Laboratorial studies on the seepage impact in open-channel flow turbulence

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Abstract. In natural streams, the interaction between water in motion and movable beds derives in transport of material. This is a fact that causes several problems for river regulation, above all in streams which were heavily modified by human interferences. Therefore, to find solutions or at least to alleviate the negative effects that sediment transport can bring with is a topic to be researched. The impact of seepage on river sedimentation processes and open-channel flow is important for environmental issues but it is commonly neglected by water specialists. The present contribution presents the output of a series of experimental works where the influence of seepage on the open channel turbulence is analyzed at the laboratory scale. Even though that the magnitude of the groundwater flow is significantly smaller than the magnitude of the open channel flow; the output of the experiments demonstrates that seepage not only modifies the water-sediment interaction as demonstrated Herrera Granados (2008; 2010); but also is affecting the velocity field and turbulence dynamics of the open-channel flow.

1. Introduction

Seepage can be defined as the motion of any fluid through a porous medium. In river engineering, groundwater flow is equivalent to the percolation of water through the soil from unlined canals and watercourses. The importance of seepage for engineering problems lies in the fact that this flow has a direct relation to the resistance and behavior of soils. Due to the fact that groundwater flow rates are much smaller than open-channel flow rates; seepage is commonly neglected by river engineers in the analysis of water and environmental issues. Nevertheless, this small flow not only affects the sediment transport processes; but also is influencing the velocity field and consequently, the values of some turbulence parameters.

Theoretical analyses concerning seepage’s influence in river dynamics were previously done by Dey & Cheng (2005), Chahar (2007) or Franchalanci et al. (2008). Experimental works on the same topic were carried out by Cheng & Chiew (1998), Ali et al. (2003), Dey & Sarkar (2007), Lu & Chiew (2007), Herrera Granados (2008) and Herrera Granados & Kostecki (2011). It is necessary to highlight that in the majority of the previously mentioned experimental works, seepage’s flow rates were considerably high and its influence on turbulence dynamics was not fully analyzed. But in natural conditions, groundwater flows are much smaller in comparison with stream and river flows. The aim of this paper is to show some of the groundwater’s flow effects in free-surface hydrodynamics based on the results of several turbulent flow measurements. This researching was carried out in a flume where upward seepage was induced by external hydrostatic
pressures acting on the channel bed. For these experiments, the maximum seepage’s flow rate was less than 0.015% of the open-channel flow value. The output of the laboratorial studies demonstrates that the induced flow through the porous medium is considerably affecting the turbulence dynamics of the open-channel flow (regardless the small seepage’s magnitude). A statistical analysis of the open channel flow measurements was performed and some turbulence parameters are compared with and without the presence of upward seepage.

2. Experimental Set-up

The laboratorial research was carried out at the open air laboratory of the Wrocław University of Technology. The figure 1 depicts the general scheme of the flume were the turbulent flow measurements were carried out. In order to allocate a 0.20 m porous bed, constituted by a sandy fine soil, a special structure was built 0.30 m over the lowest part of the flume to protect the small pipes at the bottom of the channel. These pipes (see fig. 1) played a crucial role because water flowed from an external tank through them and provoked distributed hydraulic pressures acting on the lowest part of the channel bed (Herrera Granados, 2008). The external tank was able to vary its position in order to have different water levels and therefore to control the intensity of the seepage flowing through the sandy bed of the experimental channel.

![Figure 1. General scheme of the flume and the location of the E-30 probes.](image)

This tank was provided with one flowmeter and a small spillway to have constant induced hydraulic pressures. A thin layer of geotextile was allocated in between the sandy layer and the metal base that was symmetrically drilled to allow upward or downward water flow. This geotextile let the induced pressures to be distributed uniformly. A scheme of the connection between the tank and the flume is depicted in the figure 2. This scheme depicts as well the parts of the flume and the location of the velocimeter P-EMS according to the established reference frame, shown in the same figure. This apparatus (with its different probes) is able to measure the instantaneous velocities in two directions \((x,y)\) or \((x,z)\) with an accuracy of 0.001 \(ms^{-1}\) and a frequency of 10 \(Hz\). For these experiments, 2D velocity time series were taken for similar hydraulic conditions but varying the intensity of the water flowing through the sandy bed.

Four different hydraulic heads were induced in order to vary the groundwater flow’s magnitude: \(\Delta H = 00\) (no seepage); 10, 20 & 30 (upward seepage) \(cm\). Descriptive statistics and a brief turbulence statistical analysis were carried out. The objective and scope of this paper is to present some results of those analyses for one experimental flow rate \((Q = 10 \, dm^3s^{-1})\) at one cross section of the experimental zone \((X = 3.0 \, m\) from the origin depicted in the figure 1).
3. Descriptive and turbulence statistics

At a first stage, the influence of seepage in the flow velocity components and in velocity fluctuations of the open-channel flow was analyzed by obtaining one-point statistical moments of the flow measurements. In addition, some turbulent parameters were estimated such as the Reynolds stresses in the $xy$ plane ($-\rho u'v'$) and the Turbulent Kinetic Energy ($TKE$). The descriptive statistical analysis was based on the expectation theory.

