Turbulent water flow over rough bed – part I

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Abstract. Restitution of diadromic fish requires restoration of ecological continuity of watercourses, e.g. by building fish ladders. Directions for fish ladders require that ichthyofauna is granted accurate conditions of water flow. To describe them, average values are used, that do not convey e.g. turbulence intensity or its spatial differentiation.

The paper presents results of research on the turbulent water flow over the rough bed. The measurements were carried out with high sampling frequency probe for three velocity components. Bed configuration, distribution of average velocities and turbulence intensity were defined. The range of bed influence for the discussed water flow conditions was ascertained to reach the maximum of about 0.25 of height and decline at 0.35. The lowest turbulence and relatively lowest velocities near the bed may promote successive stages of ichthyofauna development.

1. Introduction

Rivers and streams are ecological corridors in which water, debris movement and migration of living organisms occur. Buildings in the stream channels disturb these natural processes [Bartel 2002, Wiśniewolski 2003]. Restitution of migratory fish requires installation of fish ladders by each weir. This creates a barrier to river waters. The ladders enable fish migration upstream [Prawo wodne 2005, Bojarski et al 2005]. Fish ladder recommendations need to meet a number of conditions. In each case, maximum velocities of water flow through the ladder cannot be higher than the velocity that results from fish ability to exceed the water speed limit. Average water velocity ranges from 0.4 to 0.6 ms⁻¹, and only locally reaches 2.0 ms⁻¹. Water flow velocity at the inlet ranges between: 0.90+1.20 ms⁻¹; at the exit it cannot exceed 1.8+1.90 ms⁻¹. Using average values simplifies the approach and raises the suspicion that the average velocities are not sufficient to describe the operation conditions. Local velocity in the cross section can be even 51% higher than the average values [Michalik & Książek 2009]. Using 2-dimension models may provide better results, due to spatial analysis of velocity distribution [Książek et al 2008]. Nevertheless, also in this case vertical average values are used. Understanding the conditions of velocity distribution, turbulence intensity in the inner layer and range of the bottom influence in fish ladders is a crucial element of ecological continuity restoration of watercourses and restitution of diadromic fish [Wiśniewolski 2008] and, in further perspective, building the concept of restoration of fish population [Hauer et al 2010]. Combination of digital modelling [Hauer et al 2008, Tritthart et al 2008, Książek & Bartnik 2009] with necessity of fish restitution evaluates usefulness of habitat conditions for each stage of rheophilic fish development from spawning to adulthood.

The objective of the research is to describe the conditions of water flow which promote the existence of ichthyofauna. First the possibility of using equipment of high measurement frequency for analyses of three components of velocity was tested and then bottom influence on intensity of
turbulence of the flowing stream in spatial terms as well as verification of river wall influence on water stream were analysed. The presented results will serve as a reference to subsequent work.

2. Material and methods

Accurate mathematical description of stream flow is a complicated issue. Laws of fluid movement are described by a basic Navier–Stokes equation. Its exact solutions are known only for small number of cases, among all because of turbulent movement complexity [Feynman et al 2005]. In this movement, due to viscosity and shear stress forces between adjacent particles, small whirls occur continuously, and then fluctuate, increase and quench. This leads to continuous stirring of particles and exchange of momentum [Lewandowski 2006].

Description of such movement by differential equation is very difficult [Kubrak 1998]. Consequently, to describe the characteristics of turbulent flow, semi-empirical method is used. It relies on description of roughness characteristics and then its connection with average velocity [Lewandowski 2006, Sawicki 1998]. For relatively long period of averaging, average velocity can be designated:

$$\overline{\tau} = \frac{1}{T} \int_{t}^{t+T} \tilde{u} dt$$  \hspace{1cm} (1)

If the fluctuation of velocity is marked as $u'$, a turbulent velocity vector can be described as:

$$\bar{u} = \bar{\tau} + \bar{u}'$$  \hspace{1cm} (2)

Time averaged turbulent velocity $\bar{u}'$ must be equal to zero [Lewandowski 2006, Puzyrewwski & Sawicki 1998]. On the other hand, nonzero value will be taken by root mean square amplitude of pulsation velocity:

$$\frac{1}{T} \int_{t}^{t+T} (u')^2 dt = \bar{u}^2 = \delta^2 = s$$  \hspace{1cm} (3)

Square root of the expression (3) is called the average value of pulsation velocity and corresponds with a standard deviation of the average velocity $\bar{u}$.

