The effect of bed porosity on near-bed turbulent flow characteristics in gravel-bed rivers

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Sammendrag

Denne artikkelen presenterer en litteraturstudie på strømningstyper og -lag over elveleier av grov grus, og hvilken innvirkning bunnens porøsitet har på strømningens karakteristika. Strømningstyper og -lag er definert i henhold til relativ dybde. Viktigheten av utvekslingsprosesser mellom overflatestrøm og strømning i grusen er diskutert. Litteraturstudien viser at effekten av elveleiets porøsitet på strømmingsforholdene nær bunnen enda ikke er fullstendig forstått, og at en porøs bunn viser større strømningsmotstand (friksjon) enn en ikke porøs bunn med identisk ruhet. Videre beskriver artikkelen et pågående forskningsprosjekt ved NTNU som har som mål å kvantifisere effekten av bunnens porøsitet på strømningens karakteristika.

Summary

This paper provides a brief literature review on flow types and layers over rough gravel beds which is extended towards the effect of bed porosity on surface flow characteristics. Dependent on the relative submergence, different flow layers and types are defined and the significance of exchange processes between surface and sub-surface flows is highlighted. The literature review shows that the effect of bed porosity on near bed flow hydraulics is not yet completely understood and that porous beds impose higher resistance to flow than non-porous beds with an identical roughness texture. Moreover, the paper briefly describes an ongoing research project at NTNU aiming to quantify the effect of gravel bed porosity on surface flow characteristics.

Introduction

Gravel bed rivers represent an important streamtype in the fluvial environment and are the dominating river type in mountainous areas. They are characterized by a variable morphology ranging from step-pool-systems through braided channels to static and mobile armor layers (e.g. Church, 2006). The occurrence of morphological features in gravel-bed rivers is directly linked to dynamic fluvial processes which depend on a number of parameters such as hydrology, near-bed hydraulics, sediment size and composition, slope and anthropogenic influences. Moreover, gravel bed rivers play an important role in regard to ecological considerations as they provide habitat for fauna and flora, which in turn dynamically interact with the aforementioned parameters and hence the morphology of gravel-bed rivers (e.g., Beschta and Ripple, 2012, Boano *et al.*, 2014, Marion *et al.*, 2014, Hauer *et al.*, 2016, Forseth and Harby, 2016). Consequently, gravel bed rivers have been in the focus of research for a long time due to their importance for many engineering and ecological applications.

The present paper focuses on flow features associated with armoured gravel beds by providing a brief overview of the state-of-the-art of rough bed hydrodynamics. Following a brief introduction into the double-averaging methodology for the analysis of spatially variable flows, an overview of different flow types and flow layers over rough gravel beds is given. The review is then extended towards the effect of the porous subsurface on near bed surface flow characteristics in order to discuss exchange processes between the surface and subsurface flows (hyporheic exchange). The paper is concluded by a brief description of an ongoing research project at the Norwegian University of Science and Technology (NTNU) aiming at an experimental quantification of the significance of hyporheic exchange processes on surface flow characteristics over armour layers.

Double-averaging methodology (DAM)

Although the hydrodynamics of rough bed flows, in general, and of gravel bed rivers, in particular, has been investigated extensively in the past, there are still many problems awaiting clarification. Most of these are associated with the spatial flow heterogeneity in the near bed region due to low relative submergences (ratio between the water depth and roughness height) and the associated complex interaction of the flow with large roughness elements and the bed-surface texture (e.g., Nikora *et al.*., 2007a, b, Cooper *et al.*., 2013). Until today, the flow structure in the near-bed region of rough beds has mainly been investigated based on the Reynolds equations, i.e., time-averaged Navier-Stokes equations. These equations have served for both experimental data interpretation and modelling although the time averaged flow field of rough bed flows is highly three-dimensional which makes the application of the solely time-averaged momentum equations rather impracticable (Nikora *et al.*., 2001, 2004, 2007a, b, Aberle *et al.*, 2008).

