PRELIMINARY STUDY OF THE IMPACT OF BED SURFACE ROUGHNESS ON FLOW TURBULENCE AND SEDIMENT GRAINS TRANSPORT: INFERENCES FROM LABORATORY FLUME EXPERIMENT.

Abstract

Bed surface textures and related roughness (including bedforms such as ripples and mega-ripples, biogenic structures as well as individual sediment grains size and shape) are generally regarded to contribute to near-bed flow turbulence generation which may affect both water movement and sediment grain transport.

This work presents preliminary series of observations from laboratory flume experiments to assess and understand the impact of bed surface roughness and textures on flow turbulence and sediment grain transport. Two artificial bed surfaces, made of fine sand and a rough gravelly bed surfaces were used for this study. A Vectrino ADV profiler was also used to measure the instantaneous flow velocities at different flow depths above the bed surface. Preliminary findings indicate that flow 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 velocity profiles where fluctuations around the mean flow height shows higher 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 magnitude of velocity fluctuation drops with height. Thus, flow turbulence is controlled by the roughness at the flow base which can be produced by bed forms (such as ripples and mega ripples), biogenic sedimentary structures as well as by individual sediment grains. Future study will dwell on predicting and assessing roughness parameter for a given flow condition, comparing the shear stresses and drag coefficients so generated by the two bed surfaces respectively.

Key words: *Flow turbulence, Bed Roughness, bedforms, Sediment transport, Flume experiment*

Introduction

Sediment grains are mainly transported by fluids in fluvial, coastal and aeolian sedimentary environments, with water medium (others are wind and glacier ice) being the most common and significant for such movement. This is because water have a higher density and can exert a larger bed shear stress required for sediment grain motion in contrast to others. Based on grain characteristics such as size, shape, and density as well as the viscosity of the transporting medium, Van Rijn (2007) described three modes of sediment grain motion to include suspended load, rolling and/ or sliding motion as well as the saltation motion. The last two are commonly grouped as bedload transport and accounts for up to 60% of the total sediments transported in rivers, oceans, lakes, seas and other water bodies. Here, sediments with grain sizes above 0.10mm (sand and gravel), being moved in flow, are in continuous contact with the bed (Gao et al., 2005). In suspended load transport, sediment grains are supported above the bed by the turbulent forces in the water and can travel far distances without coming directly in contact with the underlying flow bed and usually have velocity similar to the flow velocity. Mechanisms that cause sediment grain motion in flowing waters include flow velocity, shear, and normal stresses due to flow turbulence (Jain and Kothyari, 2010).

