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Experimental study on the seepage flow through the ice jam

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In light of the observed climate change, there is a need for better understanding of river ice processes for managing water resources in the cold regions. Ice jams produce significant resistance which may cause rise of water level and flooding. The jam resistance is only referred to the roughness of its underside, and this approach lead to exceptional roughness coefficients which has no physical explanation. Number of evidences and facts showed the analogy between the seepage flow in the ice jam and flow in open channel over rough, permeable bed. Base on the experiments where flow over rough, gravel bed was investigated it was concluded that the velocity over the bed is not zero, thus the seepage flow in the gravel exists. Taking all this into consideration, experiments conducted on ice jam model can help to develop theories on gravel bed, as well as during the study some theories from permeable bed can be adopted.

This paper describes the first approach to gain preliminary understanding on the flow resistance of river ice jams. The study was carried out using the facilities at Gdansk University of Technology (GUT) where all hydraulic experiments were conducted. Experiments were proceed in hydraulic laboratory as a scale model of the real ice jam, because measurements in rivers are extremely dangerous and nearly impossible due to the risk of ice jam release during the surveying of the water velocity. Therefore scale model was set up to reproduce the typical condition observed in rivers. Since the facility on Gdansk University of Technology has no possibility to lower the room temperature to below freezing, the material similar to the ice was used instead (polypropylene, PP). Results shown that significant amount of water discharge formed the seepage flow through the jam voids.

1. **Introduction**

In cold and temperate regions of the world, wintertime operation of river systems is a key element in managing surface water resources. Climate change, either natural or anthropogenic, could have serious implications in the management of water resources. In addition to changes in mean conditions, global warming produces more extreme events caused by climate variability. Aside from more frequent extreme floods and droughts, it was also observed that more ice jam events have occurred in warmer winters (Jones et al. 2004), and cold spells have become more frequent (Shabbar and Bonsal 2003). River ice is known to affect many of the world's rivers. In the Northern Hemisphere about 60% of rivers experience significant seasonal effects of river ice (Prowse 2005). In the United States alone, there have been over 14,000 ice jam events observed between 1950 and 1999 (White and Eames 1999). The formation of river ice jam has serious effects on extreme floods, low winter flows, inland navigations, hydropower productions, sediment regime, and riparian structures. While the economic cost of ice-induced extreme events is significant, river ice can also have serious implications on environmental and ecological effects. These concerns bring the added urgency to the quantitative understanding of river ice processes.

River ice jams can produce extensive blockage of river flow and severe flooding due to the reduction of flow area by the jam mass as well as its excessive flow resistance, i.e. the head loss (Ashton 1986). Based on field data, Nezhikhovskiy related Manning's roughness coefficient n_i to its thickness for ice covers formed by accumulations of ice floes, dense slush, and loose slush to thickness (Nezhikhovskiy 1964). Existing empirical formulations attributed the entire jam resistance to the undersurface resistance of the jam, but relate the jam resistance to jam thickness with no theoretical basis (Shen 2010):

For breakup jams:

$$n_i = 0.0690H^{-0.23}t^{0.54} \text{ for } t > 0.5 \text{ m} \quad \textbf{[1]}$$

$$n_i = 0.0593H^{-0.23}t^{0.77} \text{ for } t < 0.5 \text{ m} \quad \textbf{[2]}$$

For freeze up jams:

$$n_i = 0.0262H^{-0.23}t^{0.54} \quad \textbf{[3]}$$

in which, H = depth of flow under the jam; and t = jam thickness. Base on the Thames River ice jam data Beltaos (1988, 1993) developed theory on seepage flow through the voids of the jam having effect on hydraulic resistance. He relates the resistance to the water discharge flow through the jam by incorporating water surface slope. The seepage flow Qp, through the voids of the jam was expressed as (Beltaos 1988):

$$Q_p = \lambda A\sqrt{S} \quad \textbf{[4]}$$

Calibrated mathematical model DynaRICE was implemented to the Thames river reproducing the historical ice jam case from February 1986. Simulation results shown that the significant percentage of the total discharge forming the seepage flow (Kolerski 2016, Kolerski, Huang, Shen, 2016). In this study the percentage of the seepage flow was calculated based on the calibration of the water level and ice thickness measured during the 1986 ice jam event. The amount of seepage flow varied along the jam structure and reached 6% of the total discharge (Figure 1.).