The proper assessment of near bed hydrodynamics requires the consideration of the flow field over a certain spatial scale, and a methodological approach for this purpose is the Double-Averaging Methodology (DAM). The terminology double-averaging is related to the averaging of the Navier-Stokes equations in both the temporal and spatial domain, or in other words by spatially averaging the Reynolds equations. The DAM-approach provides a solid theoretical background for the assessment of the spatial flow variability of the time averaged flow field based on form-induced stresses describing the spatial correlation between time-averaged velocity components within the averaging domain (Nikora *et al.*, 2007a, b). The theoretical background of DAM and various applications can be found in the recent scientific literature (e.g., Nikora *et al.*., 2001, 2004, 2007a, b, 2013, Nikora and Rowinski, 2008, Dey and Das, 2012, Cooper *et al.*., 2013, and references therein) and will not be repeated here.

Vertical flow field of rough bed flows

The DAM-approach allows for a classification of rough-bed flow types with respect to the flow submergence. Figure 1a shows these flow types and corresponding flow layers as defined by Nikora *et al.* (2007a, b). Before discussing the flow types and layers in more detail below it should be noted that the flow depth is defined as the distance from the free water surface, z_{ws}, to the roughness trough, z_t, and the roughness height as the distance from roughness tops, z_c, to roughness trough, z_t.

Flow layers

The subsurface layer occupies the flow in the substratum (i.e. in the pore space between granular particles) and its upper boundary may be defined as the location where the bed porosity ϕ does not significantly change with depth (i.e. $d\phi/dz \approx 0$). Physically measured vertical porosity-profiles of an armoured gravel bed are shown in Figure 1b.