Fig. 1 presents graphical values from the equation (2), where the middle line reflects the average value $\bar{u}$, and the green line reflects standard deviation.

Standard deviation is calculated from the formula:

$$\delta = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n-1}}$$  \hspace{1cm} (4)

where: $x_i$ – momentary value of velocity, $\bar{x}$ - average value of velocity, $n$ – number of measurements.

Standard deviation is sufficient to assess the level of turbulence, because it reflects dispersion of the measured values around the expected value – in this case estimated by arithmetic mean. In comparison to variance, standard deviation enables better insight into lower fluctuations, reducing a relation of the highest to the lowest values of velocity anomalies.

Fig. 1. Water flow velocity in selected point in time
Analyses of flow conditions were performed in hydraulic tilting flume 12.0x0.5x0.6 m. Inclination of the flume may be changed from negative slopes of 0.0268 to 0.0847. The channel is supplied by pumps, which capacity up to 0.15 m$^3$s$^{-1}$. It is equipped with flowmeter and kit to measure water surface level [Michalik & Ksiażek 2000].

Artificial surface of the channel’s bed consisted of the:
- adhering natural debris with mean diameter $d_m=0.0096$ m, $d_{\text{max}}=0.020$ m – run D1,
- natural grains of the range 0.02-0.04 m – run D2.

The measurements were carried out for discharge $Q=0.0375$ m$^3$s$^{-1}$. Channel’s bed was set with negative slope of 0.0084, water height $h=0.190$ m (run D1) and 0.181 (D2). Water temperature was $t=16.5^\circ$C and 19.6$^\circ$C for cases D1 and D2 respectively, salinity reached 0.24 ppt. Reynolds number $Re_{\text{D1}}=7.0\times10^4$ and $Re_{\text{D2}}=7.6\times10^4$ confirms that water flow was turbulent and Froude number $Fr_{\text{D1}}=0.09$ and $Fr_{\text{D1}}=0.10$ the was subcritical flow.

Water flow velocity was measured with a probe, which is laboratory gauge ADV type (Acoustic Doppler Velocimeter). It is a single-point meter characterised by high sampling frequency (to 50 Hz) for very precise measurement of three components of water velocity. The apparatus enables measurement of water flow velocity from 0.001 ms$^{-1}$ to 2.5 ms$^{-1}$. The probe samples 0.09 m$^3$ of water. The probe is built of centrally located transmitter and three side arms in which receivers are located. The measurement of flow velocity is made within measurement cell placed at the intersection of the axis of receivers, 5 cm from the probe front.

Water velocity measurements were carried out in thirteen hydrometric verticals consisting of ten points of different height above the bed (case D1) and ten hydrometric verticals (D2) - 230 measuring points altogether, but made in the same planes for the same case. Time of a single velocity measurement was 60 s, and minimum distance of sampling from the bed was 5 mm. Distance between subsequent samples equalled 0.004 m up to 0.015 m with water surface direction.

Three velocity components $v_x$, $v_y$ and $v_z$, value of signal quality SNR [dB] and correlation [-] were obtained as a result of measurements. The results of velocity measurements, which quality of signal decreased below the required value or correlation was very low were filtered using phase space threshold despiking [Goring & Nikora 2002].

### 3. Results

Configuration of the bed was measured using ADV probe at 0.002 x 0.004 m (case D1) and 0.005 x 0.005 m (D2) resolution. Area of 0.192 x 0.290 m and 0.120 x 0.170 m respectively for case D1 and D2, were measured. Average bed’s level for case D1 was 0.0148 m, maximum 0.0282 m (standard deviation $\delta=0.0041$ m). For case D2 maximum bed level was 0.0472 m, average 0.0322 m (standard deviation $\delta=0.0066$ m). Fig. 2 presents the change of water volume (roughness) in the area bounded by the plane of bed and horizontal plane which creates three-dimensional picture of the bed. Volume above the bed was obtained with software for planes’ creation and analysis. Above the average bed level $z_{\text{mean}}$ relation between roughness and height for the debris in the channel is linear.