The figures 3 and 4 depict the mean velocity profiles and the measured $-\rho u'v'$ for four different hydraulic pressures $\Delta H = 00$ (A), 10 (B), 20 (C) and 30 (D) cm at the previously mentioned cross section. In these figures are plotted five profiles according to fig. 2 at a distance of 5 (I, blue dashed line), 20 (II, blue continuous line), 25 (III, magenta dashed line), 30 (IV, red continuous line) & 45 (V, purple continuous line) cm away from the left wall of the flume. The maximum seepage’s magnitude reached 0.015% of the open-channel flow rate value.

The figure 5 shows the measured $TKE$ for three different hydraulic pressures $\Delta H = 00$ (A), 10 (B), 30 (C) cm. Based on the figure 3, there is not clear evidence of the seepage’s impact on the mean velocity profiles. Nevertheless, the figures 4 and 5 demonstrated that the turbulence parameters are affected. The $Re$ stresses profiles along the cross section are more regular when the intensity of seepage is larger, contrary to what happens with the $TKE$. Hence, seepage is influencing the behavior of the velocity fluctuations but not the mean values.
Scatter plots of the velocity fluctuations ($u'$ vs $v'$) in both directions were drawn to visualize the effect of seepage on the velocity fluctuations. The first plot (A) of the figure 6 is the scatter plot of velocity fluctuations of a time series with no seepage acting on the bed, the second plot (B) represents the velocity fluctuations affected by $\Delta H = 20 \text{ cm}$ and the last one (C) is the scatter plot of the velocity fluctuations with more intensive seepage acting on the bed ($\Delta H = 30 \text{ cm}$). The case of the figures (B) and (C) are examples of anisotropic velocity fields where the velocity fluctuations ($u'$) in the $x$-direction tend to be the same as the fluctuations ($v'$) in $y$.

Descriptive statistics are limited for a better analysis of turbulence dynamics. Hence, spatial correlations and structure functions were obtained in order to check the seepage’s impact on the local isotropic behavior of the open-channel flow.
For this second stage of the experiments, three time series were taken for the longitudinal \( (u') \) and vertical \( (w') \) velocity fluctuations close to the bottom, which can be identified in the next figures as follows: A) Time series without induced seepage (continuous line, red or black); B) Time series affected by a small upward seepage \( (\Delta H = 10 \text{ cm}, \) short-dashed black line \) & C) Time series affected by a larger upward seepage \( (\Delta H = 30 \text{ cm}, \) long-dashed blue line \). The Taylor’s hypothesis was assumed as valid to estimate these statistical parameters.

The figures 7 and 8 depict the autocorrelation functions for the longitudinal and vertical velocity time series. Upward seepage tends to better correlate the velocity for larger distances and therefore the turbulence length scales are affected, e.g. the Taylor’s microscale. It is possible to observe how vertical autocorrelation functions drop much faster than the longitudinal.

![Figure 9. 2nd order struct. functions of \( u \).](image)

![Figure 10. 2nd order struct. functions of \( w \).](image)

![Figure 11. 1D energy spectra for \( u \).](image)

![Figure 12. 1D energy spectra for \( w \).](image)

The figures 9 and 10 are the second order structure functions for the \( u \) and \( w \) time series. In the second order structure function for \( w \), it is not observable the theoretical power-law. Seepage is not only changing the shape of the second order structure functions, but also the initiation of the inertial subrange seems to be dependent on seepage’s intensity. This fact can be as well visualized in the 1D energy spectra (figures 11 and 12). In the case of the figure 11, we can observe that there is relation between the hydraulic head \( (\Delta H) \) that induces seepage...
and the initiation of the inertial subrange. For $\Delta H = 30$ cm, the inertial subrange initiates at a smaller wavenumber and the dissipation range is reached. Looking at the spectra that are affected by seepage, there is a short range following the $-1$ law; contrary to what happens with the flow without seepage. The figure 12 demonstrates that not only the groundwater but also the presence of the porous medium are changing completely the shape of the spectrum (no filtering process was done) and the theoretical solution of Kolmogorov ($-5/3$) is not visible.

4. Conclusions

The previous analysis demonstrates that presence of upward seepage influences the velocity fluctuations of the open channel turbulent flow rather than the mean values. The presented figures (descriptive statistics) showed how the velocity field of open channel flows are more irregular when flow through the hyporheic zone exists. Thus, the $TKE$ and the $Re$ stresses are affected by the presence of this seepage. The scatter plots indicate that seepage is changing the statistical homogeneity of the velocity fluctuations, which tend to form anisotropic velocity fields. Therefore, seepage seems to affect the local isotropic behavior of the open channel instantaneous velocity field as visualized by the spatial correlations and by the 1D energy spectra. In addition, we can observe a direct correlation between the intensity of seepage and the boundaries of the energy ranges of the Kolmogorov’s Spectrum as well as with the scales of the turbulent motion. The effect of the groundwater flow is more visible in the $z$ direction because the induced groundwater flow was practically upward and it directly impacted on the vertical velocity components. Regardless the small magnitude of the groundwater flow; the impact of seepage flow becomes very important because it is changing the behavior of the turbulent stresses and therefore the initiation of sediment motion, which is a fundamental aspect in river engineering.

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