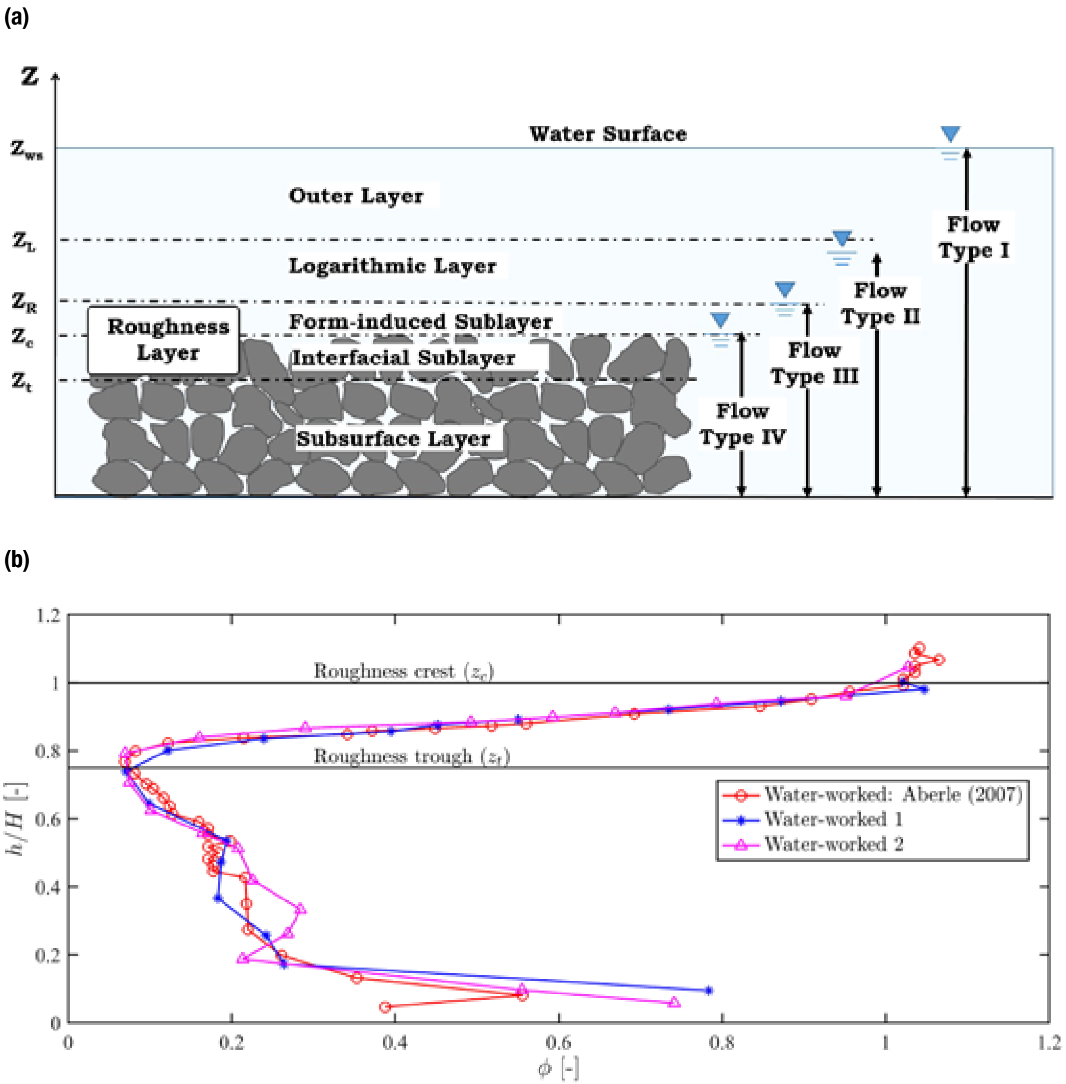

Figure 1. (a) Flow layers and flow type classification over rough permeable beds (adapted from Nikora et.al 2007b). (b) Vertical distribution of porosity ϕ, where h is distance from the flume bottom and H is the total bed height (the porosity distributions for water-worked beds 1 and 2 were obtained in the NTNU-experiments presented later; see also Navaratnam et al., 2017).

These profiles were obtained using the so-called water displacement method in a laboratory flume (e.g., Aberle, 2007) and indicate a monotonically decrease of porosity from the roughness tops towards the troughs. Note that the minimum-value of porosity in the region of the roughness trough may partly be caused by an artefact from the measurement technique (capillary action during the measurements; Navaratnam *et al.*, 2017) or the depth of the active sediment layer during armouring (Aberle, 2007). In general, it may be expected that the porosity will be approximately constant just below the roughness trough within the undisturbed subsurface layer (see the range form 0.2 < h/H < 0.6 in Figure 1b). As a rough approximation, the upper boundary of the subsurface layer may therefore be assumed to correspond to the elevation of the roughness trough z_t. For completeness, it should be mentioned that the increase of porosity for $h/H < 0.2$ in Figure 1b can be associated with the solid flume bottom (Aberle, 2007, Navaratnam *et al.*, 2017).

The interfacial sublayer occupies the region between the roughness troughs and crests, i.e. the region from z_t to z_c which is occupied by roughness elements. In this layer, the porosity changes from the subsurface-porosity value to $\phi = 1$ just above the roughness crest z_c (Figure 1b). The flow in this region is highly three dimensional and affected by form drag of the roughness elements. The so-called form-induced sublayer is found above the roughness crests (extending from z_c to z_R) and is affected by form-induced stresses arising due to flow separation from the roughness elements (e.g., Nikora *et al.*, 2001). The combination of the form-induced and interfacial sublayer is also called the roughness layer. An example of the spatial flow heterogeneity in the roughness layer is shown in Figure 2 presenting 48 velocity profiles measured at different locations over a rough permeable gravel bed using Laser-Doppler Anemometry. The velocity data were acquired in the study described by Aberle et al. (2008) and highlight the large variation of flow velocities around the mean value (indicated by the bold red line). In fact, the variability of flow velocities increases below the roughness crest (interfacial sublayer) and negative values of flow velocities can be observed in wake zones behind larger cobbles. Above the roughness crest (form-induced sublayer), the spatial heterogeneity is not as pronounced but still clearly visible. Note that flow velocities could only be measured up to $z = 0.15$ m due to experimental peculiarities.