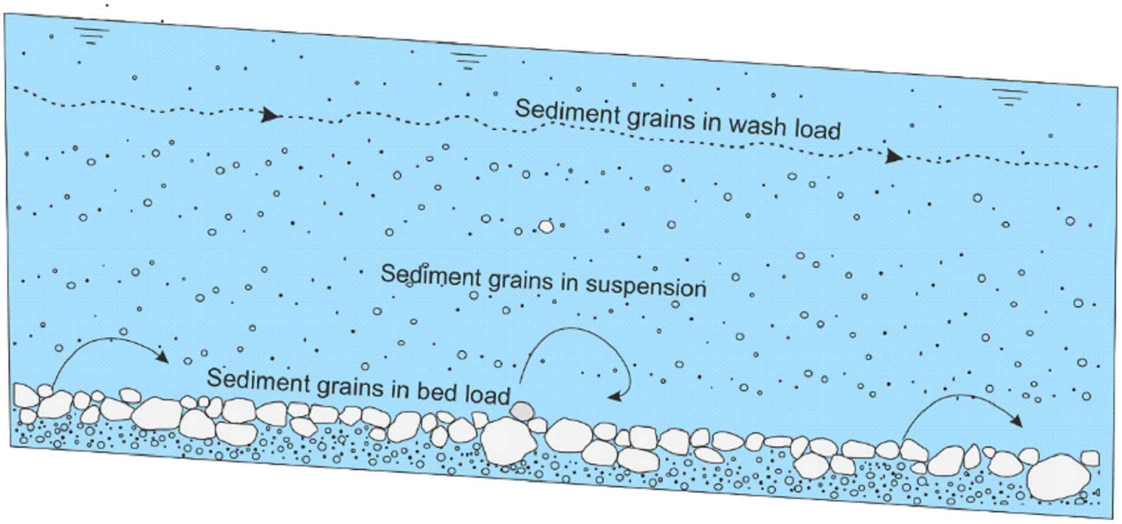


Figure 1: Sketch of modes of sediment grain transport

To fully understand the dynamics of sediment grains motion, several investigations on the sediment transport mechanisms had led to theories proposed and developed more than half a century ago by Shields (1936); Einstein (1950) and Bagnold (1956, 1966,) with later significant contributions from 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) among several others. Bagnold (1956, 1966) derived quantitative relations for the transport of sediment grains as bed load and suspended load based on the Energetics-based 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.

Sediment bed surface texture includes bed roughness that have been noted to be irregularities, relief structures or obstacles on the underlying bed of a flow which generate eddies that influence the magnitude of flow resistance, mean flow, turbulence, and grain motion in a flow. It is produced by bedforms, biogenic structures as well as individual sediment grains. Theoretically, bed roughness expresses the magnitude of the frictional resistance and effect that the underlying bed or boundary has on the flow. There are two main components of bed roughness, and these includes the form roughness and sediment grain roughness. The sediment grain roughness relates the effect of frictional resistance to the grain size.

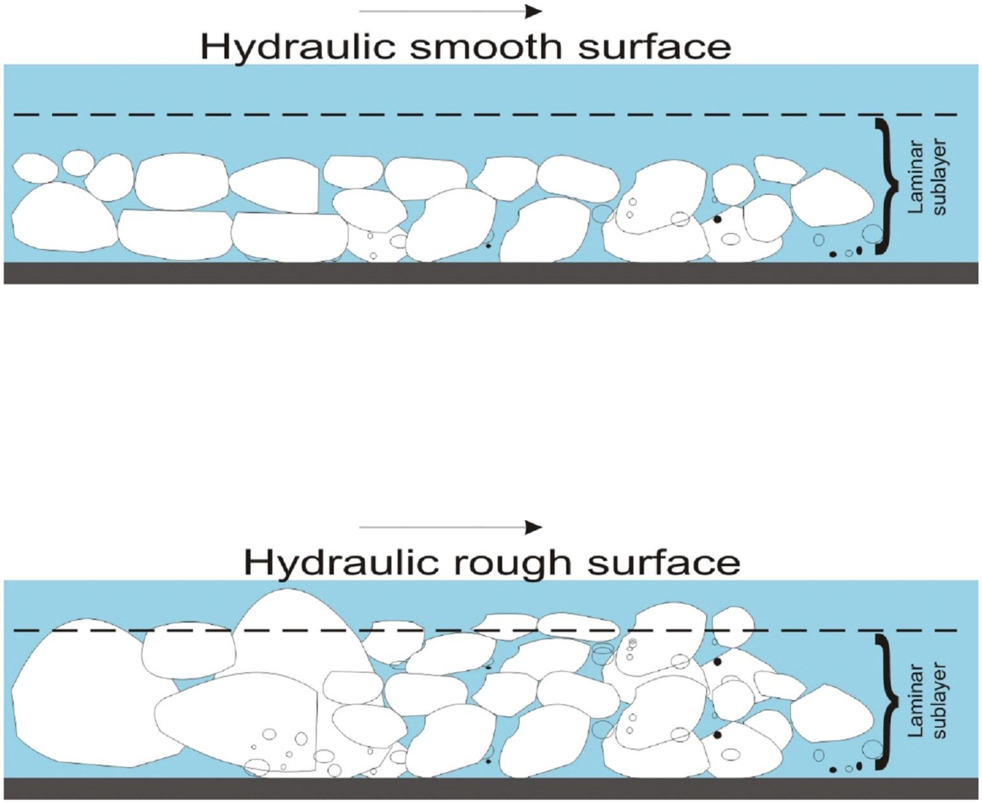


Figure 2. a and b: Schematic diagram describing hydraulic smooth and rough surfaces

