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Impact of Bed Surface Roughness on Flow Turbulence and Sediment Grains Transport: A Preliminary Laboratory Flume Study

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Author's contribution

The sole author designed, analysed, interpreted and prepared the manuscript.

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ABSTRACT

This study examines how sediment bed characteristics can influence flow turbulence that may modulate the initiation of sediment grain movement and suspension during transport. A series of laboratory flume experiments was carried out to investigate near-bed flow turbulence under varying flow conditions using fixed sand and gravelly beds respectively. Flow velocity fluctuation was used to determine the magnitude of turbulence which was measured using a 3-C Vectrino ADV profiler. The findings demonstrated that turbulence was greater on flows over rough gravelly bed surface than on sandy bed surface. Also, with the same flow thickness, the mean flow velocity for flows under sand bed ranged between 0.306 -0.333m/s, while that of flows under gravel bed was 0.551–0617m/s. Thus, an increase in bed roughness leads to an increase in turbulence which controls sediment grain motion and its suspension during transport.

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Keywords: Flow turbulence; bed roughness; sediment transport; flume experiment.

1. INTRODUCTION

Sediment bed texture broadly refers to the grain size distribution, bedforms, bed irregularities, relief structures or obstacles on a bed surface. These bed features not only influence roughness at the flow-bed interface but can modulate flows by increasing near-bed turbulence which exerts significant control on sediment transport and deposition (Yang et al., 2021; Zhang et. al., 2023; Ferguson et. al., 2024). Theoretically, bed roughness refers to the frictional resistance and effect that the underlying bed has on the flow. There are two main components of bed roughness: form roughness and sediment grain roughness. Sediment grain roughness reflects the effect of frictional resistance to the grain size. Coarse sediment beds have been observed to create rougher bed surfaces with greater intergranular friction angles, which increase critical stress for grain motion over a bed (Kirchner et al., 1990; Buffington et al., 1992; Johnston et al., 1998). On the other hand, form roughness relates to the bedforms produced by sand ripples, biogenic mounds as well as benthic seagrasses. Nielsen (1981) as well as Grant and Madsen (1982) carried out extensive research on flow boundary roughness. To fully understand the mechanics of sediment grains motion, several investigations on sediment grain transport led to theories proposed and developed more than half a century ago. These initial investigations were carried out by Shields (1936); Einstein (1950) and Bagnold (1956, 1966,) followed by subsequent contributions by Graf (1984), Raudkivi (1998) Wilcock (2001), Wilcock and Crowe (2003), Parker (2008), Lajeunesse et al. (2010), Hurther and Thorne (2011), Buscombe and Conley (2012), Castro-Orgaz et al.(2012), Schmeeckle (2014) and Hill et al. (2017), Brakenhoff et al. (2020), Imagbe (2021), Geng et al. (2024). Bagnold (1956, 1966) derived quantitative relations for the transport of sediment grains as bed load and suspended load based on energetics theory, with the assumption that a fixed fraction of the stream power of a flow is used to move sediment grains as bedload while the remaining is used to move the suspended load. A few published studies were conducted to evaluate the boundary roughness of sediment grain saltation in flows (Singh and Foufoula-Georgiou, (2013), Davis and Robins, (2017), Lamb et al, (2017), Hosseini and Hajibabaei, (2020), Minster et al., (2024). Bhattacharyya et al. (2013) investigated the role of bed roughness using fixed beds with varied roughnesses. Although the result of their experiments demonstrated that larger bed roughness creates higher fluid bed stress, their results was limited to saltating sediment grains.

Estimates of bed roughness with biogenic mounds on seabed has been empirically carried out from photo images of the seabed (Grant et al., 1984; Wheatcroft, 1994) and as a result, it has been a huge challenge to estimate the total roughness of sediment grain including the irregular sand ripples, biogenic mounds, benthic seagrasses and sediment saltation in the field. Therefore, the total bed roughness is now directly determined by fitting measured velocity current profiles to the logarithmic distribution, using the von Karman–Prandtl velocity equation. The roughness length generally, is taken as the distance above the bed of the position at which the extrapolation of the logarithmic profile has zero velocity (Burchard et al., 2008).

From Von Karman's turbulence model, z_0 represents the surface roughness length or height, where the instantaneous velocity equals to zero.

Raudkivi (1998), provided a relationship between z_o and the size of the elements producing the roughness, in the form

$$z_0 = \frac{x}{30.2} \tag{1.0}$$

where x represents the size of the roughness elements (equivalent sand roughness which provides indication of the grain diameter).

