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Velocity Distribution Characterization in Channels with Partial Ice Cover

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In northern climates where water bodies are subjected to sub-freezing temperatures for part of the year it is important to know how the presence of ice impacts the flow characteristics of channels. While many studies have been conducted in channels that are fully open or completely covered with ice, little is known about the hydraulic characteristics of channels with only a partial cover, such as when border ice is present. The goal of this study was to examine the impact of border ice on the discharge and streamwise velocity distribution in a channel. Using acoustic Doppler velocimetry, detailed three-dimensional velocity measurements were collected in a fully developed cross section of a rectangular flume under steady flow conditions. The influence of different coverages of simulated ice cover and different Froude numbers was explored. It was found that beneath the partial ice cover the streamwise velocity profiles were nearly identical to what would have been measured under a full cover, and the velocity profiles in the open water section were nearly identical to what would have occurred in a fully open water condition, with a transitional region separating these two zones. Increasing the Froude number in the channel decreased the size of the transition zone and low Froude numbers have the potential to expand the transitional zone over the entire open water section. Additionally, for the same Froude number, the same percentage of the open section of the channel was in transition under different amounts of coverage. The data collected thus far represents the most complete experimental dataset of velocities collected in a channel subject to a partial ice cover.

1. Introduction

In northern climates where water bodies are subjected to sub-freezing temperatures for part of the year it is important to know how the presence of ice impacts the flow characteristics of channels. While many studies have been conducted in channels that are fully open or completely covered with ice, little is known about the hydraulic characteristics of channels with only a partial cover, such as when border ice is present. Understanding border ice formation and the impact of its presence on discharge and velocity patterns can help to fill current knowledge gaps and improve existing numerical models, especially since comprehensive, two dimensional river ice models now exist. The improved capability to model ice processes can help to reduce the impact of large spring floods through better planning and management of river ice as well as to reduce ice related energy losses, and ensuing financial losses experienced at northern hydroelectric generating stations.

This paper examines the effect of different symmetric coverage ratios and Froude (F) numbers on the flow in channels with partial ice cover. The discharge distribution of partially covered channels will be re-examined and used to assess the effectiveness of the compound channel method in its prediction. Additionally, the shape and development of the streamwise velocity profile through a cross section of fully developed flow will be characterized to understand the impact of having simultaneous open water and covered sections.

2. Literature Review

For years, researchers have been making observations about how border ice progression affects the discharge and streamwise velocity distributions in natural channels (Hirayama, 1986; Majewski & Baginska, 1988; Miles, 1993; Tsang & Szucs, 1972; Tsang, 1970), but little has been done in a controlled laboratory setting. Tsang (1970) conducted field studies on the Nottawasaga River in southern Ontario to examine how freeze-up on a river alters the velocity distribution. Velocity measurements were collected in vertical profiles every five to ten feet across the river, at vertical intervals ranging from two to six inches, using a propeller-style current meter. He found that when border ice was present the main velocity core was pushed towards the open water section of the channel. Though the maximum velocity was still located beneath the cover, this was attributed to residual centrifugal effects from a meander upstream. While Tsang (1970) did not explicitly draw any conclusions about the nature of the velocity profiles in the open or covered sections, it can be seen from his results that the velocity profile beneath the partial cover has the same appearance as that of an ice covered channel and the velocity profile in the open water area is similar to that of an open channel.

A field study by Miles (1993) examined border ice growth on the Burntwood River in northern Manitoba. Over a cross section, streamwise velocity was measured beneath competent border ice by drilling holes through it. At each location measurements were taken at 20% and 80% of the depth to obtain a depth-averaged velocity. The velocity distribution in the open water section was estimated using a hydrologic, storage indication, reservoir routing model. He found that the larger wetted perimeter in the areas of border ice increased the resistance to flow and therefore decreased the conveyance capacity of those sections, forcing some of the flow into the open water section of the channel. Consequently, the average velocity in the open water section increased with the presence of border ice for the same discharge.

Hirayama (1986) used the principle of conveyance in compound channels to analyze flow beneath border ice during freeze-up on the Yubetsu River in Japan. He found that as border ice grew, a higher percentage of the total flow was located in the open water section. This was also observed by Majewski and Baginska (1988). On the Vistula River in Poland, upstream of an ice jam, flow beneath the border ice had very low velocities while the velocities in the open water section had increased.

Perhaps a more elegant application of the compound channel method was developed by Shen & Ackermann, (1980) where the cumulative discharge distribution was estimated by:

$$\frac{Q_p}{Q} = \frac{A_p\, {R_p}^{2/3}}{A\, R^{2/3}} \tag{1}$$

where $Q, A,$ and R are the discharge, area, and hydraulic radius of the entire channel and $Q_p, A_p,$ and R_p are the discharge, area and hydraulic radius of the section of the cross section being examined, respectively. Equation [1] assumes equivalent bed and ice roughness as well as equivalent wetted perimeters in the ice and bed affected zones but was found to apply well to natural channels with aspect ratios ranging from 7.34 to 134 and ice-to-bed roughness ratios of as low as 1:2. Numerical differentiation of [1] yields the transverse distribution of dimensionless discharge per unit width which means that the discharge distribution across the channel can be predicted reasonably well knowing only the channel geometry. Shen & Ackermann tested Equation [1] and its derivative against open channel, fully ice-covered and partially covered channels with good results.