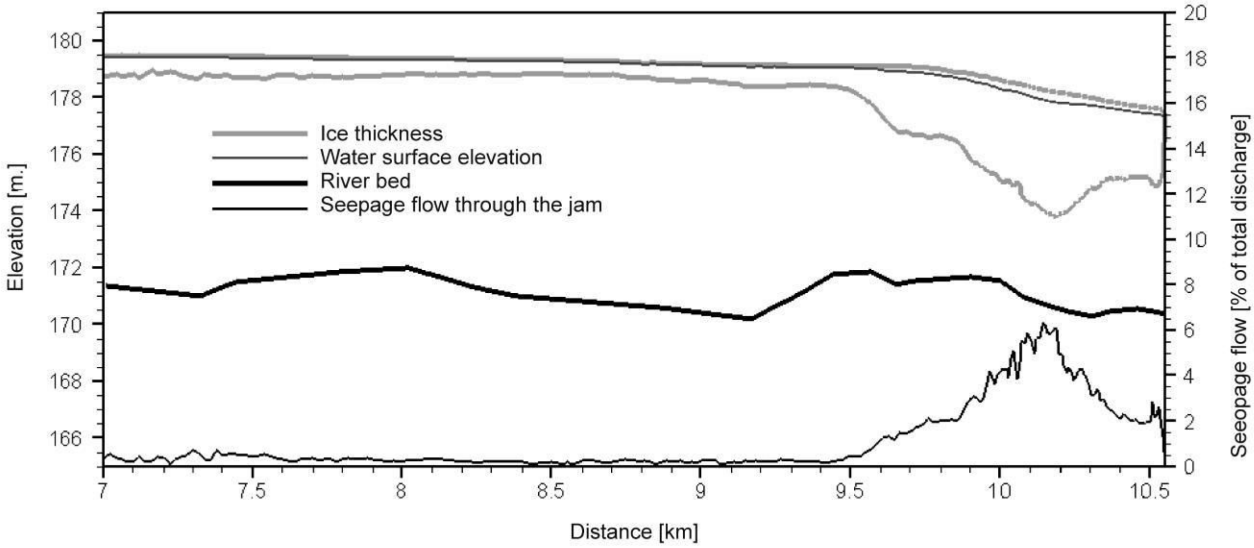

Fig. 1. Longitudinal profile of the simulated ice jam thickness and seepage flow through the jam voids, Thames River case

A preliminary analysis of the seepage flow resistance and the flow resistance of the undersurface of the jam, showed that the resistance due to the seepage flow is the dominating part of the jam resistance (Fan et al. 2016). Authors proved that in ice jammed channels, the total energy loss comprises of those due to the bed shear stress, the shear stress on the undersurface of the jam, and the energy loss due to the seepage flow through the jam. The total friction slope, S_f, between two cross sections can be expressed as:

$$S_f = S_{fb} + S_{fi1} + S_{fi2} = \frac{(P_b \tau_b + P_{i1} \tau_{i1} + D_t)}{\rho g A} \quad \textbf{[5]}$$

in which, S_{fb},S_{fi1} and S_{fi2} are friction slopes correspond to the bed resistance, resistance due to the undersurface roughness of the jam, and the resistance due to the seepage flow through the jam, respectively; ρ = water density; A = average flow area under the jam between two cross sections; $P_b$and τ_b = bed wetted perimeter and shear stress, respectively; P_{i1} and τ_{i1} = ice cover wetted perimeter and shear stress, respectively; and D_t = seepage drag on ice particles in the jam. Through a detailed analysis of the seepage flow resistance and the resistance due to the undersurface roughness of jams, the study by Fan et al. 2017, showed that the seepage flow resistance increases with the jam thickness and the flow resistance due to the undersurface roughness of the jam remains relatively constant. Moreover, the contribution of the resistance due to the undersurface roughness is relatively small compared to the seepage flow resistance.