Hence, rougher floors should have higher values of z_o.

The natural enhancement of turbulence in flows by bed forms and bed floor roughness has been discussed by (Nelson et al., 1993; 1995, Zomer et al. 2022,). Their findings, however, complimented Bagnold (1966), theory on how bed form variability and bed roughness significantly impact on turbulence generation especially in natural flows with erodible beds. Their studies also indicated that, in addition to bed shear stress, sediment transport was a function of the near-bed turbulence which could have been impacted by the bed roughness with a strong correlation between the sediment flow velocity and the observed near-bed velocity fluctuations. Their studies also indicated that, in addition to bed shear stress, sediment transport is a function of near-bed turbulence that can be impacted by bed roughness, with a strong correlation between sediment flow velocity and observed near-bed velocity fluctuations. Despite increased geologic insights about the impact of variable bed surface roughness conditions on sediment transport, only a few studies have focused on this issue.

Because of the difficulty in characterising sediment transport in natural streams and rivers due to challenges in acquiring data in such environment, laboratory flume experiments and use of numerical models is an alternative to replicate the natural systems. However, since the pioneer study of sediment transport in the laboratory flume, in the 20th century (Gilbert and Murphy, 1914), flow measuring instruments have evolved over the years but have essentially been focussed on image capture analysis (Abbott and Francis, (1977); Auel et al., (2017a). Most experimental models use time-averaged flow velocity fluctuations to characterise and quantify turbulence in natural flows, measuring flow velocity at a single point. This method has not adequately characterised the spatial variability of exchange in turbulent flow boundary layers (Offen and Kline, 1974; Laufer, 1975), as the turbulence of natural flows is based on data obtained from single current meters, which may not yield reliable outcomes.

This study utilises one of the most recent flow fluctuating velocity measuring instruments, the 3-C high resolution Acoustic Doppler Velocimeter to investigate the influence of sediment bed roughness on near-bed turbulence generation and transport of sediment grains using fixed beds of varying roughness (of several centimetres). The study was carried out in unusual clear water flow experimental conditions in contrast to those in existing published literature.

