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On the fine sediment deposition patterns in a gravel bed open-channel flow

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ABSTRACT

One of the most important problems in rivers restoration and management is the problem of fine sediment deposition in the bottom of gravel beds. In fact, such phenomena can affect fauna and flora in various area. In Present study, a series of video camera measurements in an open channel with gravel bed was carried out in order to investigate the process of fine particles entry in the matrix of a gravel bed. Specifically, the present study focuses on a spatial pattern of fine sediment deposition and entrapment. The results show that deposition and entrapment of fine particles caused by the intrusion of large gravel particles and thus fine sediment deposition pattern are mostly in agreement with bed topography. Indeed, fine particles generally deposited on the downstream side of the gravel particles, while they rarely settled down in the upstream side of the gravel particles. Moreover, the results highlighted the formation of quite long longitudinal sand bars which are repeated in whole cross-section. These observations are in agreement with near bed common flow characteristics such as sweep and ejection events and strong secondary currents formation. The combined effects of sand ribbons and bed topography lead to the complex spatial pattern of deposition which questions the applicability of common transport thresholds which were developed based on the bulk properties of the flow like shear velocity.

1. Introduction

Gravel beds are common in nature, specifically most of the mountainous rivers are composed of gravels in different sizes (Wohl. 2013). The transport and deposition of fine sediments in gravel bed river are also common in mountainous areas (Schälchli.1992; Wohl. 2013). Improved knowledge of the distinct characteristics of fine sediments, which affects their erodibility (Grabowski et al. 2011) and the flow structures above gravel beds will further our understanding of fine sediment dynamics. This is important because fine sediments deliver benefits such as nutrient supply to biota but excessive fine sediment loads and the presence of sediment-bound contaminants can cause significant environmental impacts.

The issue of fine sediment deposition in the matrix of a gravel bed and its filtration to the deeper layer is a common topic in various engineering and science disciplines (Schälchli. 1992; Brunke and Gonser.1997; Blaschke et al. 2003). Due to this fact, there are several definitions of this phenomenon. In this regard, the term colmation is commonly used where there is more emphasis on the ecological and biological aspects of sediment deposition. In the context of the physical effects of sediment deposition, the process is called clogging (Blaschke et al. 2003; Packman and MacKay 2003; Rehg et al. 2005) Infilling is more used in the field of groundwater hydrology where the emphasis is on conductivity reduction (McCloskey and Finnemore. 1996; Li and Zhou. 1997) and finally ingress is a common term in geomorphology (Li and Zhou. 1997).

Despite many studies concerning fine sediment deposition in gravel bed, many physical aspects of this process have not been clarified properly. More precisely, it is not clear how fine particles are deposited in the matrix of gravel and what would be the spatial organization of deposited materials. In the present study, we focus on the process of fine particle entry in the matrix of gravel bed. Specifically, we aim to address spatial pattern of fine particles deposition respect to near bed flow characteristics. To this end, laboratory experiments have been conducted in open channel with an immobile gravel bed and in the presence of mobile particle. The bed topography during the process was captured using a digital camera. These measurements allow us to depict spatial deposition patterns.

2. Materials and methods

2.1. Experimental setup

The experiments were conducted in a 0.4 m wide, 0.4 m deep, and 6 m long polymethylmethacrylate rectangular tilting open channel at the Hydraulic Engineering Laboratory of the University of Trento. The flume bed was covered by a thick layer of gravel. To minimize backwater effects on the intended uniform flow conditions, an adjustable tailgate weir at the end of the flume was used. Free surface profiles were measured by an ultrasonic distance transducer to check flow uniformity. The discharge at the flume inlet was controlled by an inverter for pump speed regulation and was measured by an electromagnetic flowmeter. In our study, we employ the right-hand coordinate system, i.e., the x-coordinate is oriented along the main flow positive downstream and parallel to the mean bed; the z-coordinate refers to the vertical direction, pointing upward from the gravel tops (the z origin will be explained below); and the spanwise y-axis is directed to the left wall (Fig. 1-a).

