Investigation of topographically-induced flow in a pore space using endoscopic PIV

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Abstract The flow within the pore spaces of a permeable bed beneath a turbulent free-flow is investigated through a specially-developed endoscopic PIV technique. Specifically, we present results conducted at high-Reynolds number (21,000) in the presence of a 2D-bedform. The interstitial flow induced by the bedform is investigated at different pore space locations in order to address the impact of the bedform on the pore flow structure. The interstitial flow is characterized by jets, of varying orientation and magnitude, driven by a local pressure gradient. Measurements show intense turbulence in the pore space, resulting in intense velocity fluctuations and the formation of interstitial large vortical structures. Analysis of the instantaneous data allows the mechanism of formation and advection of these structures to be established. The precise nature of the pore flow is also shown to be strongly dependent on the location of the pore with respect to the overlying bedform. For example, the structure of the flow in the region directly beneath the bedform is highly complex and characterized by the interaction of multiple jets. Conversely, the region of the bed located beneath the wake of the bedform is characterized by diagonally converging flow that then moves vertically upward. The implications of these results for the interaction of the pore flow with the free flow are discussed.

1. Introduction

Understanding the nature of flow within permeable media is vital in many industrial applications as well as in many natural systems, and encompasses research within engineering and the geosciences. Porous media are widely employed in industrial processes including catalysis, heat exchange and cross-flow filtration treatments. In thermodynamic, as well as chemical and biological reactors, porous media are largely employed in the design of the reactor and are the key element in optimising the efficiency of the system. Within many natural environments, subsurface water-flow and hydrocarbon extraction are fields of enormous scientific, industrial and societal significance that involve flows in porous media. In many of the examples listed above, a region of the permeable domain can be exposed to high pressure gradients, thus resulting in fast flowing fluid across a significant part of the porous medium. For such cases, the simple assumptions of Darcian flow within the whole porous medium, traditionally adopted for filtration problems, have been shown to be grossly oversimplified (Pokrajac et al. 2009). A typical example can be found in natural environments such as gravel-bed rivers. In such rivers, the advection of boundary layer coherent flow structures above the bed, as well as local phenomena of flow separation induced by bed-topography, may be expected to generate significant pressure gradients across the bed and into the pores beneath (Detert et al. 2004, Klar et al. 2004), resulting in intense turbulent fluctuations within the pore spaces located in the Brinkman layer (defined as the transition layer between the fully
turbulent bulk flow and the deep ground-water Darcian flow). Understanding the nature of the flow in this region is crucial for environmental reasons, since turbulence controls nutrient and dissolved oxygen exchange, the flux of both solutes and particles and plays a central role in many other chemical and microbial processes. However, current knowledge of the nature of turbulent interstitial flow within such sediments remains largely unquantified, primarily due to the significant technical challenges related to direct measurements within these porous media. Due to this lack of knowledge, natural-channel flows are thus generally assumed to operate over impermeable, or at best oversimplified, homogenous and isotropic permeable beds. While great progress has been made in applying new technologies such as Refractive Index Matching (Goharzadeh et al. 2005, Morad and Khalili 2009), and radiological computer tomographic techniques such as Magnetic Resonance Imaging (see Sederman et al. 2004, Gladden et al. 2006 and Elkin and Alley 2007 for an extensive review), to visualise and quantify flow in porous media, none of the currently available techniques meets the significant challenges required to fully quantify the complex instantaneous turbulent patterns of high Reynolds number flows, which are expected within the pore spaces of coarse river-bed sediments. A potential solution to many of the issues related to using the techniques listed above is to allow particle image velocimetry (PIV) to be employed by providing full optical access to pore spaces. This can be obtained using endoscopy. Applications of endoscopic PIV (EPIV) within a pore space are particularly challenging. For example, Klar et al. (2004) used fibrescopes in order to track the 3D motion of tracer particles within the pores of a gravel-bed; they successfully obtained the time series of the interstitial velocity components by spatial averaging of all instantaneous velocity vectors within the pore volume. However, fibrescopes, as compared with borescopes, have a low light transmittance and hence poor image resolution and contrast. Klar et al. (2004) thus concluded that lack of illumination within the pore space was the biggest experimental limitation, and resulted in low data quality for fully resolving the instantaneous flow structure.