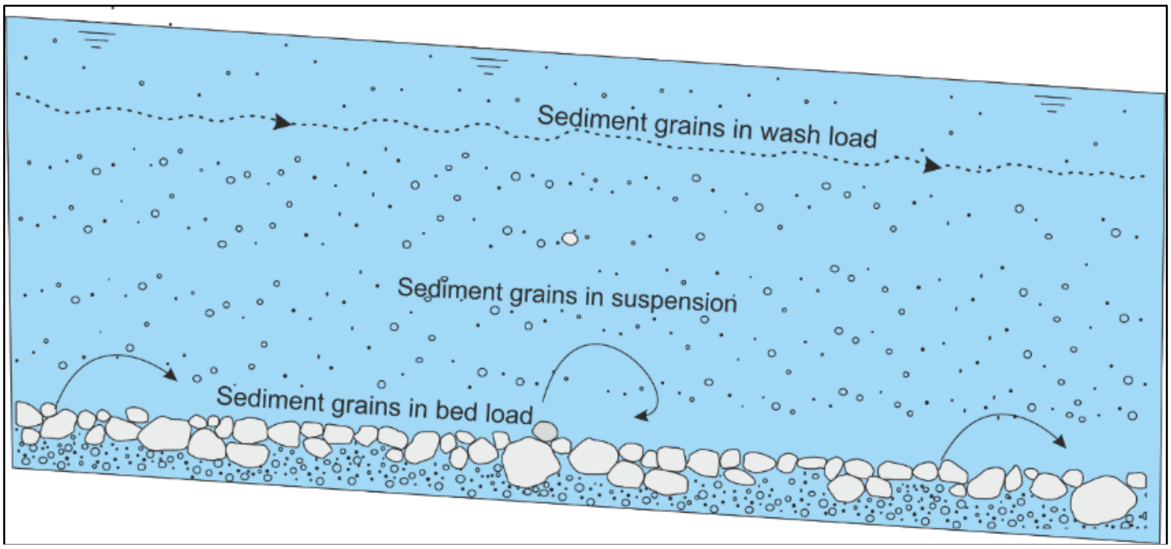
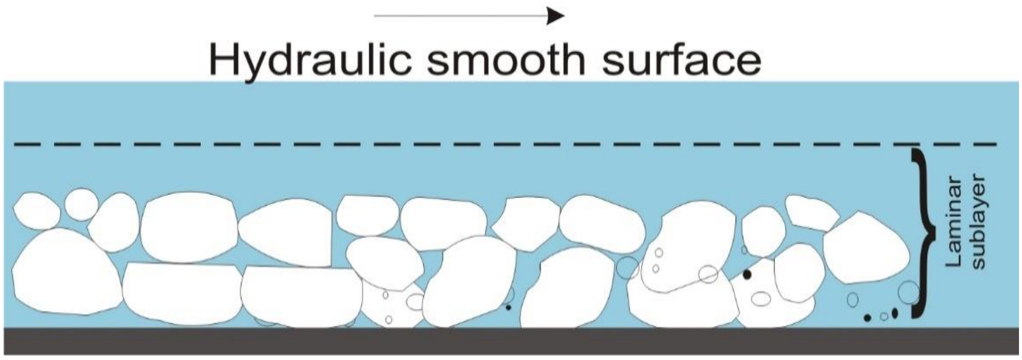
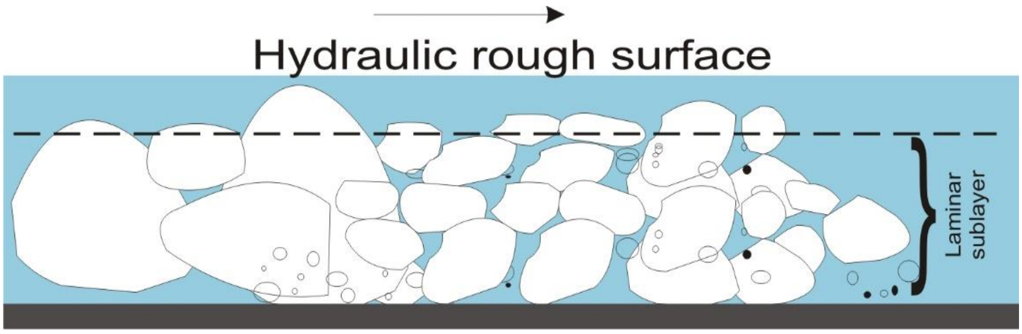


Fig. 1. Sketch of modes of sediment grain transport



(A)



(B)

Fig. 2. A and B: Schematic diagram describing hydraulic smooth and rough surfaces

2. EXPERIMENTAL SETUP AND PROCEDURE

The experiments were conducted at the Sorby Fluid Dynamics Laboratory within the School of Earth and Environmental Sciences of the University of Leeds, United Kingdom. The experiment was set up to understand the impact of bed floor texture in generating flow turbulence for sediment grains transport. The setup included a slightly tilting (0.001^0-0.002^0) re-circulating rectangular glass-sided flume, measuring approximately 8.5m in length, 0.3m in depth, and 0.3m in width, instrumented with a three-dimensional (3-D) Acoustic Doppler Velocimeter measuring system. The recirculating flume tank was used to ensure a steady uniform flow in the tank while the clear glass-sided walls provided clear views of the flow and allowed for measurement of flow properties. The test section was located at the centre of the flume, about 4.2m from the downstream end for instantaneous velocity sampling. As the flume set up was completed, clear water was pumped from an overhead tank into the flume and allowed to recirculate until a steady flow was achieved. The water level was carefully adjusted by varying the discharge rate until the water depth (flow thickness) in the flume tank was up to the desired flow height.

Experiments were conducted in six series labelled as cases 1–6, characterised by parameters as listed in Table 1. The effect of bed roughness on flow turbulence was designed to compare sediment transport in flows over two experimental beds: Bed-1 and Bed-2. Bed-1 was composed of fine sand, with median diameter (D_{50}), < 0.125mm and used for flow cases 1 and 2 (Fig. 4a). Bed-2 was composed of rough gravelly bed surface with (D_{50}) approx. 4.0 mm and used for flow cases 3-6, (Fig. 4b).