The upper boundary of the roughness layer, z_R, is the lower boundary of the logarithmic layer, in which the vertical distribution of the flow velocity can be described by the logarithmic formula arising from the law-of-the-wall (e.g., Gersten and Schlichting, 2006). The logarithmic layer occupies the flow region above the form induced sublayer up to z_L, corresponding to

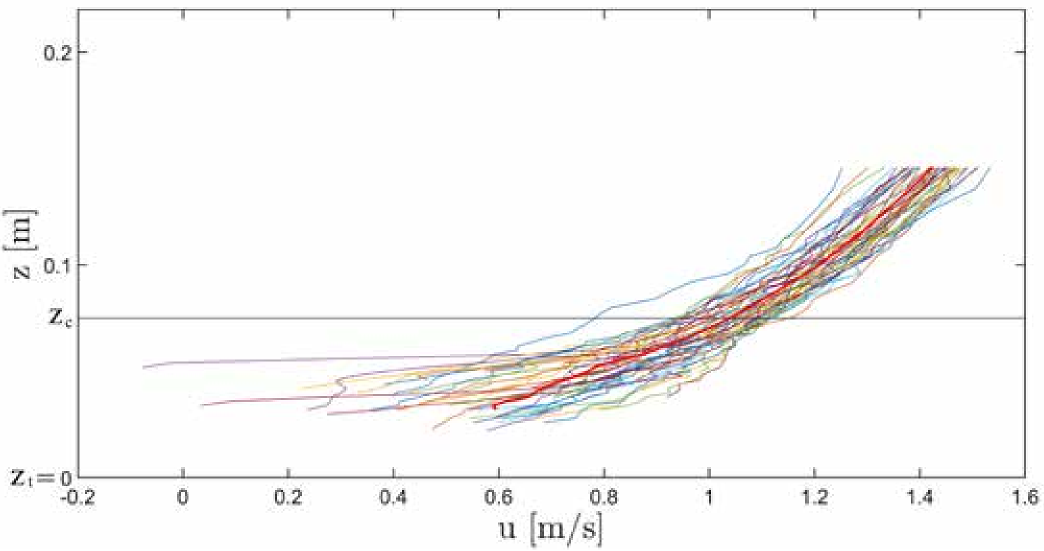

Figure 2. 48 vertical velocity profiles measured at different locations over a rough permeable gravel bed using a Laser-Doppler Anemometer in the study of Aberle et al. (2008). The data stem from an experiment carried out in a 0.9 m wide flume with a flow discharge of Q = 180 l/s and a slope of S = 1%. The extent of the interfacial sublayer was 0.075 m (from z_c to z_t; note that z_t denotes the origin of the vertical axis) and the mean water surface elevation corresponded to 0.22 m. The horizontal line indicates the elevation of the roughness crest and the bold red line indicates the averaged velocity profile.

approximately 20% of the water depth (Nezu and Nakagawa, 1993, Jiménez 2004). Compared to the roughness layer, the flow in this layer is not affected by form-induced fluxes and the spatial flow heterogeneity becomes therefore negligible. In general, this layer is similar to the logarithmic layer for flows over hydraulically smooth beds. An important prerequisite for the existence of this layer is that the water depth is much larger than the roughness height (large relative submergence).

The outer layer is located above the logarithmic layer and extends to the water surface, z_{ws}. It is, as the logarithmic layer, not affected by form-induced fluxes. As a consequence, the spatially averaged equations are identical to the time-averaged equations. In general, there are few distinct differences in the hydraulics of the logarithmic and outer layer due to the influence of the free surface (for details see Nikora *et al.*, 2001, Nikora *et al.*, 2007b).