The seepage flow resistance is a dominating part of the jam resistance excepted for a portion of the jam near its head, where the jam thickness is small with negligible seepage flow. In this study, experiments were conducted to study the flow resistance of ice jams with particular attention to the seepage flow effects for developing theories on these processes.

Number of evidences and facts showed the analogy between the seepage flow in the ice jam and flow in open channel over rough, permeable bed. Base on papers by Nikora et al, 2001, 2007, Manes et al 2009. As well as Gupta and Pudyal (1985), where flow over rough, gravel bed was investigated, it was concluded that the velocity over the bed is not zero, thus the seepage flow in the gravel exists. Taking all this into consideration, the analogy with flow in open channel over permeable surfaces could be found, where the channel bed is made of rough stones and boulders, as well as for regulated rivers where bed is stabilized by gabion baskets or mattress. Therefore experiments conducted on ice jam model can help to develop theories on gravel bed, as well as during the study some theories from permeable bed can be adopted.

2. Research methodology

In order to verify the research hypothesis, series of physical experiments were conducted where water velocity profiles were measured under and inside the ice rubble. Experiments were proceed in hydraulic laboratory as a scale model of the real ice jam, because measurements in rivers are extremely dangerous and nearly impossible due to the risk of ice jam release during the surveying of the water velocity. Therefore scale model was set up to reproduce the typical condition observed in rivers. Since the facility on Gdansk University of Technology has no possibility to lower the room temperature to below freezing, the material similar to the ice was used instead. Number of possible materials was tested such as lightweight concrete (with expanded clay aggregate), polyethylene and wood but polypropylene (PP) was finally accepted to be good imitation for the river ice. The density of polypropylene (920 kg/m^3) is very close to the density of ice (917 kg/m^3). Also the unity price of polypropylene is acceptable and the material properties will not change during the experiment due to soaking in the water. PP board was cut into required size parcels with dimension of 40 x 40 mm. The small size of single parcel helped to produce uniform distribution of ice in the jam and to get smooth velocity profiles inside the jam. Material was placed directly to the water in the upstream section of the flume, and the jam was formed due to existence the permeable barrier in the downstream section of the flume. The barrier was made of wire mesh with clearance of 10 mm, which allowed the water to flow without significant resistance but the PP material was stopped. The jam length, produced by the supplied material was sufficient to achieve equilibrium condition within short section of the rubble.

After the scale model of the ice jam was produced, the measurements of the water velocity profiles were made. The goal of the experiments was to get full profile of the water velocity under and within the ice rubble. To measure the seepage flow velocity, a micro velocity meter with sensor diameter not larger than 40 mm was needed. This type of instrument will allow direct measurements within the rubble without interaction with the material, which could cause collapsing of the jam or changing its features. Knowing the proportion between under - jam discharge and seepage flow calculations were made which can lead to establishing the better theory on hydraulic resistance in the case of ice jam.

3. Hydraulic experiment

The experimental study has been preceded in summer 2016, in small flume in the hydraulic laboratory of Department of Civil and Environmental Engineering, Gdansk University of Technology (Figure 2). 10 mm polypropylene boards were used to imitate ice. The material was cut to the parcels of the dimension 40 x 40 mm. Due to the lack of founding, only 1,5 m^2 was purchased which could produce the jam with length of 0,7 m and average thickness of 0,1 m, and thickness at the toe reached 0,16 m. The width of the jam was limited by the flume width which was 0,38 m. Water velocity was first measured by use of self-made Pitot tube. In order to measure the small water velocity, the scale of the tube was installed on slat sloped to the horizontal plane on 10^o angle. Unfortunately, Pitot tube was not reliable, and results produced by the instrument may not be trusted. Therefore the decision was made to not use this device in further measurements.