![Fig. 2. Bed roughness function in the range of $z_0$ - $z_{\text{max}}$](image-url)
Fig. 3 presents locations of hydrometric verticals, where the measurement of water stream flow conditions took place for case D1 – as well as their spatial differentiation. For the sake of spatial analysis of water flow conditions, the measurements were performed in hydrometric verticals in the same horizontal planes (disregarding different height above the bed) to enable averaging the results of measurements in time and space [Nikora et al 2007a, Nikora et al 2007b, Aberle et al 2008]. Such attitude enables characterising the velocity, turbulence and stress of stream volume that flows above the extracted part of the bed, unlike parameterisation of each liquid stream.

Fig. 3. Scheme of location of measured points, case D1, a) top view, b) front view

Fig. 4 presents histograms of water flow velocity values. Their shapes indicate normal distribution of velocity components.

Fig. 4. Histograms of velocity components $v_x$, $v_y$, and $v_z$ – measuring point IX, case D1, $z = 0.023 \text{ m}$

Fig. 5. Average values of flow velocity components $v_x$, $v_y$, and $v_z$, case D1 and $v_x$, for case D2
Average values of velocity components $v_x$, $v_y$, $v_z$ for case D1 and $v_x$ for case D2 are presented in Fig. 5. Red and black colours marks the component in the main direction of mass flow $v_x$, blue colour – component across the channel, green colour – vertical component. Components $v_x$ are consistent with the logarithmic distribution. The transverse component is mostly deviated in the inner layer, where the impact of single gravel's peaks is seen, that need to be washed by the water stream. Up to half of the height ($0.5 \, z/h$) the stream is parallel to the channel axis. Low deviation $v_y = 0.02 \, \text{ms}^{-1}$ may be caused by the lack of parallelism of liquid streams by the channel bed and on the surface may be caused by negative slope of the channel. By the bed streams are parallel but the closer to the surface, the more the gravitational force causes flattening of the water flow direction. This deviation in zone $z > z_{\text{max}}$ reaches $2.7 \, \%$ ($R^2=0.51$) and is similar to the water surface slope.

Fig. 6. Standard deviation of flow velocity components $v_x$, $v_y$ and $v_z$, case D1 and $v_x$ for case D2

Analysis of relationship of velocities $v_x$ and $v_y$ indicates the lack of influence of channel walls on water flow conditions. Ratio of these velocities $v_y/v_x$ in vertical number $V$ adopts similar values to other measurement verticals.

Fig. 6 presents values of standard deviation for turbulence. Value of turbulence, main velocity component, as well as transverse and perpendicular component for the discussed flow conditions present the highest values on the absolute height of 0.25 for the case D1 and D2 which could indicate the range of bed influence. This influence diminishes on the height of 0.35. In the area from $z < z_{\text{max}}$ turbulence is lower than in the zone $z > z_{\text{max}}$ which shows that it is suppressed inside the rough bed.

4. Conclusions

The presented research enables understanding the conditions of free surface water flow. It needs to be treated as a methodical introduction to series of measurements that leads to understanding real conditions of water flow, among all in fish ladders in nature. Replacement of average values which characterise water flow with real values will allow preparing the solutions adjusted to ichthyofauna needs. The occurring concepts of restoration of fish populations aim at habitat restoration and can enable fish occurrence in long distances of rivers.

It was ascertained that in laboratory conditions, turbulence and velocity components for the discussed conditions of water flow indicate that the highest values occur in absolute height of $z/h = 0.25$ which could inform of the range of bed influence. Bed influence diminishes in height of $z/h = 0.35$.

Understanding of water flow conditions in nature becomes particularly important.

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