Previously, the most recent and detailed experimental investigation of the hydraulic characteristics in a channel with border ice was conducted by Majewski (1992). The velocity distribution within a channel with different encroachments of simulated border ice cover and ice-to-bed roughness ratios was measured using a miniature current meter. Experiments were conducted in a 20 m long, 2 m wide flume under steady flow conditions at a discharge of 100 L/s. The depth was maintained at 0.20 m in the open water section of the channel for all tests yielding a cross sectional aspect ratio of 10:1. Time averaged velocity measurements were taken at nine vertical transects across the channel, with six to eight measurements at each transect. He found that as the ice cover encroached farther into the channel, the location of the maximum velocity depressed and the isovels along the surface became pinched together, indicating a higher velocity gradient across the surface of the open water section. By comparing the discharge in each section calculated using the measured velocity profiles to that obtained using the compound channel method, Majewski concluded that while they were qualitatively similar, the difference in the two values could be on the order of 25%, with the amount of flow beneath the ice cover being consistently underestimated by the calculations. These experiments only studied time-averaged velocity measurements in a simple rectangular cross section. Advancements in technology, such as acoustic Doppler velocimetry, should be utilized to enhance our understanding of how channels are affected by border ice. Specifically, the ability of acoustic Doppler velocimeters (ADVs) to record high frequency, three-dimensional velocity time series can be used to characterize both the mean velocity components in all three dimensions as well as explore the impact on the turbulence intensities and turbulent kinetic energy.

3. Methodology

The tests were conducted in a rectangular flume in the Hydraulics Research and Testing Facility at the University of Manitoba. The flume is approximately 14 m long, 1.2 m wide with a bed slope of 0.25%. The flume walls, bed, and simulated ice cover were constructed of high density overlay plywood. The flow depth was maintained at approximately 0.2 m, yielding a 6:1 channel aspect ratio. Ten tests were designed to isolate the effect of the Froude number, coverage ratio, and bed-to-ice roughness ratio on the hydraulic flow characteristics. Table 1 outlines the parameters of each test while this paper will only cover preliminary results from Tests 1 – 7.

Water velocity was measured with a Vectrino II profiling ADV and a Vectrino+ side-looking ADV. The probe head of the ADVs were connected to the main body by a flexible cable rather than a rigid stem, which allowed the ADVs to be oriented in different directions using custom-built mounting mechanisms. This facilitated sampling throughout most of the channel cross section. These instruments were moved through a 2D grid of points, at a cross section located 8 m downstream from the channel inlet, semi-autonomously by a computer-controlled traversing mechanism. Figure 1 illustrates the sampling locations used for three tests: open channel, fully covered, and a typical partial cover, as well as the corresponding ADV orientation. Since the down-looking ADV was found to be the most reliable, it was used whenever possible. The points labelled “Down” were acquired using the Vectrino II ADV oriented normal to the bed. The points labelled “Side” were acquired using the Vectrino II ADV turned 90 degrees so that it was normal to the wall. The points labeled “Up” were collected with the Vectrino+ side-looking ADV oriented to look upwards. Data was collected throughout the cross section except for a region in the lower corner approximately 45 mm high and 65 mm wide.

The ADV sampled data at 100 Hz for 3 minutes at each point as convergence testing indicated that there was no appreciable decrease in error by sampling for longer durations (Figure 2). Figure 3a shows the velocity profile when acquired using the full sampling range of the Vectrino II profiling ADV with some cells overlapping at the ends of each profile. The velocities did not match at the overlapping ends of the sampling ranges, which produced an incorrect saw-tooth profile. This demonstrates that while the instrument is purported to be capable of sampling over a 30 mm range, the data quality drops off at points located farther away from the centre cell and becomes less reliable. The number of cells from which data was collected was therefore limited to the 7 central cells to eliminate the overlap issue shown in Figure 3b. It can also be seen in Figure 3b that the flow became self-similar, or fully developed, 2 m from the inlet.

For the open channel and fully covered scenarios, data was collected over the entire cross section of the channel to assess symmetry. Figure 4 shows the results of the symmetry assessment for the open channel test at two locations for the three mean velocity components. The symmetrical shape of the plots is apparent, where the right hand side and left hand side (looking upstream) values overlapped reasonably well. In the case of the spanwise velocity they were equal and opposite as expected. The streamwise velocity in the profiles farther from the center did not overlap as well as the profiles closer to the center, however, they were deemed to be sufficiently close to warrant measuring flow in only half of the channel for the partial ice cover tests. Although not shown, similar analysis also demonstrated that the mean flow components in the fully covered flow and the turbulence intensities for both tests were symmetric.

