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FRICTION MEASUREMENTS OF ICE COVER: THEORY AND PRACTISE IN RIVER PÄNTÄNEENJOKI

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ABSTRACT: Estimation of resistance coefficient for ice-covered channel is much more complex than for open channel due to difficulties in determination of ice roughness. The aim of this paper is to describe different methods and problems arising in direct measurement of roughness of ice cover and especially problems in indirect measurement with the help of discharge, water level and thickness of ice cover. Results from indirect roughness measurements in River Päntäneenjoki are presented in this paper. Total resistance coefficients of the channel were remarkably lower in winter than in summer, which was quite unexpected. In this paper, reasons for illogical results are discussed.

1 INTRODUCTION

Flow resistance can vary tremendously during different seasons. For example, growth of vegetation in summer and formation of ice cover in winter can increase resistance coefficient significantly. Effect of vegetation and other factors causing roughness in summertime have been studied extensively, but the effect of ice cover is rather vague.

The roughness of ice cover has not been investigated much, although some suggestions on resistance estimation of ice-covered channels can be found in literature for hydraulic engineers. Formation and growth of ice cover has been researched quite widely. Only some studies concerning velocity distribution under ice cover have been published (e.g. [2], [5], [6], [7]), and in these articles, the roughness of ice cover or the compound roughness of bottom and ice have not been discussed in any way. Some laboratory studies have been done with artificial ice cover (e.g. [8]). Some field measurements have been carried out in natural rivers in 1970's (see references in [1]). In this article, the aim is to describe the effect of ice cover on flow and find out how the resistance coefficients vary in winter and summer conditions in a natural river. In literature (e.g. [1]) it is said that resistance of flow under ice cover is almost always higher that during open channel flow. Different measuring techniques and devices are not concerned in detail in this paper.

Ice cover is a stationary layer of ice positioned on the top surface of the waterway. It can consist of solid ice, slush ice and/or snow [4]. In normal flow condition, ice cover almost doubles the wetted perimeter and thus, has significant resistance effect on flow. However, ice cover formation process has major relevance to roughness. When discharge is increasing after solid ice cover formation, flow may become pressurised like pipe flow. Water may also flow on the top of the ice if the discharge has increased a lot. Furthermore, when flowing on ice water can freeze again and again due to temperature variations, causing situation of several ice covers on top of each other and water flowing between them. In case of decreasing discharge, there can be air between the ice cover and water and thus, flow behaves like in open channel. If freezing starts exceptionally from the middle of the channel, ice can float in water. Complexity is even larger, as all these variables depend on space and time [1].

2 DIRECT DETERMINATION OF ICE COVER ROUGHNESS

Direct determination of the roughness of the ice cover is very complex. It is not a common method [1], but basically it is possible. If roughness is directly measured, it should be measured from several places in the cross section and from many sides of each measurement hole to ensure reliable results. The roughness can vary up to 100% in the opposite sides of the hole. In case of significant variation of the ice roughness, minimum and maximum values are given along the average values in every measurement point. Another option is to saw out a piece of ice that represents well the whole ice cover and with some new computerised equipment determine the relief of the bottom of the ice. These methods are not presented in detail in this paper.

3 INDIRECT DETERMINATION OF ICE COVER ROUGHNESS

There are also ways to indirectly estimate the roughness of ice cover. One method is to determine the roughness from the velocity distribution. For example, Larsen (1969, ref. [1]) has presented a method for estimating roughness height separately for ice cover and channel bottom. The roughness height can be obtained from the formula

$$k_{si} = 30Y_i e^{-a_i} \tag{1}$$

where Y_i [m] is the distance of the boundary from the isoline of the maximum velocity and

$$a_i = \frac{V_0}{V_0 - V_{mi}} \tag{2}$$

and V_0 [m/s] is the maximum velocity of the vertical and V_{mi} [m/s] is the mean velocity (integral of the velocity over Y_i divided by Y_i). This method is said to be quite reliable in big channels with small roughness elements, i.e. channels where Karman-Prandtl logarithmic velocity profile is a reliable estimation. Also some other methods to estimate the roughness from velocity distributions are explained in [1] and [9].

Another possibility is to determine the ice roughness indirectly by the relationship between the total roughness of the channel and its bottom roughness. If the roughness of the bottom is known in the same flow situation in summertime, the roughness of the ice cover can be determined on the basis of the friction coefficient estimated from the head loss measurements in wintertime [1]. However, Kivisild (1959, ref. [1]) points out that the bottom roughness can be very different in winter and summer.