In this paper, a high-resolution EPIV technique is developed in order to characterise turbulent flow within a permeable bed. The specific application presented herein deals with the characterization of topographically-induced turbulent flow within the pore spaces of a permeable bed. More specifically, we present EPIV measurements carried out by placing an idealized 2D-bedform on top of a bed of regularly-packed spheres in order to investigate the impact of a pressure gradient on the interstitial flow.

2. Experimental setup and boundary conditions

Experiments were conducted in a recirculating water flume specifically designed for this application (Fig. 1). An idealised physical model of a gravel-bed was made by rigidly packing spheres (D = 0.04 m) in a cubic arrangement. This fixed permeable bed comprised six horizontal (bed thickness hbed = 0.24m) and nine vertical (bed width Wbed = 0.36 m) layers of spheres. The bed was placed into the flume covering the whole width (W = 0.36 m) and length (L = 2.4 m) of the flume test section. Figure 2 shows a schematic view of the experimental setup and the normalised reference system that is used. An impermeable triangular prism (base length B = 0.41 m, height H = 0.056 m, upstream (stoss) and downstream (lee) slopes of 10 and 27° respectively) was placed on top of this permeable bed in order to investigate topographically-induced subsurface flow. This object represented an idealized low-permeability 2-dimensional bedform, akin to an isolated sand bedform moving across a coarser-grained layer. All experiments were conducted under stationary boundary flow conditions. The total recirculating flow rate, Q, was measured by an electromagnetic flow meter. In order to characterise the oncoming free-stream flow, and thus define the experimental boundary conditions, vertical velocity profiles were measured using ultrasonic Doppler velocity profilers (UDVP). The profiles were measured using four probes equally spaced in the spanwise direction, located 0.2 m upstream of the
pore space. The UDVP data were used to estimate the percentage of flow moving above (Q_{stream}) and through (Q_{bed}) the bed. From these profiles, the mean free-stream velocity ($U_0$), which was used to calculate the open channel Reynolds ($Re = U_0 h_w / \nu$, where $h_w$ is the flow depth as defined in Fig. 2 and $\nu$ is the kinematic viscosity) and Froude numbers ($Fr = U_0 (g h_w)^{0.5}$, where $g$ is the acceleration due to gravity). The bedform was immersed in a turbulent subcritical free-surface flow ($Re = 25,000; Fr = 0.1$) with a height: flow depth ratio $H/h_w = 0.31$. The pore space flow measurements were carried out at a fixed pore space using the endoscopic PIV system described in the next section.

3. Endoscopic PIV (EPIV) setup

The EPIV system consisted of two rigid endoscopes, a CMOS high-resolution ($2352\times1728$ pixels) camera and a double-pulsed laser source (Fig. 1). The (CE) provided the optical access needed to image the flow within the pore space, whilst a custom-made laser endoscope (LE) directed light into the pore space. A cylindrical lens incorporated at the LE end provided the light sheet needed for planar measurements. To maximise the light energy transmitted to the camera sensor, an image-intensified camera (Redlake MotionPro X5) was used. The LE was connected to a double-pulsed Nd:YAG 532 nm New Wave laser with output energy up to 120 mJ per pulse and repetition rate up to 15 Hz. A 4Gb on-board camera memory allowed the collection of a maximum of 500 sequential image pairs at full resolution.