4. Results and Analysis

Figure 5 illustrates the streamwise velocity distribution, normalized by the average velocity of the entire cross section, for the open channel, fully covered and 67% coverage tests, all at a Froude number of 0.25 (i.e. Tests 1, 2 and 3, respectively). For the open channel flow data in Figure 5a the velocity increased monotonically from the bed and side walls towards the surface and center respectively. The fully covered channel flow in Figure 5b likewise increased from the bed and side walls but began decreasing after approximately mid-depth due to the influence of the surface cover. Figure 5c shows the velocity distribution for the channel that is partially covered, and exhibits characteristics from both the completely open and completely covered distributions. The higher valued contour levels in the central region of Figure 5c relative to both Figure 5a and Figure 5b demonstrate that flow has been redistributed from beneath the ice cover into the open water section.

4.1 Discharge Distribution

As mentioned previously, one way to determine the discharge distribution in a cross section is the compound channel method. Figure 6 shows that, when applied to the data from Tests 3-7, it provided a reasonable estimation for the allocation of discharge beneath the cover. Interestingly, while Majewski (1992) found that this method consistently underestimated discharge beneath the cover, these recent tests showed the opposite. Possible explanations for this discrepancy include: the density of collected points affecting the accuracy of the measured discharge, channel aspect ratio effects, and instrumentation accuracy.

Tests 3-5 which examined the effect of Froude number comprise the cluster of circular points labeled with 67% coverage. This implies that for identical coverage ratios different Froude numbers have no appreciable effect on the discharge distribution within a channel with partial ice cover. The influence of other parameters, such as channel shape, aspect ratio, and ice-to-bed roughness ratios on the discharge distribution has yet to be evaluated in detail.

4.2 Streamwise Velocity Distribution

An underlying assumption when using the compound channel method is that along the interface of the sections there is no mixing and no internal stresses. This implies that the characteristics in one section do not affect the other. This approach has been shown to work for discharge (Shen & Ackermann, (1980)), however, intuitively there will not be a discontinuity in the velocity distribution. Certain profiles in the open water section may not strictly follow the theoretical curves of an entirely open channel and certain profiles in the covered section may not strictly follow the theoretical equations of a fully covered channel. A different approach is required.

Based on observations from this study, channels with a partial ice cover contain regions where the streamwise velocity profiles exhibit the same characteristics as if the channel was fully covered, areas where it is the same as if the channel is open, as well as a transition region between the two where the profile was neither the same as fully covered nor open channel flow.

Figure 7 illustrates an example of each of these conditions. Each of the panels in the figure shows a streamwise velocity profile, normalized by the average velocity of the cross section, taken at the same location for three different tests: the open channel test (Test 1), the fully covered test (Test 2), and the baseline partial cover test (Test 3). By comparing the shape of the partial cover profile to the other profiles, the velocity at that location in the channel was characterized. Panel a) demonstrates a profile where the partially covered channel exhibited the same characteristics of an open channel. Under this normalization the two profiles were not self-similar, with the partial cover profile having a greater magnitude than the open channel. If, instead of the average velocity of the cross section, each profile had been normalized by its respective average velocity the profiles become self-similar, (not shown). This difference is a result of the flow redistribution that occurs in the presence of border ice. Since some flow is transferred from beneath the cover to the open water section in a partially covered channel, the streamwise velocity profiles in the open water section will have a higher value when normalized by the average velocity of the cross section. A similar observation can be made of panel c), except instead of the partial cover profile having a greater U / U_{avg} than the fully covered profile, it had a lower value. This agrees with the observations of Hirayama (1986), Majewski & Baginska (1988), Majewski (1992), and Miles (1993) that in channels with partial cover, areas beneath the cover have a lower than average velocity and the open section is higher than average indicating a transfer of discharge from beneath the cover to the open section. Unlike the previous two panels, in panel b), the velocity profile from the partial cover dataset was not similar to either the open channel or the fully covered data. The profile exhibited a transitional shape. Over the lower half of the depth the three profiles developed similarly, but towards the top of the profile the difference becomes apparent. The profile from the partially covered test continued to increase along with that of the open channel data until a relative distance from the bed of approximately $Z/D = 0.8$ where it began to decrease. The decrease was caused by lower surface velocities which resulted from resistance from the leading edge of the ice. When each profile was normalized by its respective average velocity, (not shown), the velocities near the surface exhibited a fan shape with the values for the open channel greater than the partially covered channel, both of which were greater than the fully covered channel.

A summary of the characterization for each vertical profile from Test 3 is shown in Table 2 where “O” indicates the profile has a similar shape to an open channel, “C” as similar to a covered channel, “T” as a transitional shape, and “W” meaning the velocity profile is most dominated by effects from the wall. The grey cells indicate the profiles located directly beneath the edge of the ice cover. The dominance of the cover is shown extending up to and including the ice edge where the velocity profile still exhibited the same shape as the profile from the fully covered channel data. In the open water section was a region near the center where the velocity profiles exhibited the same characteristics as an open channel. Between these two regions was the transitional zone where the velocity profile cannot be characterized as covered or open, and instead developed from one to the other.