Rough bed materials were the mixture of gravels (D_{50}=24.9 mm). Gravel-bed surface was smoothed mechanically by moving a wooden leveling table along a longitudinal guide from upstream to downstream, in order to avoid gravel clustering and produce conditions similar to water-worked gravel beds (e.g., Aberle and Nikora. 2006). In Fig. 1-b, the photo of the gravel bed in the laboratory open channel is shown. Moreover, to resemble the natural substrate in the rivers, sandy materials are also added to gravel bed (D_{50}=1.25 mm). The standard deviation of gravel bed elevations σ_1, which is a representative roughness scale (i.e., $\Delta \sim \sigma_1$, (Nikora et al. 1998) is equal to 6.1 mm.

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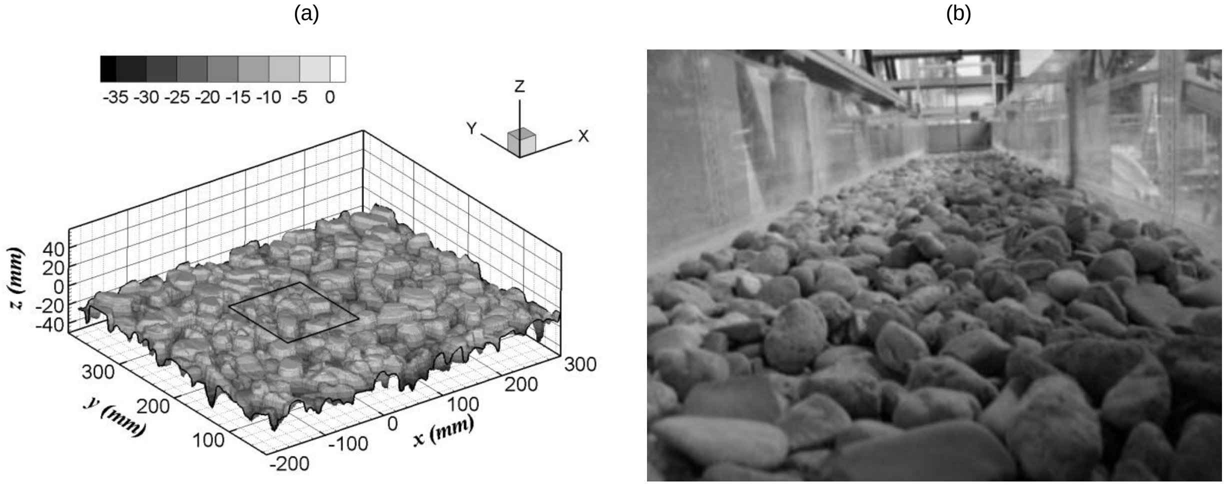

Fig. 1. (a) relative location of the PIV horizontal plane above the gravel bed, (b) photo of the gravel bed.

Two series of data have been collected during these measurements (named Series 1 and Series 2). Experimental conditions of these measurements are reported in Table 1. Hydraulic conditions were adjusted so that rough bed materials remain immobile during measurements. The aspect ratio B/H (B is channel width and *H* is water depth) was higher than 5 suggesting that effects of secondary currents in the central part of the flow should not be significant Nezu and Nakagawa [1993] The materials which were used as fine mobile particles were a plastic material named bakelite (phenol-formaldehyde resin) with density (ρ_s) equal to 1553 kg/lit. In Table 1, Rouse number ($R_0 = \omega_s/u_*$) is also reported. Settling velocity in Rouse number is a function of shape, size, and roughness of fine particles. For high Reynold's number, empirical formulas are available for estimation of settling velocity based on particle diameters. One of the most common forms of these empirical formulas is as below (Cheng. 1997; Julien. 2010):

$$\omega_s = \frac{\nu}{D}\left[\sqrt{\frac{1}{4}\left(\frac{A}{B}\right)^{2/m} + \left(\frac{4}{3}\frac{d_*^{a}}{B}\right)^{1/m} - \frac{1}{2}\left(\frac{A}{B}\right)^{1/m}}\right]^{m} \quad (1)$$