Indirect measurements are not easy to perform. To determine the roughness of ice cover indirectly, discharge, water levels in each cross section and thickness and depth of ice in each cross section should be measured. Measurement of hydraulic parameters in a river is significantly more complex and laborious to perform during ice cover than in summer conditions. In winter measurements, the river reach should be selected so that the ice cover is homogenous and continuous on the whole reach, and the reach is straight, because the thickness of ice varies in channel bends. When flow is assumed to be steady, the energy gradient is considered to be the same as the one with the same water levels without ice cover. This can lead to major error if the thickness of ice is varying much between the measured cross sections.

3.1 DISCHARGE MEASUREMENTS

The winter discharge can be determined by measuring flow velocities in short intervals throughout the whole cross section. The discharge is then the area of cross section multiplied by the average flow velocity. There are several newly developed velocity measuring instruments that can be used to determine average flow velocity. Their properties or applicability in winter conditions are not discussed in this paper. Whatever method is used, the measurements are usually carried out from holes made in the ice cover. After measuring, the holes should be filled by snow or frazil ice to prevent water from rising on ice along discharge changes [3]. If an open cross section is available near the measurement reach, it will most likely be a better place for more accurate discharge measurement.

The fewer the cross sections and the verticals selected the easier the measurement procedure. Boring of holes is slow and laborious, especially when the ice cover is thick. However, the fewer the verticals and the cross sections, more inaccuracy and possible error sources can be found. The shape and variation of the flow velocity profile requires extreme accuracy from the measurements.

According to some instructions, velocities should be measured in 10-100 points [3] or 11-121 points [2, 6] in each cross section depending on the size of the channel and method used. These mean 10-20 verticals and 1-5 depths [3] or 11 verticals and 1-11 depths [2, 6]. The verticals should be located in the bends of the bottom and places where the velocity changes are largest. The velocities are measured in certain percentage depths of the verticals.

Teal et al. [5] suggests that in some channels, the more detailed discharge measurement can be simplified reliably to e.g., one-point, two-point, three-point or five-point method so that only one, two, three or five points are measured in each vertical, respectively. Teal considers the two-point velocity estimation most reliable, as the vertical velocity profile is following the logarithmic approximation quite well.

Some one-point methods are also used. In them, the velocity is measured from depth $0.4D$, $0.5D$ or $0.6D$ to estimate the discharge. In the beginning of the measurement period, the normal discharge measurement is carried out and an individual coefficient is calculated for each channel to correct the one-point velocity. According to Walker [6], best results are achieved with the depth $0.5D$. Adequate number of verticals must be selected, to take into account large changes in velocities and bottom shape. If the ice cover melts and refreezes during winter, a new correction coefficient must be determined.

Although the fore mentioned methods might decrease the work of the measurements, in practice methods that reduce the number of verticals would be more useful, as drilling holes to the ice cover is the most laborious task in the measurements, especially when ice is thick. Because of highly variable bottom shapes and velocity distributions, this is normally not possible in general measurement guides. However, in practice, for a certain channel discharge can be approximated by reducing verticals, if good correction coefficients can be determined.

3.2 MEASUREMENT OF WATER LEVEL

The measurement of the water level can be very complex. The ice cover can float in water, or there might be space between ice and water. The ice cover may be of irregular thickness and cause error in the assumed area of cross section. Boring a hole to the ice can cause changes in the pressure under ice cover, causing rise or decrease of the water level.

The water level can be measured from the same boring holes as discharge. When measuring discharge, the water levels must be measured at the same time from the cross section of discharge measurement and three channel widths upwards and downwards [3]. The co-ordinates of each cross section with measured water level are also needed. The water level and the thickness of ice should be measured in more than one point in each cross section to ensure the uniformity of the ice cover. In case of very uniform channel reach, measurement points of the water level can be reduced.

3.3 MEASUREMENT OF THICKNESS OF THE ICE COVER

The thickness of ice is measured simultaneously with water level measurement by a thickness gauge. In case of layered ice cover, thickness of each water and ice layer is measured from bottom to the surface (fig 1). Furthermore, the water level from the bottom of the ice is measured. Water layers inside the ice cover can be neglected from discharge estimation, as the flow velocity is negligible.