Fig. 3. Photograph of the laboratory flume tank used in this research

(a) (b)

Fig. 4. (a) Fixed sand bed, (b) Fixed gravel beds used for the experiments

Table 1. Summary flow character for the six cases

Experiment	Flow Character
Case1	Flow thickness =0.192m; Mean discharge rate= 0.023m^3/s; Fixed fine sand bed floor
Case 2	Flow thickness =0.180m; Mean discharge rate= 0.040m^3/s; fixed Fine sand bed floor
Case 3	Flow thickness =0.192m Mean discharge rate= 0.025m^3/s; Fixed gravel bed floor
Case 4	Flow thickness =0.192m; Mean discharge rate= 0.031m^3/s; Fixed gravel bed floor
Case 5	Flow thickness =0.140m, Mean discharge rate= 0.022m^3/s; Fixed gravel bed floor
Case 6	Flow thickness =0.140m; Mean discharge rate= 0.033m^3/s; Fixed gravel bed floor

All six experimental flow cases (1-6) comprised of a total of forty-five flow runs with the measuring ADV instrument set at defined depth intervals. However, prior to the commencement of each experiment the metal flume tank floor was covered with beds of either fine sand or gravel to fit the entire floor. A photograph of the set-up of the experimental flume is shown in Fig. 3.

2.1 Flow Velocity Measurement Method

Considering the available flow velocity measuring devices and methods (see Table 2 below), the Acoustic Doppler Velocimeter (ADV) was used in this experiment, due to its wide use, relative simplicity, portability, high accuracy, ease of operation, and unrequired calibration. ADV is a well-established technique for sampling instantaneous flow velocity and turbulence measurements using the principle of Doppler shift effects to measure instantaneous flow velocity in a small volume. It measures the Doppler shift of any moving particle to determine their speed, based on the key assumption that the scattering particles in the water have the same velocity as the flow velocity itself. This experiment made use of the Nortek Vectrino profiler ADV (Vectrino II) which was configured to measure flow velocities at 17 different distances from the transmitter at each of the chosen probe position as set vertically beneath the transducer and oriented perpendicular to the flume bed. The 17 multiple positions were generated multiple overlapping vertical profiles so that a single time-averaged profile encompassing most of the water column could be formed. At each location, velocities were sampled at 100 Hz for 300 seconds. Each flow velocity profile consisted of six to thirteen sampling positions with over 30,000 velocity data obtained at each sampling point. The monitored signals were first transferred to a computer and later analysed using the Vetrino II software. In the experiments, the acquired flow velocity data were post-processed in-house by the University of Leeds Sorby Laboratory team, using an intelligent correlation threshold filter comprising of a phase unwrapping algorithm and the phase space threshold spike filter (see Thomas and Mclelland (2015) for more details).

Table 3 provides a summary of flume and hydraulic data that was used in this research.

Table 2. Available Flow Velocity measuring equipment

Equipment	Operating Principles	Advantages	Disadvantages
Hot-wire Anemometry	Essentially a thermal method, based on the convective heat transfer from a heated sensor element to a relatively cold surrounding fluid which varies with the flow rate	• Cost is relatively very cheap • Small measurement volume • Low SNR • Good spatial and temporal resolution	• It is an intrusive technique which can modify the local flow field • Contamination from deposition of impurities on sensor • Probe could easily break • Needs calibration
Laser-Doppler Velocimetry	Based on the Doppler shift effect. The difference in the frequency between the original beam and the moving particle known as the Doppler shift is proportional to the velocity of the moving particle.	• No pre-calibration • Negligible probe interference • Can measure a wide range of flow velocities (0.0001 to 1000m/s) • High resolution as probe volume as small as 10^{-6} size can be obtained.	• Relatively very expensive • Need for eye protection against the direct laser beam • Flows ceases to be single phase flow as soon as particles are introduced into flow • Not very suitable for 3D flows
Acoustic Doppler Velocimetry	Based on the principle of the Doppler shift effect.	• Non-intrusive and relatively cheap • 3D flow measurements • Relatively high SNR • No calibration required • Rugged and convenient to use in difficult to reach areas • Measures very low velocity	• Signals affected by velocity shear across the sampling volume and nearness to boundary • Requires post-processing
Particle-image Velocimetry	Photographic recording of tracer particle motion in a fluid which are usually well illuminated. Image processing determines the flow velocity from the recording	• Non-intrusive • Captures velocity data in multiple points in the flow • High spatial resolution	• Expensive • Size of area need to be small for greater accuracy