The results of Tests 3–5 in Table 3, demonstrate that the Froude number does have an impact on the characterization of some of the velocity profiles. Generally, for the higher Froude condition, the transition zone is smaller and closer to the edge of the ice. As the Froude number decreases the transition region extends farther into the open area of the flow. Under the lowest tested value, the velocity profiles in the open water section all exhibited transitional shapes rather than returning to fit the theoretical open channel profile. This trend occurs in spite of the fact that the discharge distribution between these tests was quite similar. Interestingly, under all three tests the cover maintains its influence up to the profile located directly beneath the edge of the ice.

Comparing the results of Tests 3, 6 and 7 in Table 4, the velocity profiles beneath the cover are all characterized as if the entire channel is covered, up to and including the edge of the ice. This agrees with the previous results examining the impact of Froude number. As the cover encroaches farther into the channel the size of the transition zone reduces. However, focusing on only the open water section and normalizing the width to be the same for each test, (Table 5), the relative size of the transitional area remains essentially constant, even though the absolute amount of the channel that is in transition decreases.

5. Conclusions and Future Work

The data collected thus far represents the most complete experimental dataset of measured water velocities in a channel with a partial ice cover; from which several conclusions may be drawn. First, the compound channel method provides a reasonable means of estimating the distribution of discharge in a channel with partial ice cover. Second, beneath the covered section, streamwise velocity profiles exhibit the same shape as if the channel at that location were completely covered, up to and including the leading edge of the ice. This occurs regardless of the Froude number or the amount of the channel that is covered. Third, higher Froude numbers reduce the amount of the open water section that is required for transitioning from covered flow profiles to open channel profiles. Further, at low Froude numbers with narrow open water widths, the width of the transition zone may expand to encompass the entire open water section. Lastly, for the same Froude number, the same percentage of the open section of the channel will be in transition under different amounts of coverage.

The data collected in this research will also be used to characterize the vertical and spanwise velocity distributions, the impact of border ice on the three dimensional turbulence intensities as well as the boundary shear stress distribution. Additional experiments should be conducted to examine the impact of channel aspect ratio, ice cover asymmetry, and channel shape as well as to supplement the observations already made and develop a more comprehensive understanding of the effects border ice has on the flow. Future researchers may well consider increasing the density of data collection in the transition zone to enable more accurate characterization. Lastly, once a more complete understanding of these data sets is obtained, the results of these and future experiments should be considered for incorporation into comprehensive numerical models.

Acknowledgments

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Tables:

Table 1. List of planned experiments with their respective testing conditions.

	Condition											
	Froude Number			**Channel Coverage**					**Roughness**			
Test	0.10	0.25	0.50	0%	25%	50%	67%	100%	Bed is rough	Ice is rough	Bed is smooth	Ice is smooth
1		X		X							X	
2		X						X			X	X
3		X					X				X	X
4	X						X				X	X
5			X				X				X	X
6		X			X						X	X
7		X				X					X	X
8		X					X		X			X
9		X					X			X	X	
10		X					X		X	X		

Table 2. Velocity profile characterization over a cross section for the base partial cover case of F = 0.25 and 67% coverage.

Y (mm)	℄	50	100	150	200	250	300	350	400	450	500	550	600
Characterization	O	O	T	T	C	C	C	C	C	C	C	W	W

Table 3. The impact of Froude number on velocity profile characterization in a cross section is isolated for channels with 67% coverage.

Y (mm)	℄	50	100	150	200	250	300	350	400	450	500	550	600
F = 0.10	T	T	T	T	C	C	C	C	C	C	C	W	W
F = 0.25	O	O	T	T	C	C	C	C	C	C	C	W	W
F = 0.50	O	O	O	T	C	C	C	C	C	C	C	W	W

Table 4. The impact of coverage ratio on velocity profile characterization in a cross section is isolated for channels with F = 0.25.

Y (mm)	℄	50	100	150	200	250	300	350	400	450	500	550	600
25%	O	O	O	O	T	T	T	T	T	C	C	W	W
50%	O	O	O	T	T	T	C	C	C	C	C	W	W
67%	O	O	T	T	C	C	C	C	C	C	C	W	W

Table 5. The impact of coverage ratio on the characterization of velocity profiles in a cross-section is re-examined after normalizing the width of the open water section.

	℄	Open Water Section	Edge
25%	O	O O O T T T T T	C
50%	O	O O T T T	C
67%	O	O T T	C

Figures:

