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On the structure of turbulent gravel bed flow: Implications for sediment transport

Seyed Hossein Mohajeri[a,b,*], Maurizio Righetti[c], Geraldene Wharton[b], Giovanni Paolo Romano[d]

[a] Department of Civil, Mechanics and Environmental Engineering, University of Trento, Trento, Italy
[b] School of Geography, Queen Mary University of London, London E1 4NS, UK
[c] Faculty of Science and technology, Free University of Bozen, Bozen, Italy
[d] Department of Mechanical and Aeronautical Engineering, University "La Sapienza", Via Eudossiana 18-00184 Roma, Italy

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ABSTRACT

The main objective of this study was to examine the turbulent flow field over gravel particles as a first step towards understanding sediment transport in a gravel bed river. Specifically, the vertical momentum flux in gravel bed turbulent flow was investigated with particular attention to the near-bed region. Spatial organization of vertical momentum flux was studied with stereoscopic Particle Image Velocimetry (PIV) measurements in a horizontal layer 1mm above the gravel crests. The vertical momentum flux through the water column was described with digital PIV measurements in three vertical planes. The data showed that near the gravel bed, net turbulent momentum flux spatially varies with respect to bed topography. Analysis of the vertical velocity data revealed that near the gravel particle crests, there is a significant net vertical form-induced momentum flux approximately with the same order of magnitude as the net vertical turbulent momentum flux. Above the crests, total net vertical momentum flux is positive. However, below the crests, despite noticeable positive form-induced momentum flux, total net vertical momentum flux is negative. Results of quadrant analysis show that variation of turbulent net vertical momentum flux through water column is in agreement with prevalence of upward movement of low velocity flow (known as ejection) above gravel crests and downward movement of high velocity flow (known as sweep) below gravel crests. Below gravel crests ($-0.1 < z/H < 0.0$), there is a region where the contribution of second quadrant to Reynolds shear stress is lower than fourth quadrant, while the contribution of second quadrant to vertical momentum flux is higher than fourth quadrant. This can be interpreted that ejection events in this region are strong enough to lift up fine particles but their contribution is not sufficient to move fine particles in the longitudinal direction.

1. Introduction

Transport and deposition of fine sediments above gravel bed rivers is common especially in mountainous areas (Schälchi, 1992; Wohl and Chin, 2006). 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 enhance our understanding of fine sediment dynamics. This is important because fine sediments deliver benefits such as a nutrient supply to biota living in the fluvial system, but excessive fine sediment loads and the presence of sediment-bound contaminants can cause significant environmental impacts (Heppell et al., 2009; Wood and Armitage, 1997a). Deposition of finer material in the matrix of a gravel bed and its filtration to the deeper layer (known as colmation) affects the fluvial system by reducing hydraulic conductivity (Brunke and Gonser, 1997; McCloskey and Finnemore, 1996) and can alter the physical, chemical and biological properties of the hyporheic zone and benthic layer (Brunke and Gonser, 1997). Decolmation, the entrainment of fine particles from the matrix of a gravel bed, also impacts the fluvial system by increasing the surface and subsurface interconnection (Blaschke et al., 2003). As a consequence, fish spawning and incubation, invertebrate development, oxygen availability, and microbial activity can all be affected by colmation and decolmation (Bo et al., 2007; Wood and Armitage, 1997b).

* Corresponding author. Tel.: +393426355208.
E-mail addresses: hossein.mohajeri@gmail.com, hossein.mohajeri@unitn.it (S.H. Mohajeri), maurizio.righetti@unibz.it (M. Righetti), g.wharton@qmul.ac.uk (G. Wharton), romano@dma.ing.uniroma1.it (G.P. Romano).

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Transport of fine sediment in a free surface flow is triggered by near-bed turbulence (Bagnold, 1966; Niño and Garcia, 1996; Papanicolaou et al., 2001; Sutherland, 1967). The interaction between particles and bed turbulence influences the diffusion and transport processes of suspended sediment in the outer part of the flow field. Different studies on the structure of turbulent flow have recognized the importance of the near-bed bursting-sweep cycle for particle entrainment and transport (Kline et al., 1967; Nelson et al., 1995; Niño and Garcia, 1996; Papanicolaou et al., 2001). Bursting is a phenomenon common in the turbulent boundary layer and open channels and provides evidence of the presence of turbulent coherent structures that develop in the near-bed region of the flow field. It comprises a quasi-cyclic process of the upward motion of low-velocity fluid parcels (ejection) and downward motion of high-velocity parcels (sweep) (Nakagawa and Nezu, 1993), which are associated with short-duration large-amplitude wall pressure fluctuations (Snarski and Lueptow, 1995; Thomas and Bull, 1983). Many studies have demonstrated the role of intense wall pressure fluctuations in sediment transport (Detert et al., 2010; Dwivedi et al., 2010, 2011). Dwivedi et al. (2010, 2011) show that vertical and horizontal pressure gradients resulting from wall pressure fluctuations are important for sediment entrainment. According to Dwivedi et al. (2011), pressure fluctuations can cause sediment entrainment. Although the reasoning of Dwivedi et al. (2010, 2011) is slightly different, both agreed that sediments are more probably entrained during sweep events. However, at high flow rate and bed-load discharge Radice et al. (2013) found high correlation of bed load transport with ejection events.