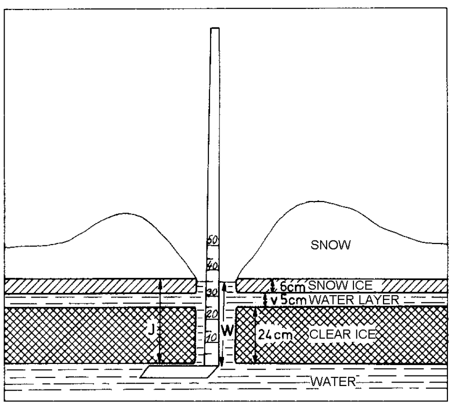

Figure 1. Measurement of ice thickness [3]

4 INDIRECT FRICTION MEASUREMENTS IN RIVER PÄNTÄNEENJOKI

4.1 MEASUREMENTS

Discharge, water level and ice measurements were carried out in 1997-2000 in River Päntäneenjoki, to compare the resistances during ice cover and open water flow conditions. River Päntäneenjoki situates in Western Finland. Its mean high discharge is 22 m^3/s and the catchment area is 210 km^2. Three rather uniform reaches were selected for measurements. Reach P1 is fairly sinuous with very little bottom vegetation but some bank vegetation. Reach P2 was constructed in 1998 with various bioengineering methods. The reach has large sinuosity and moderate vegetation in both bottom and banks. Some woody debris can be found in several cross sections of the reach. Reach P3 has high sinuosity and moderate bottom vegetation. However, the bank vegetation is dense and woody debris can also be found quite a lot. Soil is cohesive, mainly silt or clayey silt.

In winter, discharge measurements were carried out in 8-12 verticals and 1-6 depths of the vertical in each cross section. A propeller type current meter with a rod suspension was used. Because of laborious weather conditions, winter measurement reaches in River Päntäneenjoki were only one hundred meters long, compared to about 1000-m reaches in summer. Number of measurements in each section is presented in Table 1. Winter measurements were carried out in February-April when the ice cover was thick enough for safe measurements, and summer measurements were made between April and October.

Table 1. Number of discharge and water level measurements each year (o = before construction, n = after construction)

Number of measurements	Measurement reach of the river		
	P1	P2	P3
open water 1997	2	3(o)	0
open water 1998	6	4(o)+2(n)	6
open water 1999	5	4(n)	4
open water 2000	3	5(n)	3
open water / total	16	18	13
ice cover 1998	2	2(o)	2
ice cover 1999	3	2(n)	2
ice cover 2000	2	2(n)	2
ice cover / total	7	6	6
total	23	24	19

4.2 COMPUTATION OF FIELD DATA

When computing results, the flow was assumed steady; i.e. Bernoulli's equation was used:

$$z_1 + h_1 + \frac{v_1^2}{2g} = z_2 + h_2 + \frac{v_2^2}{2g} + f\frac{L}{4R}\frac{v^2}{2g} \qquad (3)$$

where z is the bottom elevation [m]
h is the water depth [m]
v is the mean velocity [m/s]
f is Darcy-Weisbach resistance coefficient to be solved [-]

L is the distance between cross sections [m]
R is the average hydraulic radius of the cross sections $=A/p$ [m]

Darcy-Weisbach friction factor f can also be determined with the help of roughness height k [m] from the iterative equation

$$\frac{1}{\sqrt{f}} = -2\log\left(\frac{2.51}{\mathrm{Re}\sqrt{f}} + \frac{k/4R}{3.71}\right) \qquad (4)$$

where Re is Reynolds' number $=vR/\nu$ [-]
R is hydraulic radius [m].

This formula can thus be used to estimate the roughness height from the indirect measurements of Darcy-Weisbach friction factor.

4.3 RESULTS

In every measurement made during ice cover, flow was pressurised i.e. water rose to the measuring hole although not on ice. Thickness of ice varied from 0.18 m up to 1.60 m. During open water, the measured discharges varied from 0.3 m^3/s to 20.6 m^3/s, and in winter only from 0.3 m^3/s to 0.85 m^3/s. Therefore, the results of the winter measurements were compared only to summer measurements with small discharge. However, the results from the summer measurements (discharge 0…20.6 m^3/s) are presented in fig. 2. Values of the resistance coefficient f varied from 0.07 to 20.3 in summertime (although in the figure, the largest f values have been left out due to the size of the figure).

