Experiments were performed in a high density overlay (HDO) plywood flume at the Hydraulic Research & Testing Facility (HRTF) of the University of Manitoba. The flume was 14 m long, 1.22 m top width, 0.65 m bottom width, and 0.6 m high with a bed slope of 0.25% and side slopes of 1:1.4 (H:V) (Fig. 1). Water level was adjusted using a downstream tailgate. Water flowed from a 20 m^3 head tank to the flume using a 20 hp. pump and PVC pipes. Discharge was measured with an ultrasonic flow meter and kept nearly constant at 65 ± 2 L/s for all experiments. The water level was adjusted using the downstream gate to be 0.2 ± 0.002 m at the measurement location for open water conditions. The average stream-wise velocity was approximately 0.35 m/s at the measurement location for all experiments. Experiments were performed under seven testing scenarios to investigate the effects of partial covers on flow characteristics. Symmetric plywood covers were used to simulate border ice. Four experiments were conducted under a smooth boundary condition (SS) and different coverage ratios of 0%, 25%, 50%, and 67%. The coverage ratio is the ratio of the cover length to the top open water width. Three experiments were conducted under different rough boundary conditions (rough partial ice cover (RI), rough bed and sidewall (RB), and all rough boundary (RR)), all at a coverage ratio of 67%. Rough boundaries were simulated by attaching 13 by 13 mm acrylic bars with 13 cm spacing over the entire flume length (Fig. 1a). To install the partial covers the flow and downstream tailwater level were set, and then the plywood sheets were floated on the water from downstream to upstream to allow water level variation due to the presence of the covers. Once steady state conditions were reached, the covers were fixed to the sidewalls to ensure that they did not move during the long days of testing. Each testing scenario was completed over a duration of 2 days.

Velocity data were collected over a cross section using a Nortek Vectrino II acoustic Doppler velocimeter (ADV) and a Nortek Vectrino + side-looking ADV with an accuracy of ± 1% of the measured value, ± 1 mm/s. A computer-controlled traversing mechanism was used to move the ADVs along the vertical and span-wise directions. Three minute measurements at 100 Hz for the Vectrino II and 200 Hz for Vectrino + were conducted at each measurement point to collect adequate samples to perform analyses (Peters et al., 2015). The ADV signal-to-noise ratio (SNR) was kept above 15 dB by adding seeding material to the water. Measurements were collected each 5 cm along the span-wise and 0.8–1 cm along the vertical direction to cover the whole cross section. Measurements were collected 8 m downstream of the flume inlet where preliminary measurements showed that the flow was fully developed at this location (Peters et al., 2015). The channel bed elevation and water surface profile were recorded at the centerline using a point gage(± 0.002 m) at 2 m intervals along the flume for each experiment to calculate changes in water level and hydraulic gradeline. Energy grade-line was calculated by adding the calculated hydraulic head to calculated velocity head from the average cross sectional velocity.

3. Data analysis

Prior to analysis the collected data was post-processed using two steps to ensure that noise and spikes were removed. Bad data cells were first identified and removed using SNR and correlation thresholds of 15 dB and 30%, respectively. Cells with > 10% of the data below the thresholds were removed. Cleaned data was then de-spiked using the Goring and Nikora (2002) and Islam and Zhu (2013) methods.

The two-layer theory (Chen et al., 2015) was used to divide the velocity profiles into cover and bed zones and then the Clauser plotting technique (Clauser, 1956) was used to calculate friction velocity for the bed and cover boundaries separately using available high resolution velocity data (± 1% of measured value ± 1 m/s) and the following equation:

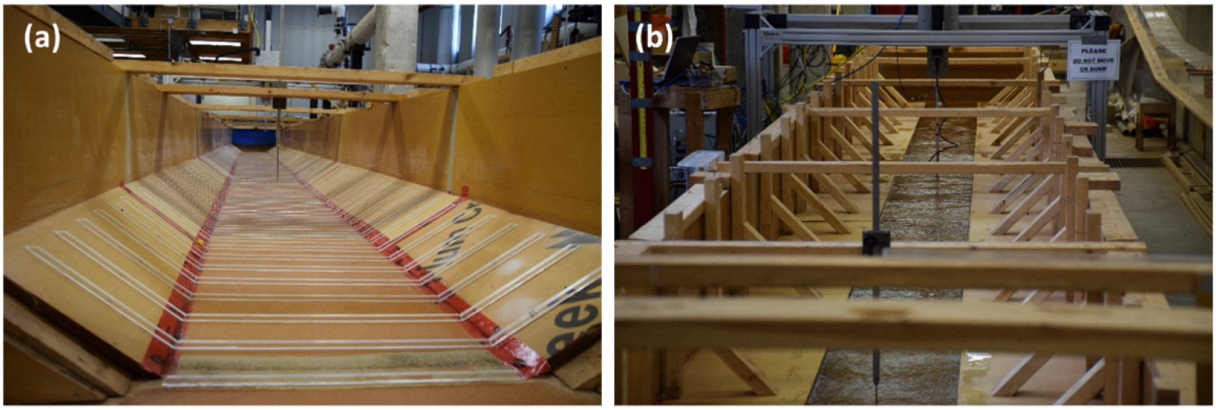

Fig. 1. Experimental setup in the HTRF: (a) open water condition with roughness bars; (b) 67% symmetric partial ice cover.