The interaction between free surface and sub-surface flows in open channels with permeable beds

Dubravka Pokrajac, Costantino Manes, Ian McEwan, Vladimir Nikora
Department of Engineering, University of Aberdeen, United Kingdom

We study shallow open channel flows over rough bed using a series of laboratory experiments with uniform, gravity-driven flow (linear shear stress boundary layer), in a tilting hydraulic flume. The rough bed was made of uniform spheres packed in a cubic pattern, with the following two arrangements: *(i) Impermeable* bed made of one layer of spheres and *(ii) Permeable* bed composed of five layers. Comparison of the stream-wise velocity profiles above the bed *(i)* and *(ii)* showed that, for the same flow depth, velocities above the permeable bed are lower, indicating higher efficiency of the porous bed in extracting momentum from the mean flow. Although this effect of bed permeability is well-known, the actual physical mechanisms causing it are still poorly understood.

For the purpose of investigating the interaction between flow above and inside permeable bed, the detailed measurements of velocities above and inside the rough bed were carried out. Particle image velocimetry (PIV) was used to obtain time series of stream-wise and bed-normal velocity across a measurement window above the bed, while an ultrasound velocity profiler (UVP) was implanted into various pores of the permeable bed and produced time series of velocity inside them. The following characteristics of flow above and inside permeable bed were analysed: mean velocity, turbulent intensities, skewness, kurtosis, cross-correlation functions, and spatial spectra. A sample of experimental result is shown in Figure 1.

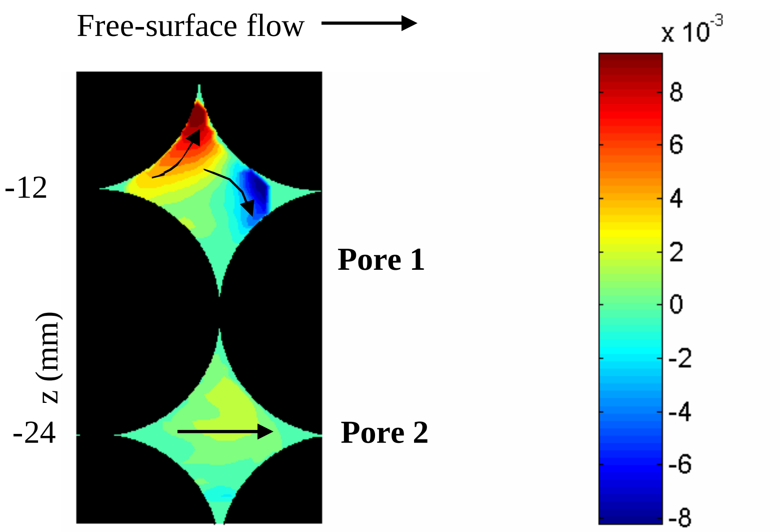

Figure 1 *Contour map of the time averaged bed normal velocity* $\overline{w}$ *, within pore 1 and 2 obtained from PIV measurements. The colour-bar is in m/s; black regions represent the surface of the beads.*

The friction velocity u_* was evaluated from the measured turbulent shear stress extrapolated to the level of the roughness crest (top of the highest layer of spheres). Mean flow velocities inside the pores of the permeable bed did not scale with the friction velocity. In the highest pore, which was in the direct contact with the turbulent free surface flow they appeared to be affected by the water depth, while in all other pores they showed the dependence on the bed slope (momentum supply), typical for porous media flow. This, and very low turbulent shear stress measured below the highest pore, indicate that turbulent momentum extracted from the free-surface flow does not penetrate further than the highest pore. However, higher velocity moments were influenced by the friction velocity in all four pores of the permeable bed, indicating that the influence of the free-surface flow penetrates deeper than the turbulent momentum. This was explained by the action of the fluctuating pressure field. The support for such hypothesis was found by detecting the presence of large scales in the pores. Indeed, two-point statistics indicate the presence of two different length scales in flow inside the pores. Based on the correlation length the large scales were found to be similar to the free-surface flow depth. They contain less energy but are still present in the lower pores.

In summary, our experiments indicate that momentum flux from the free-surface flow into the permeable bed is limited to a relatively thin zone, however the influence of the free-surface flow is felt much deeper.