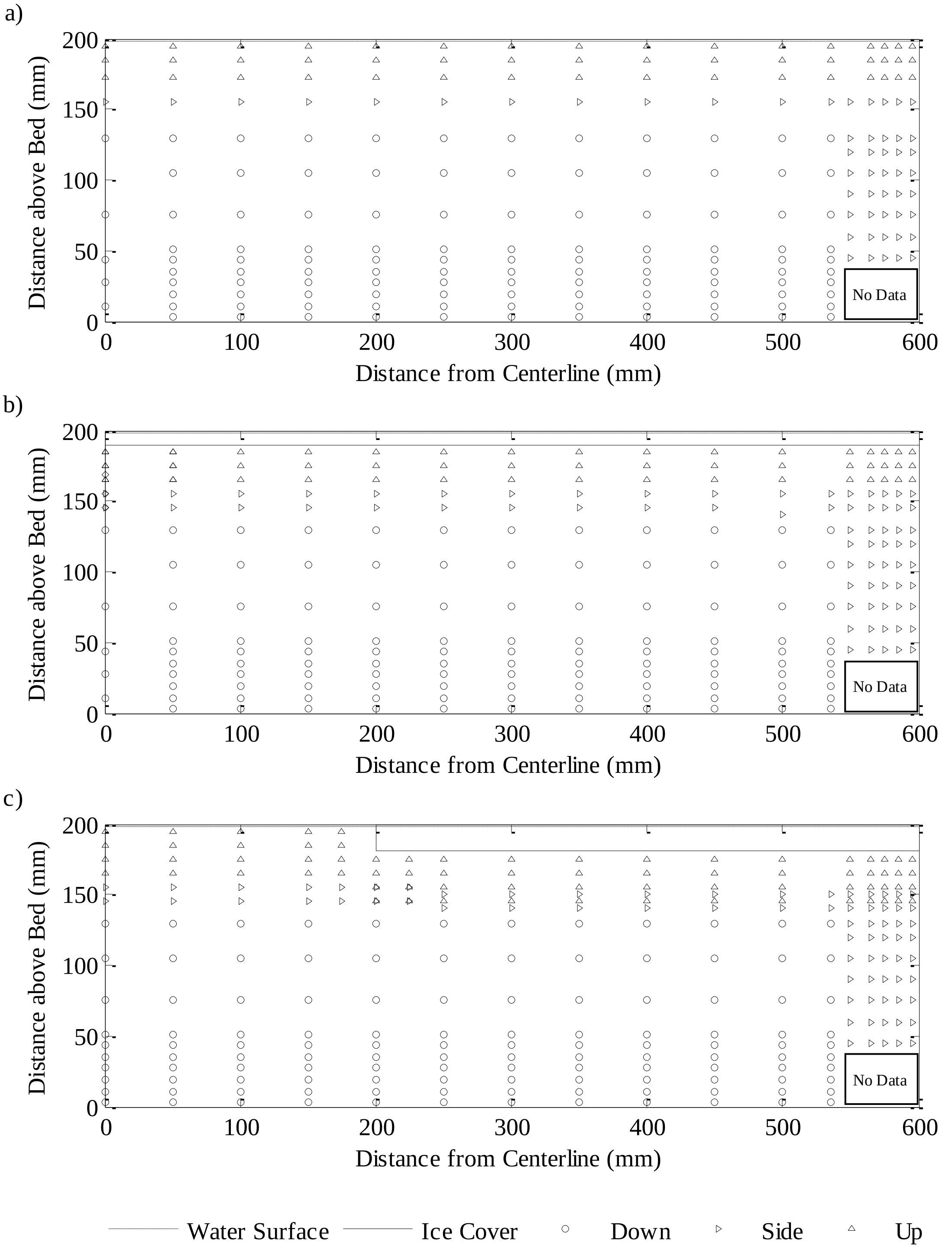

Figure 1 . Typical sample locations and orientations for: a) open channel, b) fully covered, and c) partially covered testing schemes.

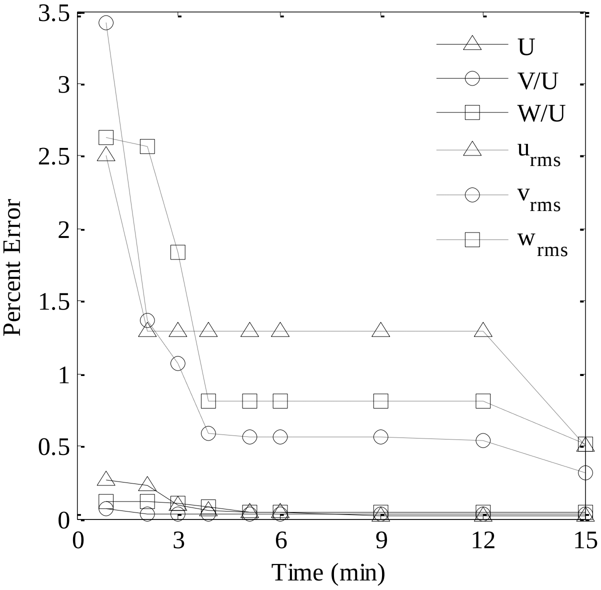

Figure 2. Convergence test results for selected flow statistics.