Table 3. Summary of flume hydraulic data for all six experimental cases

Flow conditions	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Type of Bed floor	Fine sand	Fine sand	Gravel	Gravel	Gravel	Gravel
Flow height to roughness (m)	0.92	0.18	0.192	0.192	0.14	0.14
Flow area (m^2)	0.058	0.054	0.058	0.058	0.042	0.042
Flume average slope	0.053	0.071	0.079	0.088	0.132	0.141
Mean discharge rate (l/s)	21.6	39.6	24.6	31.3	21.6	33.19
Mean discharge rate (m^3/s)	0.022	0.04	0.025	0.031	0.022	0.033
Mean flow velocity (m/s)	0.36	0.551	0.333	0.512	0.443	0.616

Table 4. Estimates of roughness lengths for surfaces used in the experiment

Parameter	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Bed Surface	Fine Sand	Fine Sand	Gravel	Gravel	Gravel	Gravel
Flow height, m	0.19200	0.18000	0.19200	0.19200	0.14000	0.14000
Roughness, m	0.00012	0.00014	0.00357	0.00157	0.00109	0.00132
Uncertainty	0.00003	0.00005	0.00023	0.00014	0.00008	0.00040

The parameters include the flume tank floor character, flume tank slope, the mean discharge rate of clear water entering the flume tank as well as the flow height.

3. RESULTS AND DISCUSSION

3.1 Time-averaged Instantaneous Velocities

Figs. 6 and 7 show the instantaneous streamwise velocity-time series for both fine sand and gravel bed floors for the flume experiments. The instantaneous streamwise velocity, here implies the sum of the time-averaged velocity and the fluctuating velocity components in the streamwise direction. Separate velocity profiles correspond to different heights of the velocity sampling device (ADV) above the tank floor and different experimental flow conditions. From these Figs. (6 and 7), it is observed that the data spikes mostly occurred proximal to the base of flow.

3.2 Bed Surface Roughness

Bed roughness could significantly contribute to flow turbulence. The surface roughness height, z_0, of the two types of slabs (fine sand and gravel) used on the floor of the flume tank was based on the velocity profiles generated by the von Karman's turbulence model. The roughness estimates and their uncertainties are presented in Table 4.

In Figs. 6 and 7, it is observed that turbulence is generated more at the base of flow under a gravelly floor than on the fine sand bed floor. This is evident from the fluctuations around the mean which shows the degree of turbulence in the flow and its consistency at any given height. Also, the mean flow velocity is observed to increase with height whilst the fluctuation strength drops with height. Thus, flow turbulence is controlled by the roughness at the flow base and the size of this coefficient is greater than the roughness element, z_0, which supports the theory proposed by Raudkivi (1998). Bed surface roughness can be produced by bed forms (ripples and mega ripples) as well as by individual sediment grains. From Von Karman's turbulence model, z_0 represents the surface roughness length, where the instantaneous velocity equals to zero. In this work, the value of roughness length, z_0, was derived from the fitting of the velocity profiles obtained from mean velocity values. The relationship between z_0 and the size of the roughness element provided a measure of the bed grain size as derived by Raudkivi (1998) in equation (1.0). It is expected that rougher floors should have higher values of z_0 and consequently, greater turbulence. Fig. 8 above, also demonstrates the roughness lengths for the fine sand bed floor and gravel bed floors respectively. Comparatively, it is obvious that the roughness length is greater for the gravelly bed floor. This have a corresponding effect on the bed shear stress. Chen and Chiew (2003), in their experiment also found that shear velocity in marble bed was higher compared to sand bed due to the relative roughness of the marble bed. The implication is that rough beds create more eddies and turbulence which facilitate sediment grain suspension. Mazumder et al. (2005), from investigation, also revealed that higher bed roughness significantly controls the size distribution of suspended load and accounts for keeping sand-size sediment grains in suspension.