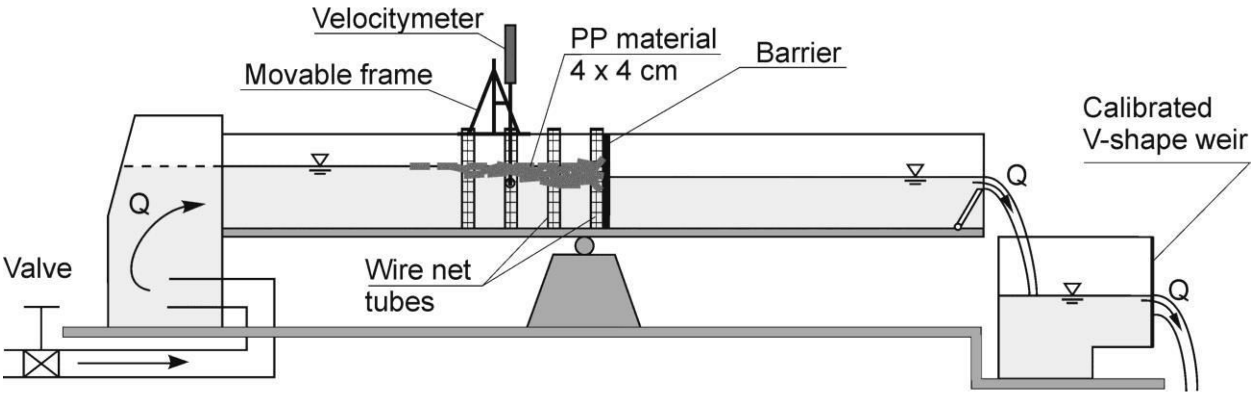

Fig. 2. Layout of the laboratory flume and the locations of the instrumentation in small flume of the Gdansk University of Technology (GUT)

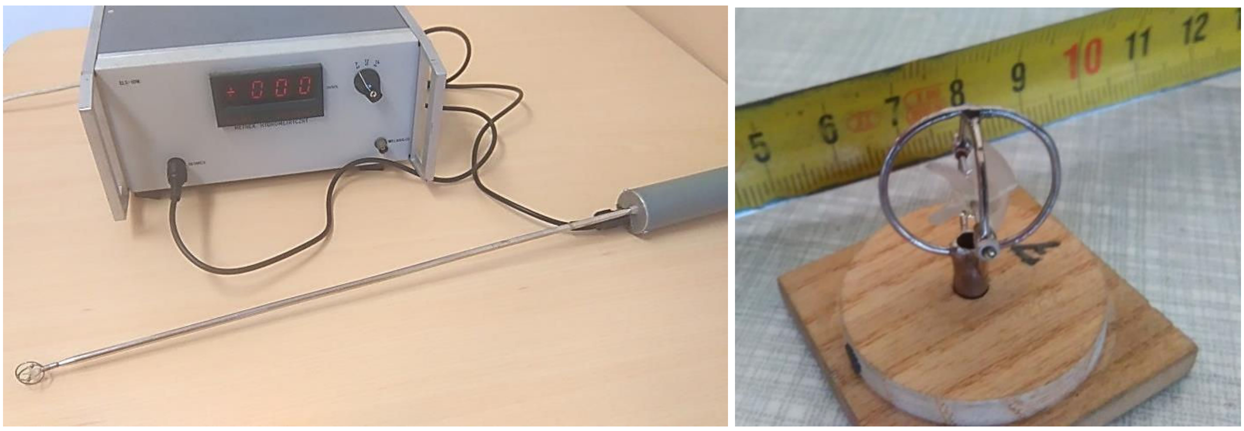

Fig. 3. Propeller type micro-velocity meter with the counting device (a); propeller in a casing basket – measuring tape's scale in centimeters (b)