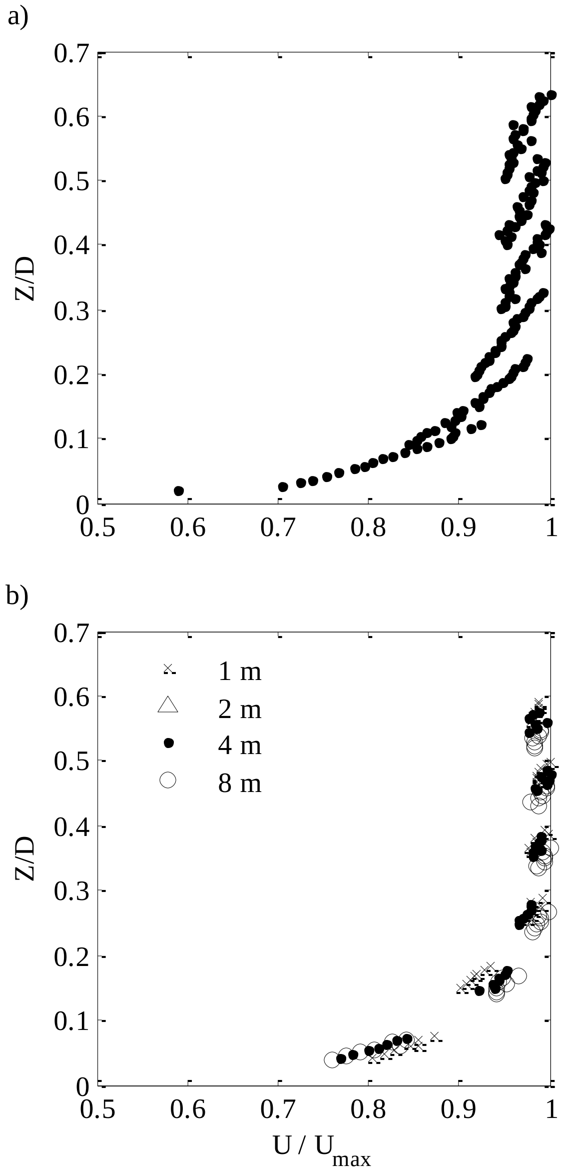

Figure 3. Developing length assessment showing: (a) the normalized streamwise velocity profile 4 m from the inlet, showing data collected over the full sampling range of the instrument; and (b) the self-similarity of dimensionless velocity profiles for different distances from the inlet with data collected using only the central 7 cells.

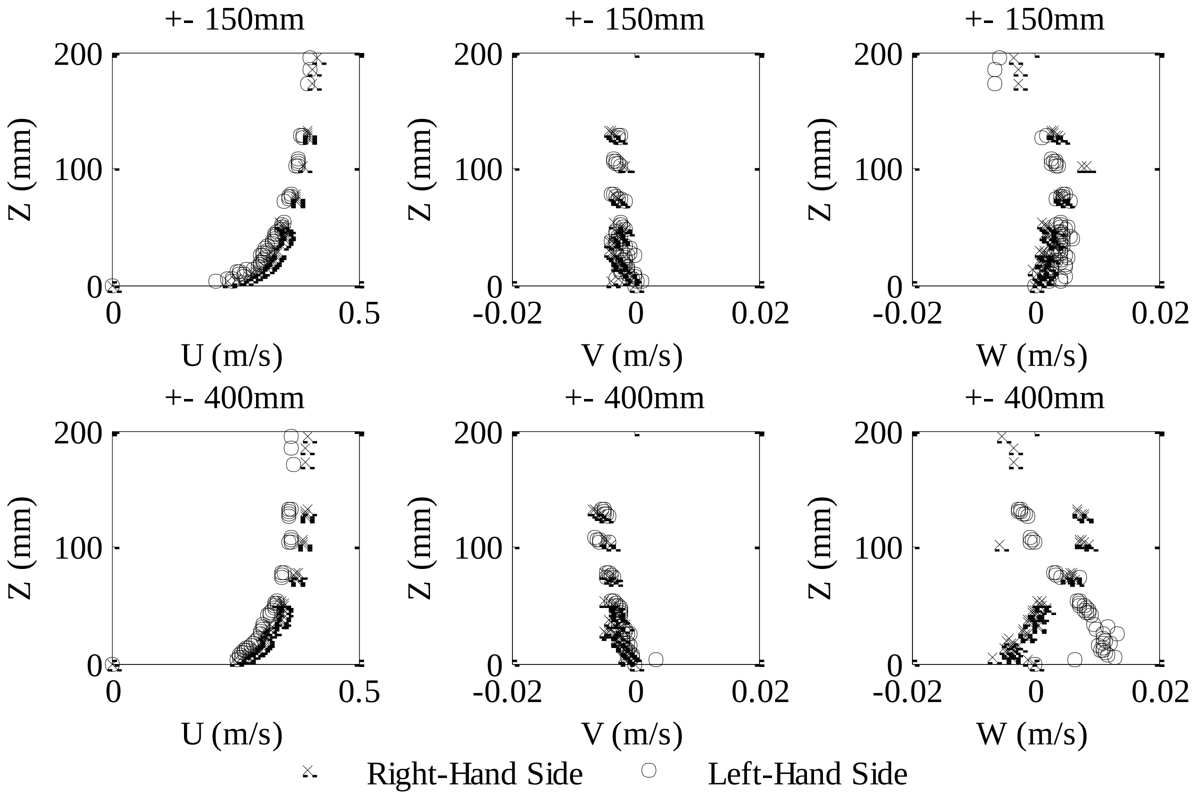

Figure 4. Plots showing symmetry in the mean velocity components of flow for two distances from the centerline of the channel: 150mm (top) and 400mm (bottom).