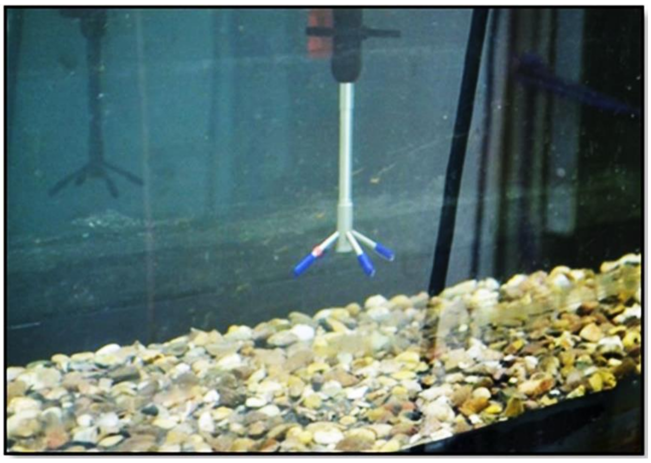


Fig. 5. The Four signal receiving beams of an ADV

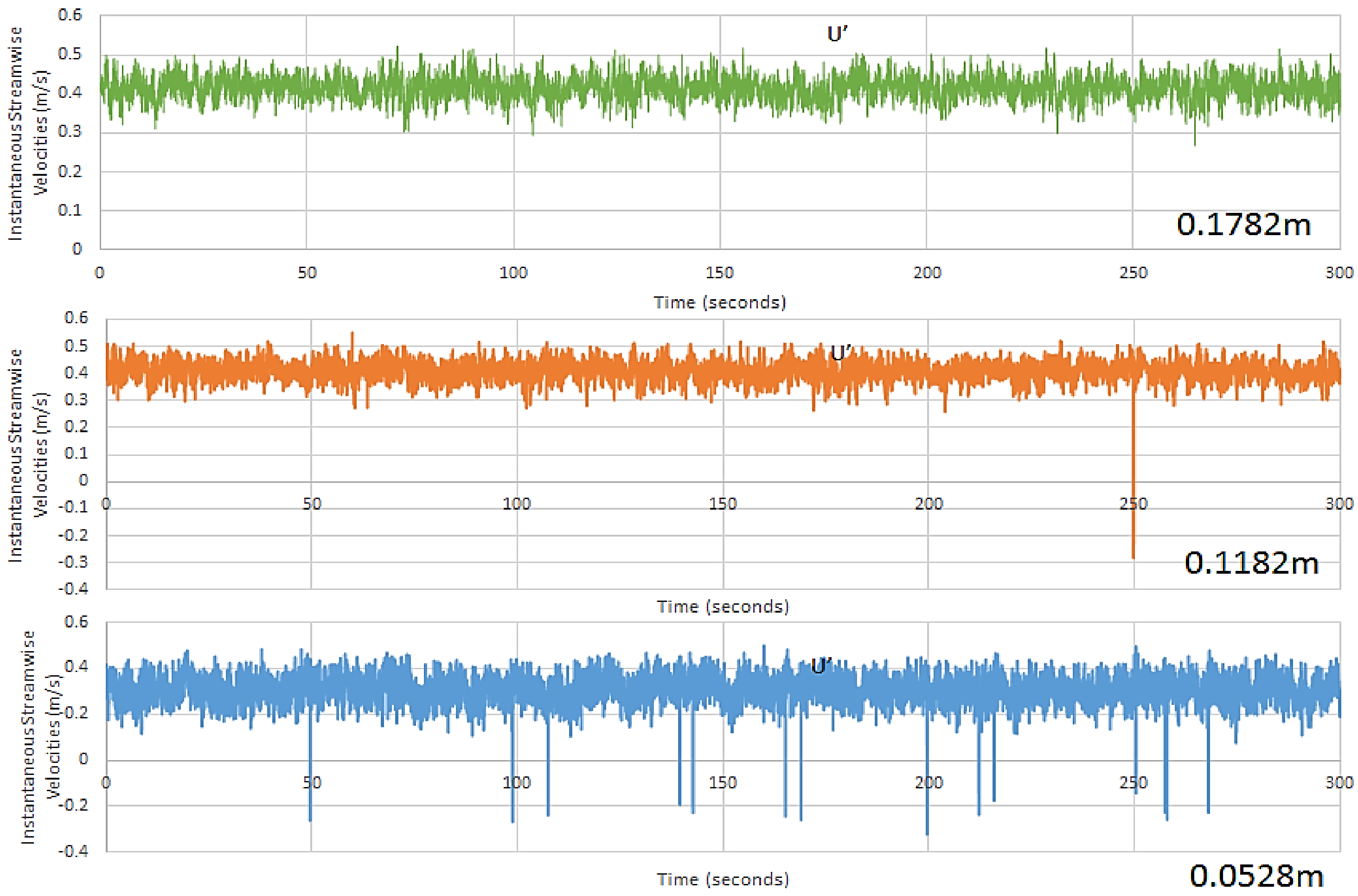


Fig. 6. Instantaneous velocity –time series for case 1(Fine sand bed floor)