Figure 2b shows a schematic diagram of the endoscope setup in cross section. The CE was 300 mm long with an 8 mm external diameter shaft borescope. The choice of the CE diameter was a compromise between the requirement for a small diameter to enable image capture within the pore spaces so minimising flow perturbations, but a large enough optic aperture to minimise loss of light. To overcome loss of light through the CE, a rod lens system was used as opposed to an achromatic lens system, due to better light transmission so resulting in enhanced resolution and brightness. The CE had a $0^\circ$ view direction and a $67^\circ$ angle of view and was connected to the camera through a 50 mm focal length Nikon lens to provide appropriate magnification of the pore space. The CE was mounted horizontally through the wall of the flume (Fig. 2) in order to image a pore space close to the centre of the flume (which in our reference system is $Z = 0$). Four equally-spaced endoscopic ports have been set up in the vertical direction in order to allow quantification of the flow at different depths within the bed; the results reported herein are from the second pore space beneath the surface bed (Fig. 2b, port B). The minimum distance between the end of the CE and the measurement plane was 0.038 m, thereby resulting in negligible flow perturbation, maximum image resolution and a more complete field of view (FOV) in comparison to external PIV applications in packed bed of spheres (Pokrajac et al. 2009).

A customised $0^\circ$ view angle LE was used to convey the laser beam and illuminate the pore space (Fig. 2). The LE consisted of a 27 mm long cylindrical probe (with 12 mm external diameter) and the probe terminated at a cylindrical lens (8 mm diameter) that produced a light sheet (0.5-1 mm thick) with a lateral divergence angle of approximately $26^\circ$. The cylindrical lens was sealed within a special casing designed for water applications. The LE probe was connected to an optical chamber housing a spherical lens with fixed focal length; the axial position of the lens within the mounting chamber is adjustable to allow collimation of the beam focus; a spherical lens with a focal length of 300 mm was used. The laser beam is precisely conveyed to the LE through an optical articulated arm rigidly connected to the chamber of the LE. In order to avoid any disturbance to the free-stream flow above the sediment bed, the LE probe was inserted vertically through the floor of the flume via a customised port. This allowed adjustable positioning in the XZ (horizontal) plane, thus permitting precise alignment of the light sheet. The end of the LE was positioned 0.076 m from the pore space.
(Fig. 2b), this configuration providing the desired aim of negligible local flow perturbation and complete illumination of the whole pore space.

4. Image capturing and processing

Data were taken at a specific pore space located \( X = 1.68 \, \text{m} \) from the inlet section (section 1 in Fig. 2a), \( Y = 0.08 \, \text{m} \) underneath the bed interface and \( Z = 0.16 \, \text{m} \) from the wall (see Fig. 2). In our reference system, the trailing corner of the bedform is chosen as the origin of the axis (see Fig. 2) and the particle diameter \( D \) is used as the representative length scale for normalization. In order to study the pore flow at variable distances from the bedform, fifteen experiments were conducted in which the hydrodynamic boundary conditions were kept constant but the bedform location \( (x/D) \) was changed with respect to the measurement pore space.

A single-exposure, double-frame, PIV approach was used. For the experimental condition presented in this paper, an image acquisition rate of 15 \( \text{Hz} \) was sufficient to fully characterise the evolution and periodicity of large vortical structures within the pore space, prevent aliasing problems, and maximise the length of sequential image capture. Neutrally buoyant, spherical, hollow glass particles \( (\rho_p = 1050 \, \text{g cm}^{-3}) \) with a nominal mean diameter of 11 µm were used to seed the flow. The strong distortion due to the large angle of view of the CE was removed by use of a calibration target placed in the measurement plane within the pore space, prior to experiments taking place. The target consisted of a plate (30*30 mm) with a regular grid of circular dots, spaced 1 mm apart.

Image processing based upon application of a threshold was applied to the calibration image and automatic blob analysis algorithms were applied in order to determine the centroid location of each dot. Due to the strong spherical aberration of the endoscope optic, the magnification factor \( \alpha_m \) is a maximum in the image centre and minimum on the border. A mean \( \alpha_m \) of 18 µm·pixel\(^{-1} \) was found to be an acceptable compromise between maximization of spatial resolution and maximization of field of view. Based on the mapping function concept the image distortion was therefore evaluated. A fourth-order polynomial function was judged appropriate to quantify the effect of the spherical aberration, and in order to correct the image distortion all the collected raw images were dewarped before data interrogation on the basis of the calibration function.