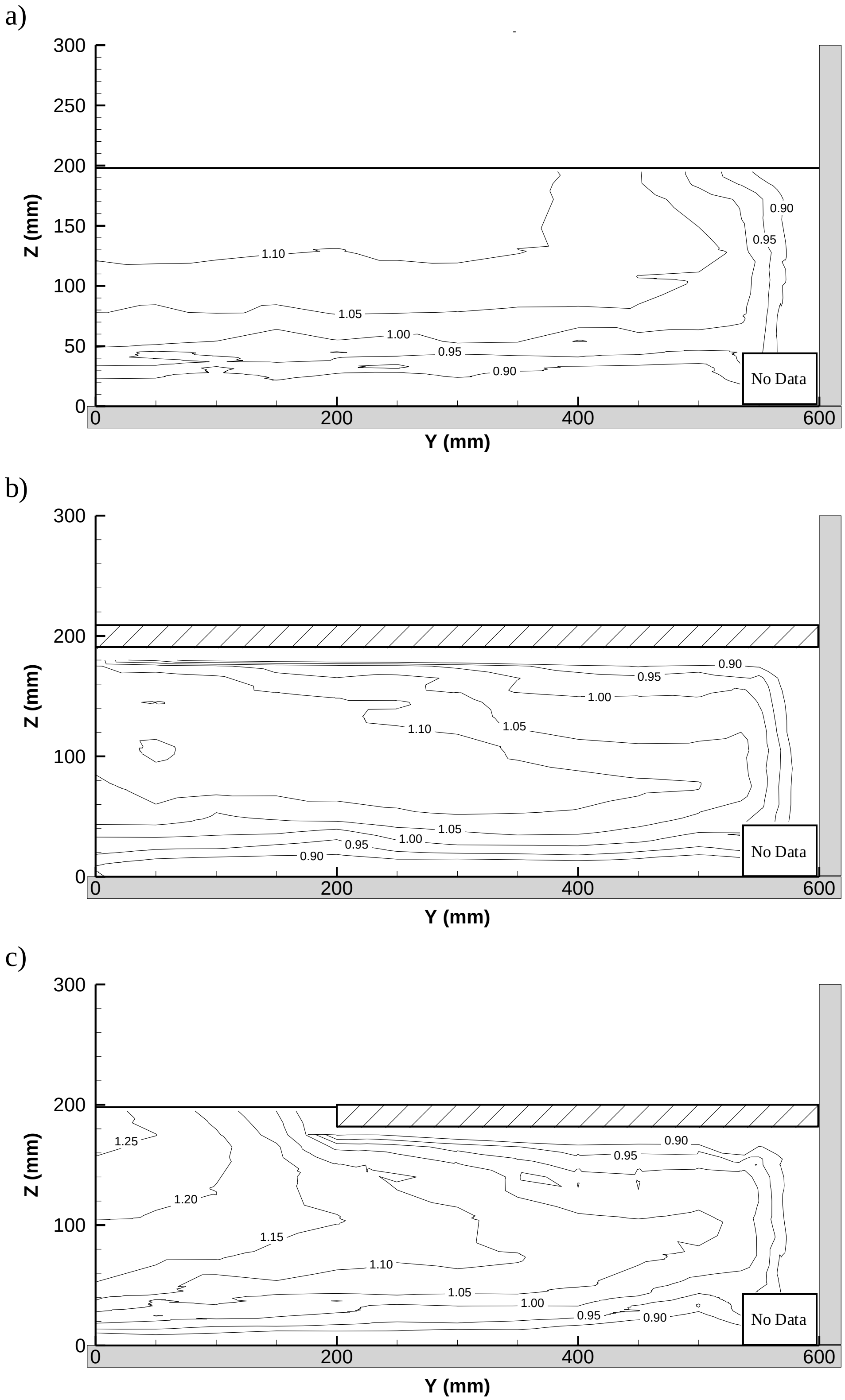

Figure 5. Contours showing U / U_{avg} for: a) Open Channel, b) Fully Covered, and c) 67% Coverage, all at a Froude number of 0.25.