Occasional "blips" in this data were removed during processing by increasing the cut-off values until the blips reduce. Bold numbers give height above tank floor at which measurements were taken. Note that the fluctuations around the mean show the degree of turbulence in the flow and that this is consistent at any given height. Also note that the mean velocity increases with height whilst the fluctuation strength drops with height

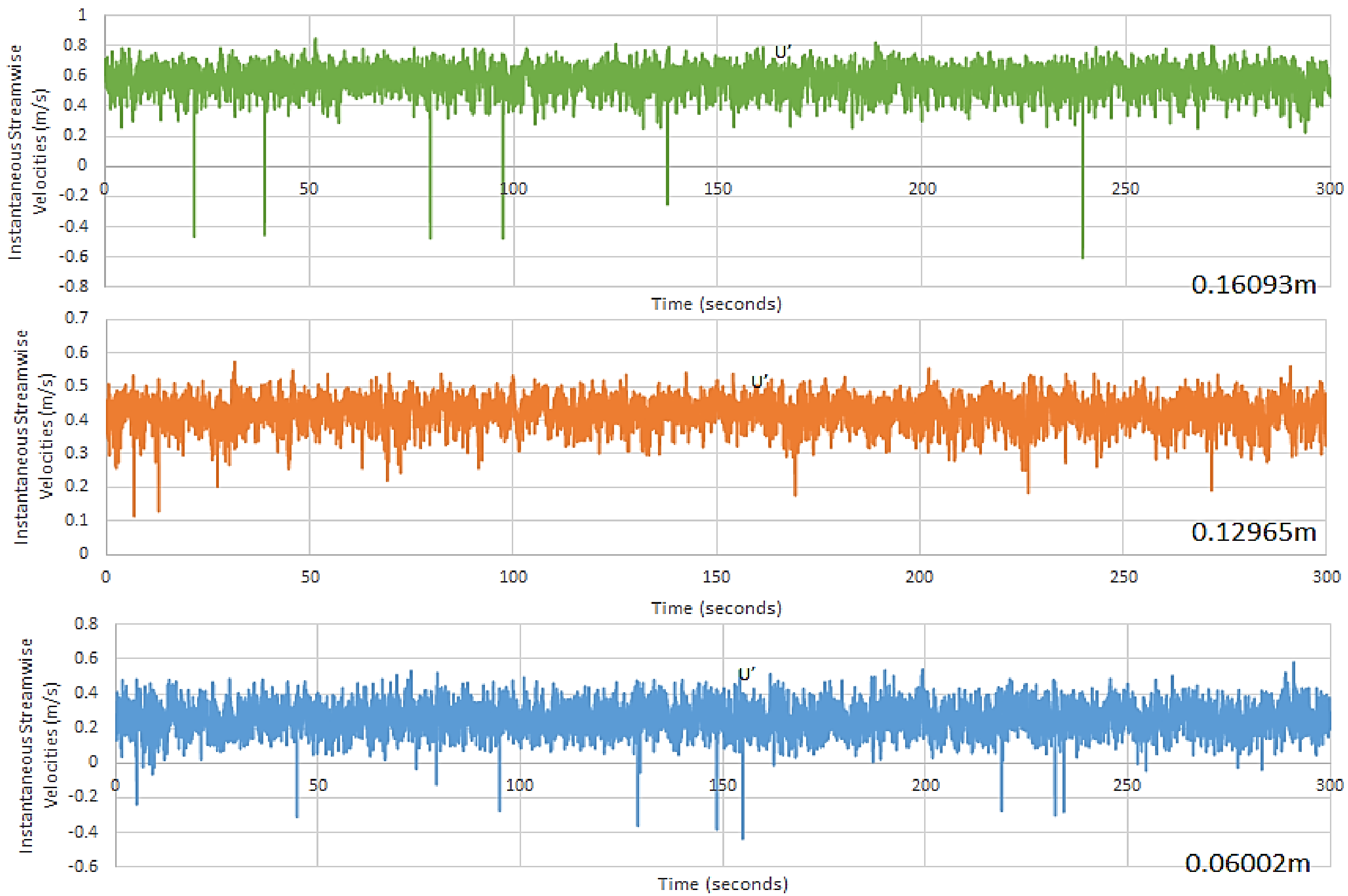


Fig. 7. Instantaneous velocity –time series for case 1(Rough Gravel bed floor)