Recent developments in research suggest a turbulent burst is the outcome of a succession of ejections due to the passage of a packet of hairpin vortices (Adrian et al., 2000b). The bursting process in the near-wall region interacts with large scale coherent structures in the outer layer (Adrian et al., 2000b; Shvidchenko and Pender, 2001; Tamburrino and Gulliver, 2007) and is considered to play an important role in the overall dynamics of the boundary layer and sediment transport processes. Ejections are considered to be primarily responsible for particle entrainment and resuspension (Bagnold, 1966; Bennett et al., 1998; Grass, 1971; Nelson et al., 1995; Righetti and Romano, 2004; Singh et al., 2007; Wei and Willmarth, 1991) whereas transport of fine sediment as bed load is mostly attributed to sweeps impinging on the bed (Drake et al., 1988; Sterk et al., 1998).

There is experimental evidence that the main features of bursting phenomena are common on both smooth and rough beds (Grass, 1971; Shvidchenko and Pender, 2001; Singh et al., 2007). On the other hand, there are fundamental differences between the two classes of beds. In smooth wall conditions, bursting is related to flow instabilities taking place in the alternating high and low velocity streaks belonging to the viscous sublayer, while for a rough bed, the protrusion of roughness elements disrupts the viscous sublayer and buffer layer and bursting seems to be triggered by the wake-like vortex shedding at roughness crests (Bandyopadhyay and Watson, 1988; Bomminayuni and Stoesser, 2011; Guala et al., 2012). Moreover, these features of the bursting phenomena in gravel bed flow are accompanied by the experimental evidence that for this kind of flow the time-averaged velocity field and higher order turbulence moments at the near-bed region (known as *roughness layer* in fluid mechanics studies (Jimenez, 2004; Nikora et al., 2001; Rajagopalan et al, 1991)) vary spatially in accordance with bed topography (Buffin-Bélanger et al., 2006; McLean and Nikora, 2006).

To properly consider the near-bed spatial variability of the flow in transport equations, locally time-averaged flow characteristics should also be averaged in space, which leads to the Double-Averaged Navier-Stokes (DANS) equations (Finnigan, 2000; Nikora et al., 2007a; Righetti and Armanini, 2002). In DANS equations viscous drag, form drag, and correlation of spatial fluctuation of time-averaged velocities (known as form-induced stresses) are explicitly expressed (Nikora et al., 2007a). Form-induced stresses in DANS equations contribute momentum flux in addition to Reynolds stresses (Pokrajac et al., 2007). Despite the common use of the double averaging method in rough bed flow studies, vertical momentum transport has not been examined in detail by applying the double averaging method. Specifically, the spatial organization of near-bed vertical momentum flux has not been properly described and the importance of form-induced stresses in vertical momentum flux and in comparison to double-averaged vertical Reynolds stress has not been fully addressed.

The aim of this research was to analyse those characteristics of turbulent flow which are important for the vertical transport. First, the vertical velocity and vertical momentum flux over a gravel bed was studied through application of the extended Wei and Willmarth's (1991) method by applying the double averaging method. The extension of Wei and Willmarth's (1991) analysis through the double averaging method improves understanding of the role of near-bed turbulence heterogeneity and form-induced stresses in vertical momentum flux. Secondly, to demonstrate the relationship between spatial variations of vertical momentum flux and the bursting process, quadrant analysis was applied to the experimental data.

The flow field was measured experimentally through the PIV technique (Nezu and Sanjou, 2011; Weitbrecht et al., 2011). All experimental measurements and analyses were conducted for flows over a fixed gravel bed in the absence of fine sediments. Any addition of fine sediment particles in the flow field could lead to unwanted misunderstanding in the velocity signal measured with PIV. This is because even very small sediment particles may not exactly follow the flow and therefore have different velocities with respect to the water and can give an optical signal for the PIV as tracer particles. This can be particularly true at the near-bed region (see as an example, (Righetti and Romano, 2004)). Working in clear water allowed the authors to avoid this potential source of error in the water velocity signal and so clearly depict the aspects of the flow fields previously mentioned and establish its implications for sediment transport. The clear water experiments discussed in the paper could be extended in the future by investigating fine sediment-laden flows on immobile gravel, or at least an experimental set-up of cobbles partially covered by fine sediments. In this case the overall effect could be seen as a first approximation, in its simplest form the reduction of the absolute bed roughness of the gravel bed (e.g. reduction of inter-cobbles cavities depths due to partial filling by sand). Moreover, the aim of the present work was not to consider the "*two-phase*" flow which does not consider the effect of particle-particle or fluid-particle interaction. The results of the present study can inform understanding of the basic mechanisms of the entrainment and deposition of fine particles on an immobile gravel bed in relation to the flow structure in the near-bed region. The "*closure*" of the problem of an "*equilibrium*" sediment laden flow over a gravel bed is beyond the aim of the paper.

2. Theoretical background

According to the double averaging methodology in steady, uniform, rough bed, open channel flow, the following simplifying assumptions are generally applied: 1) $\partial\langle\ \bar{}\ \rangle/\partial x = 0$; 2) $\partial\ \bar{}\ /\partial t = 0$ 3) $\langle\overline{w}\rangle = 0$, where the overbar denotes a time/ensemble average and the angle brackets denote a spatial average. As a result, the double-averaged momentum transport equation in vertical