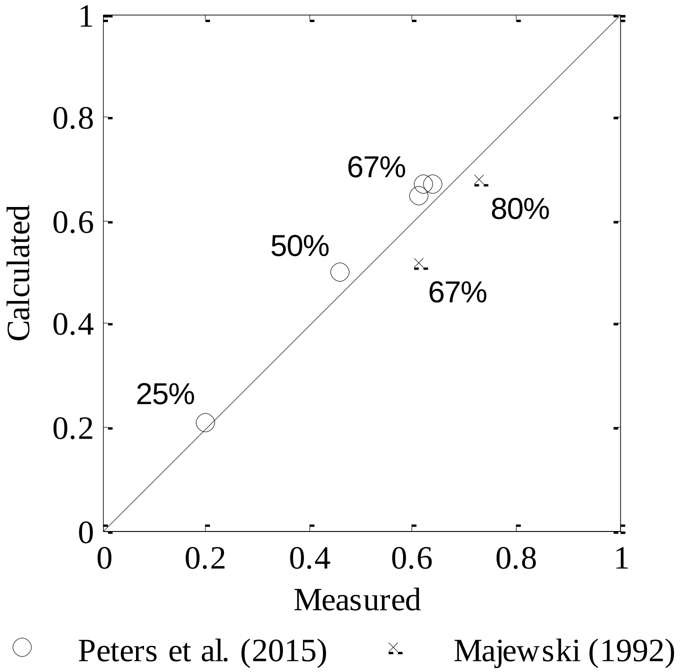

Figure 6. A comparison of the discharge obtained by integrating the measured velocity (measured) and using the compound channel method (calculated). Labels indicate surface coverage as a percent.

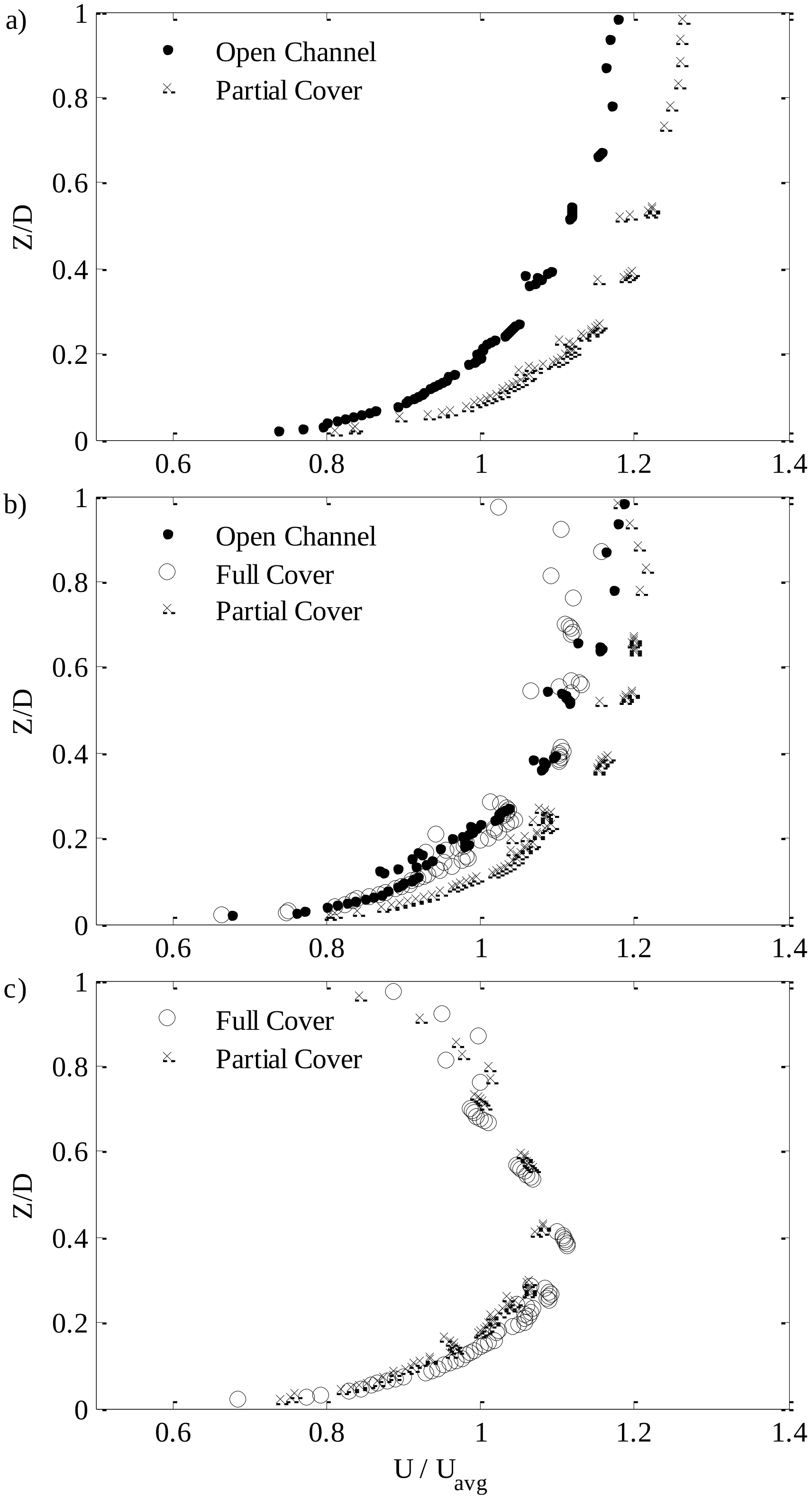

Figure 7. Streamwise velocity profiles normalized by their respective average cross sectional velocity are shown where the profile from the partial cover test can be characterized as: a) similar to the open channel profile, b) transitional, and c) similar to the fully covered profile.