Further water velocity measurements were made with use of the micro velocity meter, which was self-made instrument constructed by faculty of Institute of Hydro-engineering Polish Academy of Science in eighties last century. The device is propeller type, electromagnetic meter which include micro propeller with diameter of 10 mm, installed inside the 25 mm protective basket (Figure 3). The propeller rotate on the horizontal ax causing interference noise on the sensor installed at the end of the rode. The calibrated signal was next transfer to the counting device where velocity of flowing water was displayed with accuracy of 1 mm/s and the range of the measurements was 0,02 – 2 m/s. The velocity meter was validated prior to the experiments, by comparison the measured velocity recorded by ADV meter and HEGA propeller type velocity meter, showing sufficient accuracy. The micro velocity meter is very fragile instrument, and it required special shields in a form of steel wire net tubes of dimeter of 30 mm (Figure 5.). The tubes were installed in four, previously selected locations along the jam and the velocity was measured inside them. The first profile was at the jam toe (3,5 cm upstream of the barrier), and the next tubes were installed with 0,2 m spacing in upstream direction (see Figure 2 and photograph on Figure 5).

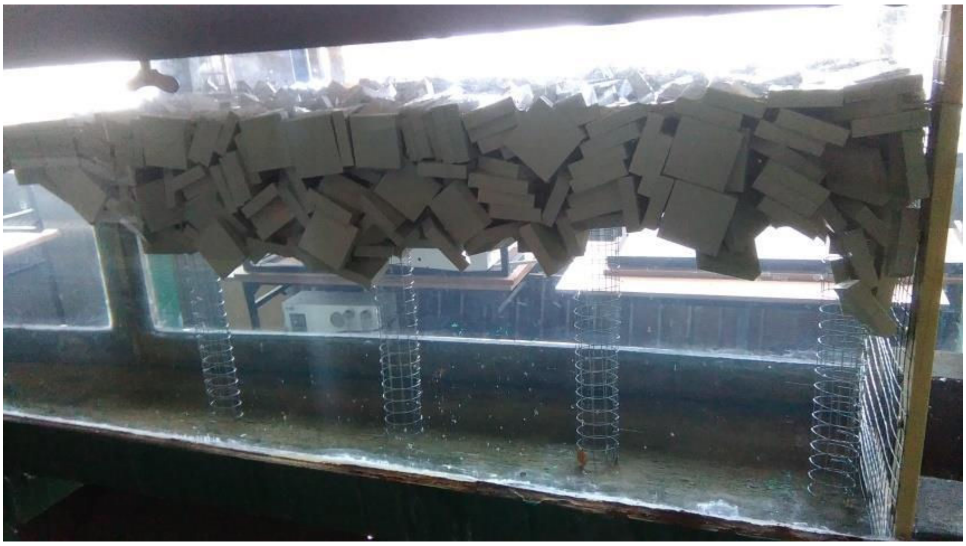

Fig. 4. Ice jam model in GUT hydraulic laboratory, flow direction from left to right

4. Results

All results collected during the laboratory experiments are presented below in a form of velocity plots for each profile (Figure 5) and a table summarizing the seepage flow percentage calculated based on the measured velocities.

The results shown significant amount of flow goes through the jam reaching nearly 40% of total discharge in the profile near the barrier. The average porosity of the entire jam was estimated to reach 54%, which was calculated based on jam thickness and amount of material used in the model. By analogy with the ground flow, the porosity of the material may play important role in the seepage, however this parameter was not tested and requires further studies. The profile I, where the larges seepage occurred, was set inside the jam toe. In this location almost half of the cross section was filled with the material causing significant blockage of the water flow. The water velocity distribution shown two zones from which in the area near the water surface the low velocity occurred (below 0,1 m/s). In the zone below the mid line of the jam thickness, water velocity increases significantly, reaching the maximum at the underside of the jam formation.