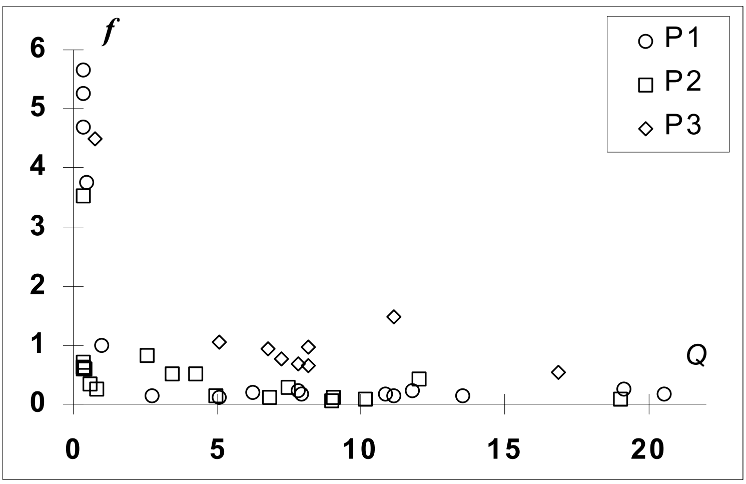

Figure 2. Results of indirect friction measurements in Päntäneenjoki, without ice cover: Darcy-Weisbach f as a function of discharge Q (m^3/s)

During ice cover, the pressurised water level (i.e. the level where water rises in hole) was higher than water level in open water condition at the same discharge, as it should be also according to [4]. The flow depth (i.e. the depth of water under ice cover) was almost the same as water depth during open water, only about 10% lower. The water level varied from 1.2 m to 2.3 m in ice conditions, and the average flow depth under ice from 0.58 m to 1.04 m. In summertime, average water depth was from 0.77 m to 1.13 m during small discharges and up to 4.1 m in mean high discharge (fig. 3).

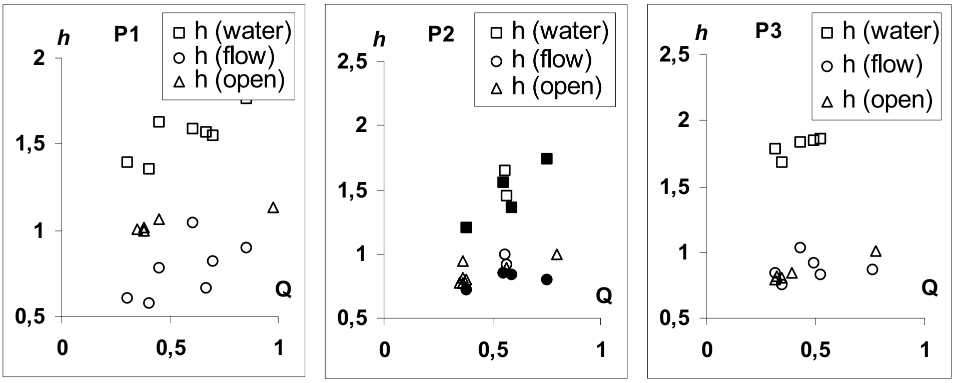

Figure 3. Water depths (i.e. the level where water rises in hole) and flow depths in winter and depths in summer as function of discharge Q (m^3/s) in River Päntäneenjoki (in P2 filled circles and squares after engineering works).

Resistance coefficient f was found to be significantly smaller in wintertime than in summertime (fig. 4). Reasons for small resistance values can be speculated in many ways. Due to the ice cover, the area of cross section somewhat reduces. This causes increase in the flow velocity compared to similar open channel conditions. Also the wetted perimeter is significantly larger, reducing hydraulic radius. In addition, vegetative roughness is almost totally missing in winter conditions.

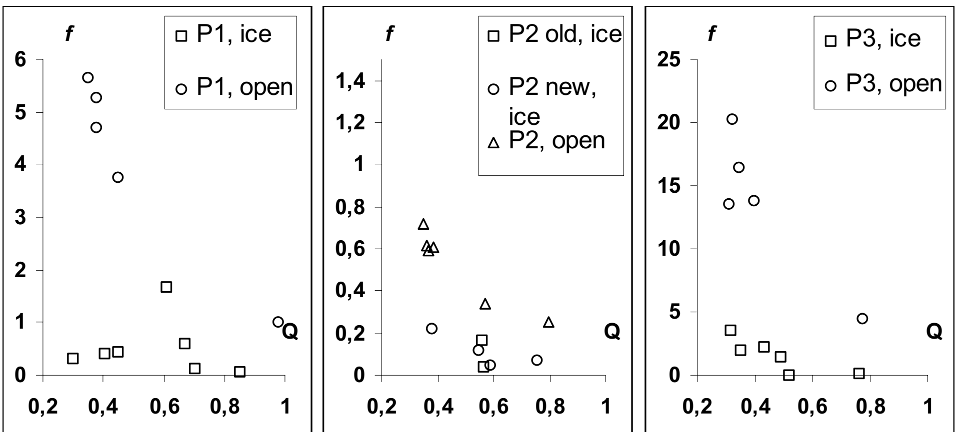

Figure 4. Darcy-Weisbach f as function of discharge Q (m^3/s) in River Päntäneenjoki. Results with and without ice cover are compared.