Flow types

If all the aforementioned flow layers exist in a flow, the water depth will be much larger than the roughness height (Flow type I; Figure 1a). The velocity distribution will have the classical shape with larger velocities in the outer and logarithmic layer and reduced velocities in the near bed region due to roughness effects. Flow type II (Figure 1a) is characterized by an intermediate relative submergence (e.g., below 10) and consists of the subsurface and roughness layer along with an upper flow region which does not necessarily manifest a logarithmic velocity profile, as the relative submergence is not large enough (Nikora *et al.*., 2004). Note that such a case is shown in Figure 2. Nonetheless, the corresponding velocity profile has often been parameterized in the upper flow region of this flow type using the logarithmic function (see also Koll, 2002) or alternatively in analogy to the mixing layer theory (e.g., Katul *et al.*, 2002).

Flow type III corresponds to flows with small relative submergence where the roughness layer extends to the free surface. The shape of the flow velocity distribution for this flow type will be similar to the distribution for flow type II, i.e. larger velocities above the roughness crests and spatial heterogeneous velocities in the interfacial layer (see Figure 2). Flow type IV describes flow situations over partially inundated beds and the velocity distribution for this flow type depends significantly on roughness characteristics (Nikora *et al.*, 2004). Dependent on the vertical distribution of the roughness, different theoretical velocity profile shapes can be derived within the interfacial sublayer ranging from constant velocity over depth (no vertical variation of roughness characteristics– e.g., cylinder-arrays) through exponential (e.g., well submerged roughness elements with low variability in roughness geometry over depth while the overlying layer is the dominant source of momentum) to linear velocity distributions (monotonically decrease of porosity – e.g. sediment beds), as described in detail in Nikora *et al.* (2004).

The above review focused on surface flow processes, i.e. flows that can be directly seen, but it needs to be extended towards effect of flow processes within the subsurface layer for which relevant information may be found in textbooks (e.g., Bear, 1979) or the scientific literature. The following section focuses on how subsurface-layer characteristics can affect the hydraulics of surface flow. For this purpose, we will briefly highlight exchange processes between the main stream and groundwater flow from a hydraulic point of view.

Effect of subsurface characteristics on surface flow

Hyporheic Exchange

The exchange of mass, energy and momentum in the water-sediment interfacial region, i.e. between surface and subsurface flow, is also known as hyporheic exchange. Hyporheic flow itself is controlled by hydrodynamic processes operating across a range of spatial and temporal scales (e.g., Boano *et al.*., 2014, Marion *et al.*., 2014, Tonina and Buffington, 2007). Moreover, in case fine particles are transported by the surface flow, hyporheic exchange can lead to the entrainment of these fine particles into the subsurface layer.

This process can lead to an accumulation of fine sediment around coarse-bed grains which is also known as colmation (Brunke, 1999) or embeddedness (Boano *et al.* 2014), and which can result in the formation of a thin seal disconnecting the surface water from hyporheic water. Such a seal can thus hinder exchange processes and degrade aquatic habitat. An example for the latter is the degradation of spawning areas of lithophilic fish species such as salmon (Sternecker *et al.*, 2014). The reverse process, i.e. the entrainment of fine particles from the subsurface layer into the surface flow, is known as decolmation (Brunke,1999, Huston and Fox, 2015). This process can be associated with pressure fluctuations in the bed (Detert and Parker, 2010).