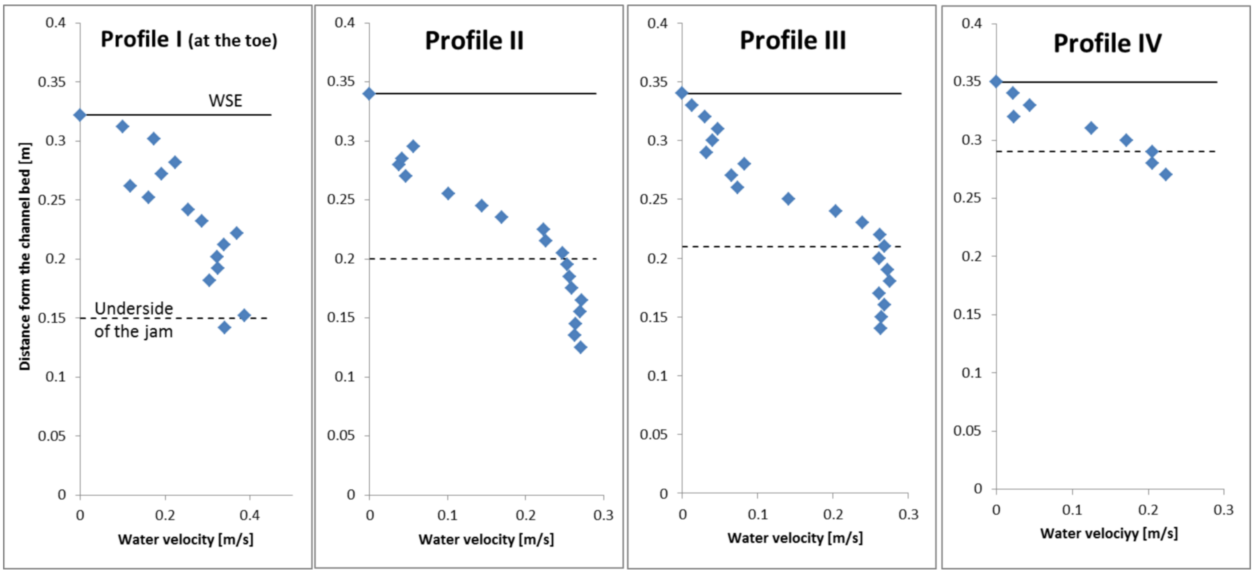

Fig. 5. Water velocity profiles measured inside and under the jam (Profiles spaced by 0,2 m distance and Profile I was measured at the toe)

Table 1. Measured seepage flow through the jam voids

Profile	Seepage flow [% of the total discharge]
I	**36**
II	**19**
III	**16**
IV	**5**

5. Conclusions

Experimental results shown significant percentage of the flow is seeping through the jam. The seepage water velocity reaching its maximum value at the underside of the jam and its only slightly lower than water velocity under the jam. The effect of the porosity and parcel size is considered to play important role in the seepage mechanism, however both were not tested at the current study.

Below all errors and malfunctions of the preliminary tests are pointed out. The results are now considered as the conclusions to improve the future tests to avoid further problems:

a) Insufficient amount of PP material caused that the modeled jam was short and barely reached equilibrium state.
b) Small flume width in comparison to the size of single parcel caused scattered velocity profiles with significant effect of the boundary condition.

c) The used instrumentations were in low quality and caused many problems, including overwarming the device (propeller-type velocity meter) or producing not reliable results (Pitot tube).
d) Micro velocity meter was very fragile, and could not be placed in the jam without shields. The protection tubes produced local velocity fields different form the velocity inside the jam.

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