The friction factor in wintertime decreased to about 40% of the one in summertime, because of the significant increase in wetter perimeter and a decrease in the area of cross section. Also the reduction of cross section caused an increase of 15-35% in flow velocity. From the last term of the eq. 3, it can be seen that 60% reduction of hydraulic radius and 20% increase in flow velocity can reduce the friction factor about 28%, if the other flow conditions remain the same.

Another reason for small values could be that the ice cover is very smooth and this over-compensates the effects of hydraulic radius. This was tested by setting the roughness height of the ice cover very smooth (k = 0.5 mm) and computing k for the bottom by compound roughness formulas. The roughness height of the bottom could be even 200 mm to get the computed friction coefficients, although in summertime bottom roughness height was computed to be only about 6…15 mm. Hence, the smoothness of ice cover would explain well the decrease in the friction coefficient f. However, by investigating the velocity distributions in cross sections (fig. 5), it could be seen that near the bottom and near the ice cover the isovels are within similar distances. This gives an idea that the roughness of ice cover and bottom are not very different i.e. ice cover is not smooth, unless the bottom is significantly smoother in winter than in summer. This does not sound very probable, because the channel is too deep for the soil to thoroughly freeze due to frost.

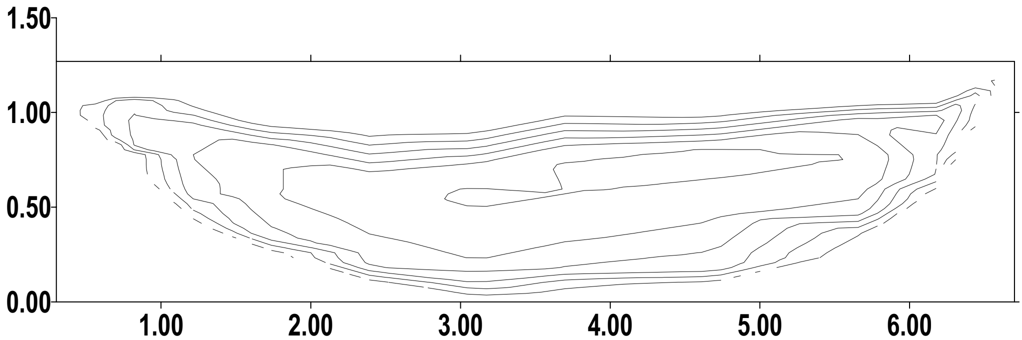

Figure 5. Example of measured velocity distribution in ice-covered channel with maximum velocity of 0.26 m/s and mean velocity 0.19 m/s. Width and height in meters.

Table 2. Sensitivity analysis for measurement or computation of resistance under ice cover

Parameter	Deviation from measured / computed value	Maximum error in resistance coeff.
h	+/- 2 cm	8 %
Q	+/- 20 %	12 %
p	+/- 20 %	8 %
A	+/- 20 %	17 %

Larsen's method (eq. 1 and eq. 2) was also tested for part of the data to see the difference in roughness height estimation. By this method, the roughness height for both ice and bottom was around 30-50 cm with variation of over 50% in a single cross section. This sounds remarkably overestimated when comparing to summertime roughness height values of the bottom, 6…15 mm.

Sensitivity analysis was carried out to estimate the error made by the measurements or computation of the cross-sectional parameters in results. Maximum errors found in analysis are presented in Table 2. It can be seen that small values cannot be explained alone with the measurement or computation errors but a physical reason must be found.

5 CONCLUSIONS

Flow measurements under ice cover are not as accurate as in open water conditions. The features of the velocity profile are not as well known as in open water flow, causing inaccuracy in discharge calculation. Furthermore, the wetted perimeter of the ice cover and thus the area of cross section are very difficult to determine accurately, due to varying thickness of the ice cover. The measurement procedure itself is a very laborious task, as e.g. in River Päntäneenjoki the ice cover was up to 1.6 m thick during the measurements.

The results gained in these measurements were quite surprising, as they were quite the opposite of what was expected. However, although the small Darcy-Weisbach friction factors were different from values presented in literature (e.g. [1]), they could be explained with changes in hydraulic radius and average flow velocity. This theory is also supported by symmetrical velocity distributions in each cross section. Further research must be carried out in this topic.

Several methods for estimating roughness of ice cover exist, but the results are very variable. More physical research should be carried out to get more reliable methods for estimating friction of ice cover e.g., in a flume with a real ice cover.

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