Form roughness on the other hand relates to the bedforms produced by sand ripples, biogenic mounds as well as benthic seagrasses. Nielsen (1981), Grant and Madsen (1982) carried out extensive research on flow boundary roughness. Also, there are a few published studies conducted to evaluate the boundary roughness of sediment grain saltation in flows (Nielsen, 1997; Raudkivi, 1998).

Currently, estimates of bed roughness with biogenic mounds on sea beds is empirically carried out from photo images of the seabed (Grant et al., 1984; Wheatcroft, 1994) and as a result, it is a huge challenge to estimate the total roughness of sediment grain which constitute the irregular sand ripples, biogenic mounds, benthic seagrasses and sediment saltation in the field. Alternatively, 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

(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 (Zomer et al. 2022, Davies and Robins 2017, Nelson et al., 1993; 1995). 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. This research intends to among others, provide better insight of how sediment transport may be impacted by variable bed surface roughness conditions from laboratory flume experiments using heterogenous artificial bed surfaces.

Experimental setup and procedure

The experiments were conducted at the Sorby Fluid Dynamics Laboratory within the School of Earth & 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 set-up of the experiment includes using a slightly tilting (0.001^0-0.002^0) re-circulating rectangular glass-sided flume, measuring approximately 8.5m long, 0.3m deep and 0.3m wide and instrumented with a three-dimensional (3-D) Acoustic Doppler Velocimeter measuring system. The re-circulating flume tank was used to ensure a steady uniform flow in the tank. 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 and all instantaneous velocity sampling were taken at this point.

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 is composed of mainly fine sand, with median diameter (D_{50}), < 0.125mm and used for flow cases 1 and 2 (figure 4). Bed-2 is composed of rough gravelly bed surface with (D_{50}) approx. 4.0mm and used for flow cases 3-6, (figure 5).

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 schematic diagram showing the set-up of the experimental flume is shown in figure 3

Figure 3: Photograph of the laboratory flume tank used in this research

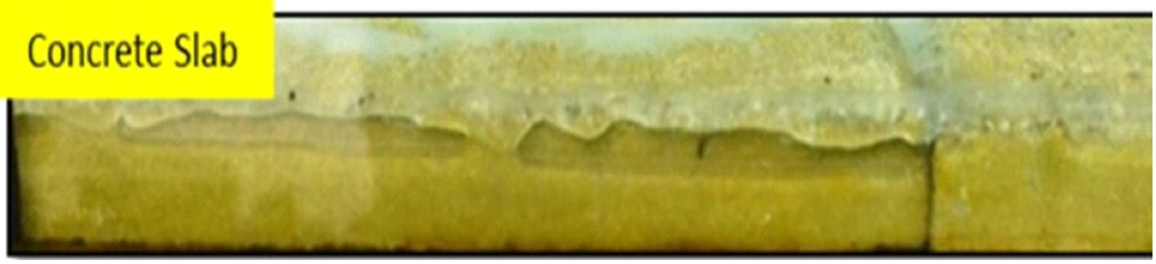


Fig 4: Bed-1 surface made of fine sand placed at base of flume tank, for flow cases 1 and 2

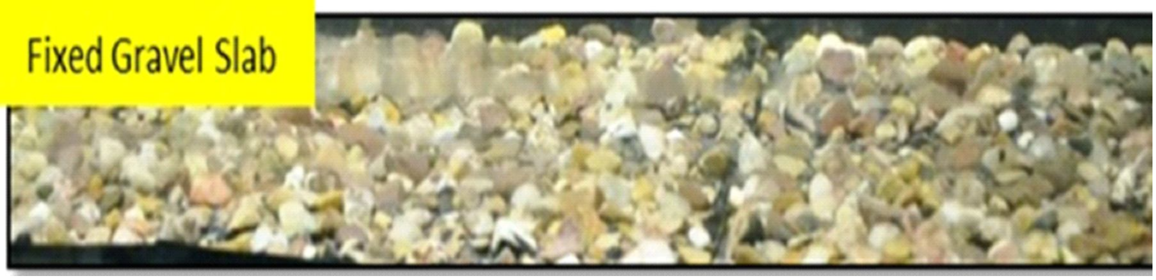


Fig 5: Bed-2 surface made of gravels placed at base of flume tank, for flow cases 3-6