Effect of porosity on surface flow characteristics

Hyporheic exchange, colmation and decolmation depends on many boundary conditions such as near-bed turbulence characteristics, the interaction of the flow with irregularities of the streambed such as gravel particles or bedforms, subsurface layer characteristics and hydraulic conductivity of the subsurface layer. As indicated in the above review, the hydraulics of gravel bed rivers has mostly been classified in regard to surface flow characteristics. For example, rough-beds have often been simulated by gluing a single layer of rough particles onto an impermeable bottom (e.g., Koll, 2002 and references therein) but there exist also many studies in which turbulent flows over porous beds have been investigated in both laboratory and field conditions (e.g., Mohajeri *et al.* 2016, Stewart, 2014, Pechlivanidis *et al.*., 2012, Aberle *et al.* 2008, Kironoto *et al.*., 1994).

However, only few studies exist in which the influence of bed-porosity on surface flow characteristics has been directly addressed and quantified. These studies revealed significant differences between flows over permeable and non-permeable beds in regard to bulk flow characteristics such as the friction factor, near bed turbulence characteristics and the shape of velocity profile. In fact, numerical simulations as well as laboratory studies carried out over beds with artificial roughness elements (e.g., spheres) revealed that the friction factors for permeable beds are higher than for impermeable beds with the same roughness texture (Zagni and Smith, 1979, Zippe and Graf, 1983, Jiménez *et al.*., 2001, Prinos *et al.*., 2003, Breugem *et al.* 2006, Manes *et al.* 2009, 2011, Sparrow *et al.* 2012, Keramaris 2016). Moreover, these studies provide evidence that the friction factor for permeable beds depends on the Reynolds number even for the hydraulically rough regime (e.g., Manes *et al.* 2011, Sparrow *et al.* 2012).

The difference in friction factor has been associated with the shear penetration within the permeable bed, i.e. with a more efficient energy dissipation as a consequence of the momentum exchange between the surface and subsurface flow (Zagni and Smith, 1979, Manes *et al.* 2009, 2012). In this context, Keramaris (2016) found for two beds with identical porosity but different subsurface texture a lower surface flow velocity for the bed which was characterized by a larger penetration depth. Further studies have addressed differences in near bed turbulence characteristics and coherent flow structures in much more detail, or investigated the pressure fluctuations in the hyporheic zone and their effect on sediment entrainment (e.g., Vollmer *et al.*., 2002, Smart and Habersack 2007, Detert *et al.* 2010, Keramaris 2016).

Most of the aforementioned studies were based on beds composed of artificial elements and a detailed quantification of the effect of bed porosity on surface flow characteristics in gravel beds is therefore still lacking. To the best of our knowledge, there exists only one study which directly addressed this issue. Ockelford *et al.* (2013) conducted hydraulic measurements over a number of water-worked gravel bed surfaces as well as impermeable facsimiles of the porous beds created using a casting technique. However, the corresponding results have so far only been reported in a conference abstract indicating that the results observed over artificial beds are also valid for gravel beds. Moreover, the study of Ockelford *et al.* (2013) indicates the effect of bed porosity depends also on surface topography characteristics.

Current research at NTNU

An ongoing study at the Department of Civil and Environmental Engineering at NTNU aims at the quantification of the effect of bed porosity on the near-bed flow turbulent flow field in gravel bed rivers. In order to study the effect of bed porosity on the near-bed flow turbulence, an armoured gravel bed surface created in a hydraulic flume will be reproduced with high accuracy (Figure 3) using a novel bed casting technique (Spiller and Rüther, 2012, Spiller, 2014, Navaratnam *et al.*, 2016). Hydraulic experiments will be performed over both the initial armoured gravel bed and its impermeable counterpart by acquiring velocity data for a range of relative submergences by means of 2D - 3C PIV technique (2 Dimension – 3 Component Particle Image Velocimetry). Figure 4 shows exemplarily a time-averaged velocity field of the longitudinal velocity component over an armored gravel bed which can be captured by this measurement technique. Within the study, the spatially and temporal high-resolution velocity data will be used to determine differences in friction factor, turbulence characteristics and spatial flow heterogeneity in the near bed region between the permeable and impermeable bed based on the DAM-approach. Such a study is also required in regard to further development of experimental techniques as the technological