Where D is diameter moveable material, A, B, m are the coefficients vary according to different authors. In present study, the coefficients suggested by Cheng [1997] are used (A= 32.0, B= 1.0, m= 1.5). Also, d_* is dimensionless particle diameter defined as:

$$d_* = \frac{(\rho_s - \rho)g}{\rho \nu^2} D \quad (2)$$

Where ρ and ρ_s are respectively water and fine sediment density and g is the acceleration of gravity equal to 9.81 m^2/s. When Rouse number is smaller than 1, it can be assumed that suspended sediments transport is initiated (Van Rijn. 1984). In both measurements, Rouse number is smaller than 1 (Table 1). This means that at least some parts of fine particles are transported in suspension.

To capture the deposition pattern of fine particles a video camera measurement technique is used. Based on this technique, a High-Resoloution video-camera is installed in a position where both stable gravel particles and fine particles are simultaneously recorded during a quite long/quite a long period. The video camera was Panasonic G-HVX200 DVC, with non-adjustable frame rate. The data was recorded for around 2 minutes in which the authors can clearly observe and describe those depositional patterns which were stable and remains for long period. The bed topography was captured in three difference views. In the first view, bed topography was captured from the side wall of the channel. The second view was from top where the plan of the bed topography was captured. Finally, the third view was again from top, but the zoom was wide to capture larger spatial patterns of the sand deposition. After experiments, the recorded videos are post-processing using Photoshop software, then proper photos are selected and extracted from the collected video record.

Table 1. Characteristics of the measurements in the presence of fine sediment.

	Q (lit/min)	H (mm)	S (-)	B (mm)	B/H (-)	D (μm)	U_* (m/s)	ω_s (m/s)	R_0 (-)
Series 1	420	50	0.002	400	8	500	0.031	0.027	0.87
Series 2	320	40	0.002	400	10	425-500	0.028	0.025	0.89

3. Results and discussion

In Fig. 2, deposition of fine particle near gravel bed in series 1 from side view (Fig. 2-a) and plan view (Fig. 2-b) are shown. It is clear that deposition of fine materials near gravel bed has a correlation with bed topography. Specifically, fine particles are generally deposited in the downstream side of gravel crests (see dashes curves in Fig. 2a and b). Indeed, the dashed curves in the downstream side of particles clearly show deposition of fine particles (materials with red color) in this region. In the upstream side of gravel crests, most of the fine particles are eroded. The same behavior is also observed out of the area covered by video camera.

There are two reasons for this tendency of deposition in correlation with bed topography. The first reason is due to the diversion of the water flow near gravel particles. Indeed, before gravel particles, water flow is diverted toward the lateral direction and after the particles the flow reattached. Accordingly, fine particles are brought up and down by the flow respectively in upstream and downstream of the particles. Another reason for this behavior can be related to the turbulence structure. Ejection, which is the upward movement of low-velocity flow and sweep, which is the movement of high-velocity flow can commonly occur in rough bed flows (Grass.1971Nezu and Nakagawa. 1993). Fine particles can also be eroded and deposited by the sweep and ejection events (Mohajeri et al. 2016). In fact, previous studies show that gravel particles intrusion can affect near bed flow characteristics and prevalence of sweep and ejection events (Sambrook Smith and Nicholas. 2005; Wren et al. 2011). In this case, it can be speculated that ejection is more common in the upstream side of the particles, while sweep is more common in the downstream side of the particles. Both of the assumptions should beexamined by comparison of flow structure measurements near gravel particles.

In Fig. 2-b, it can be observed that in some cases, the fine particles are not deposited on the downstream side of the gravel particles. Indeed, fine particles cannot be deposited in the small spaces between the gravel particles. Moreover, the shape of gravel particles and their orientation can also change deposition pattern. This observation shows that the bed topography can affect the spatial deposition pattern of the fine particles.

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Fig. 2. fine sediment deposition in comparison to bed topography (a) side view (b) plan view.