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

The Acoustic Doppler Velocimetry

This experiment made use of the Vectrino profiler ADV (Vectrino II), which was configured to simultaneously measure flow velocities at 17 different distances from the transmitter at each of the chosen probe position as set with the trolley which was vertically beneath the transducer (oriented perpendicular to the flume bed). The 17 multiple positions were performed to generate 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 by the Vetrino II software.

Figure 6: The Four signal receiving beams of an Acoustic Doppler Velocimeter (ADV)

Table 2 below provides a summary of flume and hydraulic data that was used in this research 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.

Table 2: 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

Preliminary Results and Discussion

Time-averaged instantaneous velocities

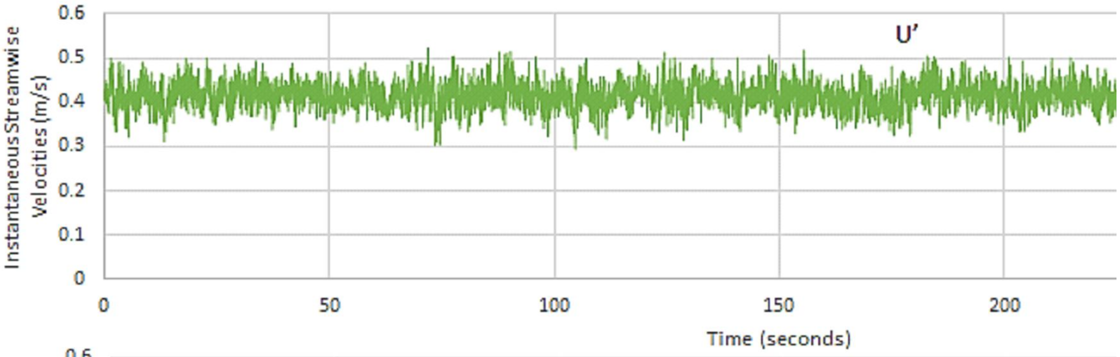
Figures 7 and 8 show the instantaneous streamwise velocity-time series for both fine sand and gravel bed floors for the flume experiments. The instantaneous streamwise velocity, here implies the sum of the time-averaged velocity and the fluctuating velocity components in the streamwise direction. Separate velocity profiles correspond to different heights of the velocity sampling device (ADV) above the tank floor and different experimental flow conditions. From these figures (7 and 8), it is observed that the data spikes mostly occurred proximal to the base of flow.