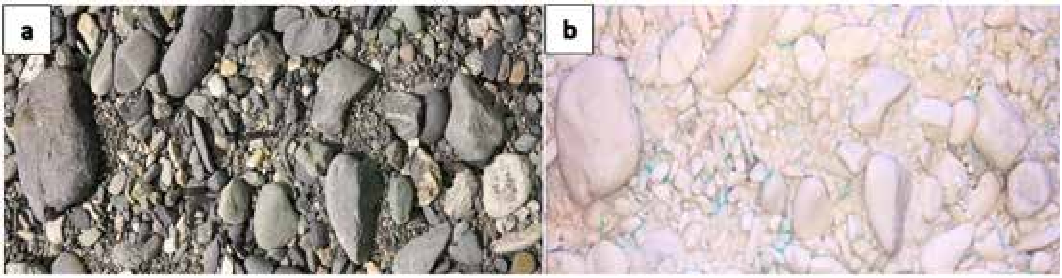

Figure 3. Photographs of a) gravel bed armour layer and b) its artificially reproduced counterpart without porous subsurface.

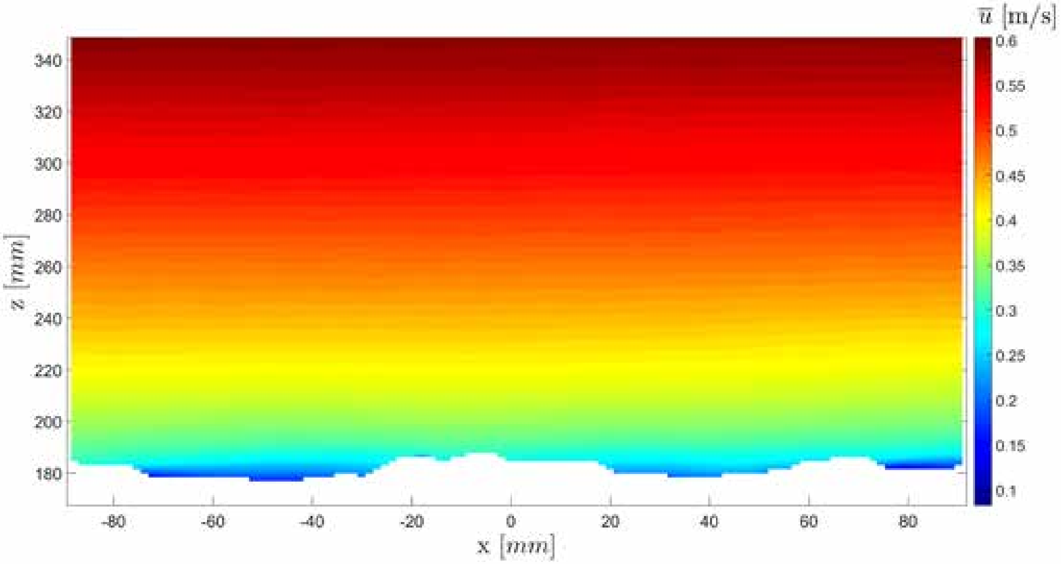

Figure 4. The time-averaged velocity field over an armoured-gravel bed.

development allows nowadays for the printing of 3D surfaces (e.g., Bertin *et al.* 2014) but not yet for the accurate reproduction of subsurface characteristics.

Conclusions

This paper reviewed flow features over rough gravel bed surfaces and addressed additionally the significance of bed porosity on the hydrodynamics of such flows. Dependent on the relative submergence, different flow layers and flow types have been defined in accordance with recent literature. The literature review revealed also that permeable beds impose higher resistance on the flow than the impermeable beds due to the flow penetration into the porous medium and that the friction factor for permeable beds depends on the Reynolds number. The paper concluded with the brief introduction to an undergoing research project focusing on the quantification of the effect of the gravel bed porosity on the near-bed flow turbulence.

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