An example image derived from using the technique is shown in Fig. 3a, which illustrates the geometrical proportion between the size of the field of view obtained through this configuration (circular FOV, about 26 mm diameter) and the whole pore space size. Importantly, it can be seen (Fig. 3) that significant areas, hidden by the spheres and hence those that would not be visualized by external PIV techniques, are imaged using EPIV.

Image interrogation was performed by applying a fast Fourier transform (FFT) cross-correlation function to each image pair. Sub-pixel accuracy was obtained by a standard three-point Gaussian fitting technique. Instantaneous velocity vector maps over a grid of equally-spaced points were calculated. A 64*64 pixel interrogation window was used, which corresponds to an average window size in the range of 1*1 to 1.5*1.5 mm, thus respecting the ¼ rule which prevents problems of aliasing in the correlation plane (Adrian 1986). The interrogation scheme was considered appropriate to provide a reasonable compromise between the smallest detectable turbulent structure and the mean number of particles pairs within each interrogation window.

An example of instantaneous flow field obtained applying EPIV into the pore space is illustrated in Fig. 3b and shows a large vortical structure due to high pore space turbulence. In particular, the example reported in Fig. 3b shows that a significant part of the vortex would be hidden by the spheres, thus demonstrating how the maximization of the FOV is important for capturing
successfully the dynamics of turbulent structures within the pore space.

5. Results

Mean Flow field

The instantaneous velocity data collected during each experiment were time-averaged in order resolve the mean flow structure. Each one of the fifteen averaged velocity fields characterizes the interstitial flow at a specific pore-space/bedform relative distance. In Fig. 4, the time-averaged flow fields are plotted according to their relative location (each location is labeled in Fig. 4 using a different letter), thus mapping the flow induced by the 2D-bedform across the bed. The local mean direction of the pore space flow is highlighted by the streamlines shown in the images. The main flow variables (streamwise, bed-normal velocity component and vorticity) are also reported in three different colormaps. Both the distribution of the velocity magnitude and the actual flow pattern significantly change with the x/D coordinate. Three main regions can be identified:

Region 1: The region upstream of the bedform (x/D < -10, see Fig. 5a: pores A and B) is characterized by downward moving flow. Above the bed, due to presence of the bedform, the oncoming near-bed free-flow decelerates and bifurcates: consequently, part of the free-flow is directed upward over the bedform but, as a result of the boundary permeability of the bed, part of it is deflected downward, into the bed, pushed by the high-pressure region in the bedform stoss-side. The fluid penetrates the bed and deflects downstream under a strong horizontal acceleration. This is documented in Fig. 5a which is shows that: 1) the flow structure within the two examined pore spaces in Region 1 (A and B) appears consistent; 2) the interstitial flow pattern in the single pore space displays relative uniformity with a diagonal motion characterized by a significant downward component; 3) the magnitude of the vertical component at x/D = -13 is higher than at x/D = -11, suggesting a progressive deflection of the flow at increasing x/D coordinates; and 4) at x/D = -11 the streamwise component of velocity shows higher values as compared with x/D = -13 (see Fig. 5a) thus suggesting a significant horizontal acceleration of the flow in Region 1.

Region 2: High values of the streamwise component of velocity (Fig. 4a) are the key element characterizing Region 2 located beneath the bedform (-10 < x/D < 0, see Fig. 4: pores from C to H), and suggests that the horizontal component of the pressure gradient dominates the entire region. The data show high levels of vorticity (Fig. 4c), with similarities in the patterns of vorticity at different locations. For example, elongated regions of both negative vorticity at the top of the field of view and positive vorticity at the bottom of the field of view are typical. This implies that the horizontal, non-uniform, motion of the fluid generates elongated regions of shear within the pore space that are highlighted by the concentration of vorticity. These vorticity patterns suggest that a quasi-horizontal jet, with its axis located between the regions of opposite vorticity, is the dominant flow feature for Region 2. The vertical component of velocity (Fig. 4b) shows variations with x/D, resulting in differences in angle and structure at different locations. While the flow in F and G display a relative uniformity (similar to Region 1), the flow pattern for the other locations (C, D, E and H) is more complex (see Fig. 5b) and is characterized by two subregions: 1) high-velocity, quasi-horizontal, flow at the top of the field of view; and 2) lower-velocity vertical flow at the bottom. As a consequence of these features, the mean flow patterns in Region 2 are not self-similar along the X coordinate.