In Fig. 3, the sandy-grave bedsl in the wider top view for series 1 (Fig. 3-a) and series 2 (Fig. 3-b) measurements are shown. In both measurements, longitudinal bars of fine particles are formed along the main flow direction. their longitudinal bars are formed in the whole cross-section and the length is many time higher than their width. In fact, their length is fifty times higher than the water depth. As regards of the width of these longitudinal bars, it is difficult to judge about the exact values (due to the variation of their width respect to bed topography), but their width could be around water depth. As highlighted in Fig. 3 the lateral l distance between two consecutive longitudinal bars (δ) is approximately two times of water depth. The lateral spacing of these longitudinal bars and their size are in agreement with classical sand ribbons (Nezu and Nakagawa.1993). Similar straight sand ribbons are commonly notified in natural rivers (Karcz. 1966). Also, in the wide open channel (B/H>5) such sand bars can form. The main reason for the formation of sand ribbons is due to the presence of secondary currents cells. In rough bed open channel and in the presence of mobile fine materials, cellular secondary currents and sand ribbons interact mutually. The presence of sand ribbons can stabilize secondary currents, while the occurrence of upward and downward movement in secondary current cells can cause the formation of sand ribbons (Nezu and Nakagawa. 1984; Nezu and Nakagawa. 1993). The lateral spacings of sand ribbons in the present study are similar to the lateral spacing of lower longitudinal velocity zones of secondary currents observed by Kinoshita (1967); Albayrak and Lemmin. (2011); and Mohajeri et al. (2015). This observation supports the assumption that in our gravel bed straight channel even with high aspect ratio, secondary currents can form. Consequently, the particles are regularized in the longitudinal bars which are explained in the result section.

Fig. 3. Formation of sand ribbons in rough bed (a) series 1 (b) series 2.

To further examine the of the secondary currents on fine sediment deposition, measurement of the flow structure near gravel particles should be employed. This type of measurements is extracted from Mohajeri et al. 2015). In this study, the authors measure flow structure in a horizontal PIV plan just above gravel crests. In Fig. 4, an example of their measurements is shown. Water depth in plots of Fig. 4 was 4 cm and mean size of gravel bed materials was about 22 mm. The hydraulic conditions of this measurement are approximately similar to the hydraulic conditions of measurements in the present t study which allow us to use this information for better understanding of the governing process of our measurements. As shown in Fig. 4 and also properly described by Mohajeri et al. (2015), two flow structure can be depicted in near rough bed flow. The first one is the formation of secondary currents which are elongated from right to left in the whole of the contour plots. The presence of secondary currents can be better notified by the plot of stream wise averaged velocity components which are shown in the left corner of contour plots in Fig. 4. This observation can clearly support our assumption that secondary currents in gravel bed play a crucial role in the formation of sand ribbons. On the side, previous studies show that in the case that sand ribbons are formed,

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the secondary currents will be present and these ribbons generate a maintaining mechanism of lateral flow which results in secondary currents in time averaged velocity components (Karcz. 1966; Nezu and Nakagawa. 1993). However, comparison of Fig. 3 and Fig. 4 shows that the enhanced secondary currents in gravel bed flow can lead to sand ribbons formation. The mutual relation of sand ribbons and secondary currents in newly obtained finding which should be properly considered in future studies for better description.

It should be also highlighted that possible simultaneous effects of bed topography and secondary currents cause complex spatial distribution of the preferential zones for entrainment or deposition of fine particles. Formation of these regions confined the application of common sediment transport thresholds such as Rouse criterion, Shields criterion or any other transport threshold which does not consider spatial variations of flow characteristics. In order to consider the spatial variation of flow characteristics in sediment transport criteria, the aforementioned criteria should also be expanded in this regard. This issue can also be followed in the future studies.