Occasional "blips" in this data were removed during processing by increasing the cut-off values until the blips reduce. Bold numbers give height above tank floor at which measurements were taken. Note that the fluctuations around the mean show the degree of turbulence in the flow and that this is consistent at any given height. Also note that the mean velocity increases with height whilst the fluctuation strength drops with height

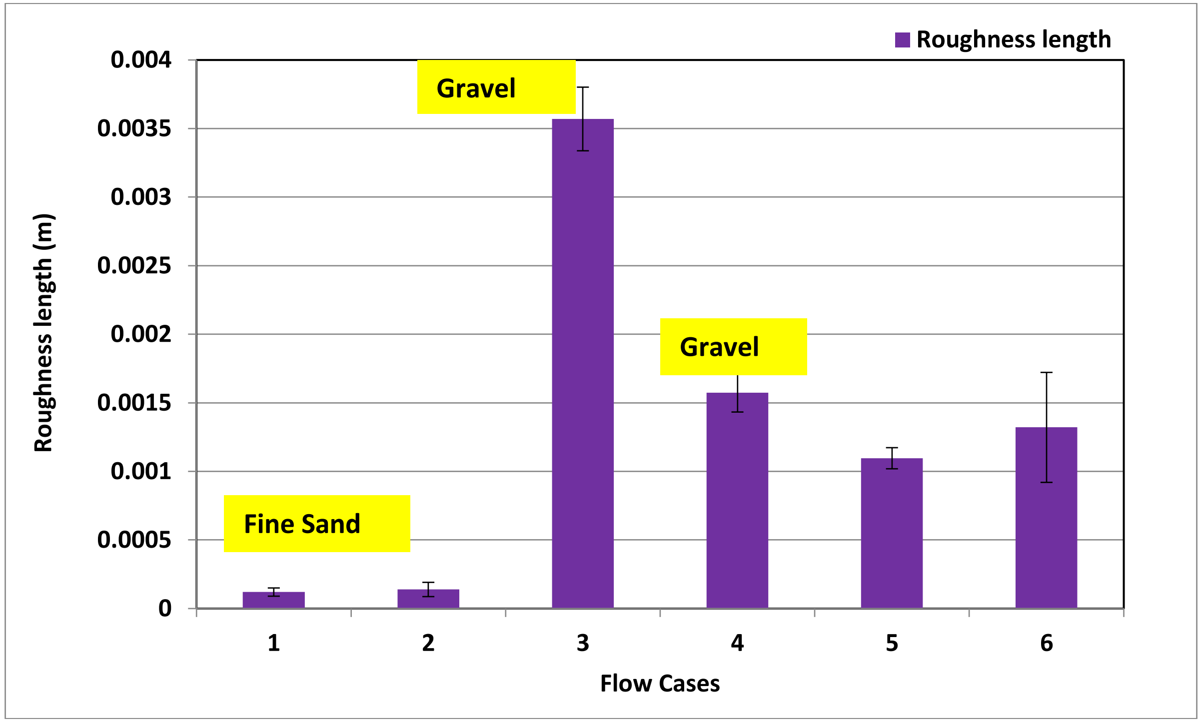


Fig. 8. Comparison of roughness length (fine sand and gravelly floors) Note that bars 1 and 2 are the roughness lengths of fine sand bed surfaces while bars 3 to 6 are for the gravelly bed surfaces

4. CONCLUSION

A series of laboratory flume experiments were carried out to understand the effect of bed roughness on turbulence generation and sediment grains transport. The study is important to us as Earth Scientists as it improves our understanding of the mechanics behind sediment grain movement in flows over varying bed roughness conditions. Despite increased research and insight in this field of geoscience, these studies remain in exhaustive. The outcome of this present study demonstrates that under similar water flow (discharges) and experimental conditions, bed surfaces with relatively higher roughness, create more turbulence which is important for the initiation of sediment grain motion. Thus, bed surfaces with relatively higher degree of roughness (with ripples, mega ripples and individual sediment coarse grains) could significantly create more turbulence which controls sediment grain motion, suspension and transport. The study is an improvement in comparison to other similar researches, as the fluctuating flow velocity data were collected using a high resolution 3-C Nortek Vectrino profiler ADV (Vectrino II). Future studies will focus on developing a realistic sediment grain transport model that can be used to predict and understand the relationship between sediment grain motion under varying hydrodynamic conditions, their deposition and bed surface roughness. In particular, the pattern of grain size distribution will help in understanding long distance sediment transport process.

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COMPETING INTERESTS

Author has declared that no competing interests exist.

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