Region 3: Downstream of the bedform (x/D > 0, see Fig. 4: pores from I to O) the pore flow is dominated by upward-moving fluid, which is induced by the low-pressure region in the wake of the bedform due to flow separation at the crest. This low-pressure causes suction of fluid from the bed,
and is consistent with the results shown in Fig. 4 (pores from I to O), where the interstitial flow displays intense upward motion, mainly concentrated at the bottom of the field of view. The strength of the upward flow changes with x/D. For example, in Fig. 5c at x/D = 3, this injection is significantly stronger than at x/D = 1. Data show that in the range 1 ≤ x/D ≤ 9 suction seems to become more intense as x/D increases. The maximum values of the vertical velocity component are found between 5 ≤ x/D ≤ 9. For x/D ≥ 9 the vertical component of velocity decreases with increasing x/D. The streamwise component of velocity is positive for 1 ≤ x/D ≤ 5, decreases to zero at x/D ~ 7, while for x/D ≥ 9 the horizontal flow is reversed. These observations suggest that the flow converges towards the region 5 < x/D < 9 and then moves upward. This conclusion thus implies that the low-pressure peak (that associated with recirculating flow in the lee-side of the bedform) may be located in the range x/D ~ 7 (~ 5H from the trailing edge). The effect of suction is visible up to pore O (x/D = 18), demonstrating that the effect of the low-pressure propagates further downstream, inducing not only strong upwelling of flow in the near wake, but also reverse flow further downstream. This may have significant implications for the potential impact on the flow structure of the separation zone behind the bedform that warrants further investigation.

Flow evolution

An example of the evolution of the pore flow induced by the bedform at a fixed pore-space/bedform location (x/D = -9, in Region 2, pore labeled as C in Fig. 4a) is shown in Fig. 6. A sequence of instantaneous flow fields, captured at a rate of 15 Hz within the pore space, shows six steps of the temporal flow evolution process. The evolution is mainly characterized by a clockwise-rotating eddy (labeled C in Fig. 6a) that is advecting downstream. This process is likely triggered by the interaction between a quasi-horizontal downstream jet (labeled jet H in Fig. 6) and a vertical jet of lower velocity (jet V); these jets initially generate a pair of counter-rotating vortices (labeled as C and A in Fig. 6a, only partially visible at the bottom left side of the field of view). The horizontal jet generates the clockwise-rotating eddy (C) whilst the vertical jet generates the anticlockwise (A) circulation. The mechanism responsible for vortex formation is believed to be a Kelvin-Helmholtz instability associated with the shear layer that originates at the sides of the jets. The presence of two orthogonal jets in the pore space suggests that the flow is induced by a diagonal pressure gradient, which results in a complex jet-to-jet interaction mechanism that leads to the processes of vortex formation and advection shown in Fig. 6. In the case examined herein, the strength of the two jets is unequal resulting in the suppression of the vortex generated by the weaker jet. Figure 6b shows that the velocity of jet H is much stronger than jet V, and consequently the shear layer associated with jet H is able to: 1) entrain fluid from the region moving upward; 2) inhibit the vorticity produced by jet V, and consequently the mechanism feeding vortex A; and 3) sustain the organization of vortex C while pushing it downstream. This mechanism results in the suppression of vortex A and the enhancement of vortex C, which keeps moving downstream up to the right side of the pore space (from Fig. 6b to f), thus disappearing from the field of view. In Fig. 6f the initial condition described above, and characterized by the presence of a pair of vortices, is repeated, and thus the process appears cyclical. The advection period of the event described above is estimated to be approximately 0.6 sec.