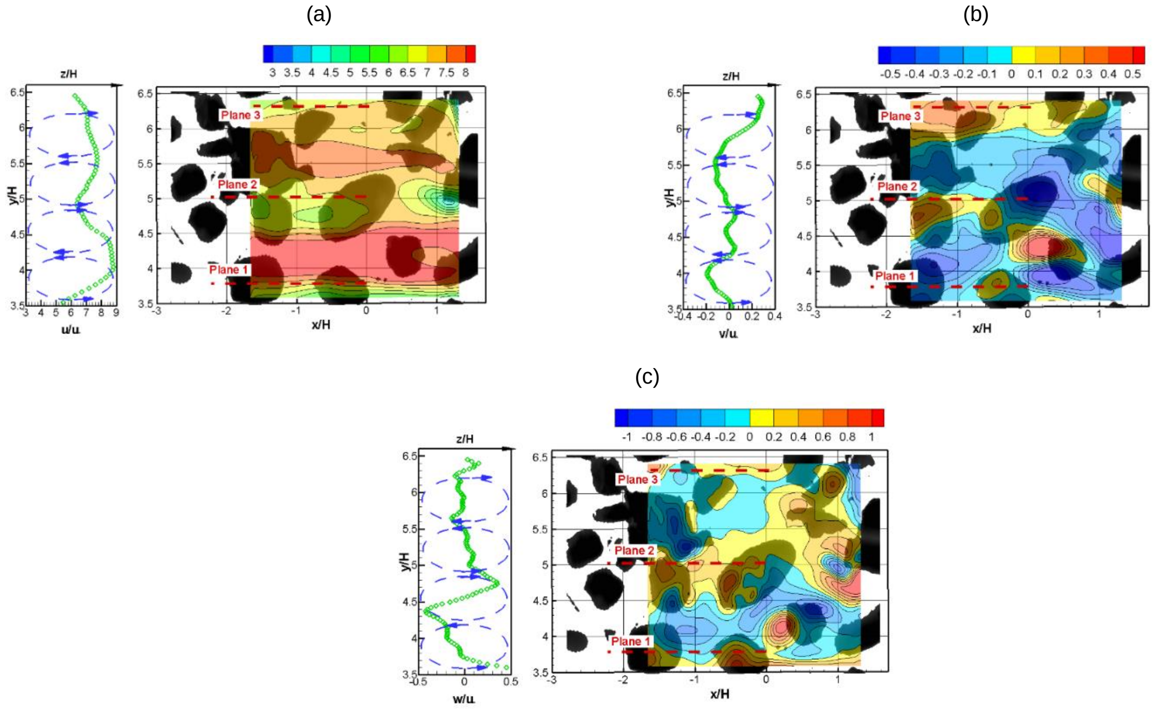

Fig. 4. Contour maps of velocity ((a) streamwise velocity (b) spanwise velocity (c) normalwise velocity) components normalized with shear velocity in the horizontal plane just above the particle crests modified from Mohajeri et al. (2015) , flowfrom left to right.

4. Conclusions

In the present study, the physical process of fine sediment deposition in gravel bed is studied using video camera measurement in a rectangular open channel. Two series of measurements were carried out in the range of shallow flow with a wide aspect ratio. The analysis of the results led to the following findings:

1- Deposition of fine particles are generally in agreement with bed topography. Fine particles rarely can be deposited on the upstream side of the gravel particles, while deposition is more common in the downstream side of the gravel particles. This observation speculates dominance of sweep and ejection events respectively in downstream and upstream sides of the gravel particles. This assumption should be examined in future studies with near bed flow field measurements.

2- It can also be observed that sand ribbons are formed in our experiments. Formation of these ribbons is mostly the result of secondary currents presence in the whole cross-section. It is interesting that in rough bed wide open channel secondary currents are present and sand ribbons are formed. Indeed, sand ribbons and secondary currents interact mutually in the smooth wide open channel. While in our experiments, sand ribbons are formed due to the secondary currents presence.

3- Combined effects of bed topography and sand ribbons formation make a very complex spatial variation of deposition zones. There are some zones where the depositin is more probable. This fact, challenge application of common sediment transport criteria. Therefore, it can also be suggested that in future studies sediment transport threshold should be somehow modified in order to take into account spatial variability of fine sediment deposition and entrapment.

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