Conclusion

Development of a novel endoscopic PIV technique has allowed investigation of the flow induced within the pore spaces of a permeable bed. An idealized 2d-bedform placed above the bed was used in order to simulate a low-permeability bedform on top of a high-permeability bed and thus characterize the topographically-induced pore flow for a case that is analogous to a gravel-bed river. The bedform was immersed in a free-surface flow (flow Reynolds number Re = 25,000; Froude
number Fr = 0.1) with a height: flow depth ratio = 0.31. The data show that the interstitial mean flow is strongly dependent on the location of the bedform, thus confirming that the flow is controlled by the pressure gradient induced by topography. The main conclusions of the study are:

1) The flow is characterized by jets with different direction and strength that are driven by the local pressure gradient.
2) The structure of the pore flow is a function of the characteristics of the jet and thus, indirectly, of the local pressure gradient.
3) Three discrete flow regions have been identified: i) upstream of the bedform - flow that is moving downward deflects downstream with significant horizontal flow accelerations; ii) beneath the bedform - flow is predominantly horizontal and characterized by the interaction of multiple interacting jets that result in a complex flow pattern; and iii) downstream of the bedform - pore water flow, although displaying a strong upward component, is mainly directed diagonally (i.e. downstream flow is significant) before converging at x/D ~ 7 and then moves vertically upward.

One case of temporal-evolution has been examined showing formation of coherent structures and providing a mechanism for their formation and advection. Based on these observations, it is suggested that the movement of fluid from the permeable bed to the free flow may thus have a significant impact upon the recirculation zone in the wake of the bedform that has hitherto not been quantified. Further work is clearly required to quantify this effect and improve understanding of the interaction between the turbulent wake produced by the dune and the flow within a permeable bed.

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References


**Fig. 1** Photograph of the experimental set-up: the figure shows the test section (which contains the packed permeable bed) and the EPIV set-up; the camera-endoscope (CE) is connected to the high-resolution camera; the laser-endoscope (LE) is connected to the articulated arm (AA).
Fig. 2 Schematic diagram of the experimental set-up used in this study: a) longitudinal view (X-Y plane) of the flume test section (length L = 2.40 m, height Hf = 0.60 m, slope α = 0). Flow is from left to right; Qstream and Qbed refer to the mean flow discharge above and through the bed respectively. The cross-section of the 2d-bedform used is shown. The location of the pore space volume instrumented with EPIV is shown. b) transverse section (width = 0.36 m) showing the set-up of the endoscopes in the Y-Z plane: the camera-endoscope is inserted horizontally from the wall while the laser-endoscope is inserted vertically through the floor. The multiple camera-endoscope port system installed in the wall is also shown.
Fig. 3 a) Example of EPIV image taken within the pore space at location B (see Fig. 2b); b) Instantaneous flow field boundary condition are: $D/h_w = 0.21$; $Re = 2.1 \times 10^4$; plane bed. The color-map shows the velocity magnitude expressed in ms$^{-1}$ and the flow streamlines.
Fig. 4 Mean flow field induced by the 2d-bedform within the bed at different pore-space locations showing: a) streamwise velocity component, b) bed-normal velocity component, c) vorticity.
Fig. 5 Averaged flow fields induced by the 2d-bedform within the bed in three different regions: a) upstream (pore A and B of Fig. 4), b) beneath (pore C and D of Fig. 4) and c) downstream (pore I and J of Fig. 4) the bedform. Streamlines are superimposed in order to aid visualization of the flow direction; the colormap refers to the vertical component.
Fig. 6 Sequence of images of instantaneous flow fields showing the evolution of flow driven by interaction between a horizontal and a vertical jet (within pore at x/D = -9) leading to formation of a vortical pathway.