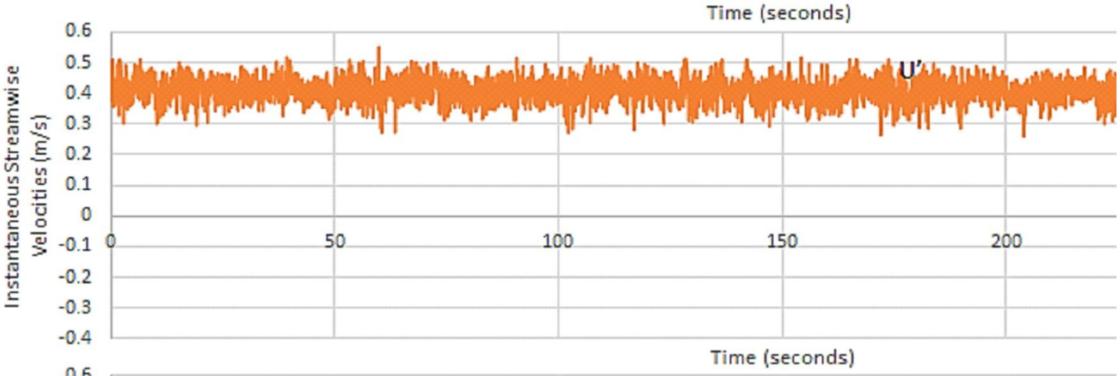
Bed surface roughness

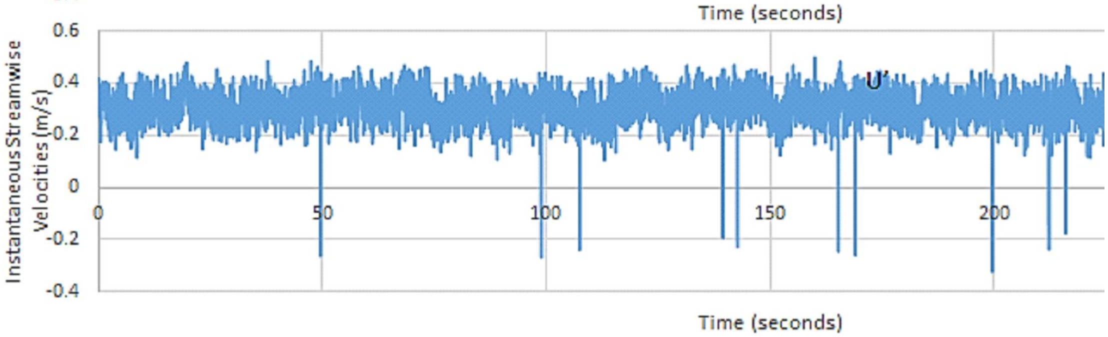
Bed roughness could significantly contribute to turbulence in a flow. The surface roughness height, z_0, of the two types of slabs (fine sand and gravel) used on the floor of the flume tank were, from the velocity profiles generated by the von Karman's turbulence model. The roughness estimates and their uncertainties are presented in table 3 below.

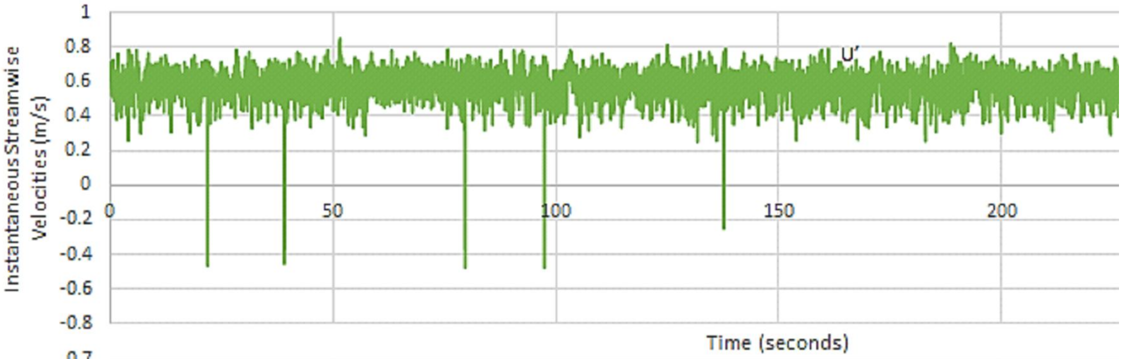
Table 3: Estimates of roughness lengths for surfaces used in the experiment.

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


U’
Instantaneous Streamwise Velocities (m/s)
0.6
0.5
0.4
0.3
0.2
0.1
0
0
50
100
150
200
Time (seconds)


U’
Instantaneous Streamwise Velocities (m/s)
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
0
50
100
150
200
Time (seconds)


U’
Instantaneous Streamwise Velocities (m/s)
0.6
0.4
0.2
0
-0.2
-0.4
0
50
100
150
200
Time (seconds)


Instantaneous Streamwise Velocities (m/s)
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
0
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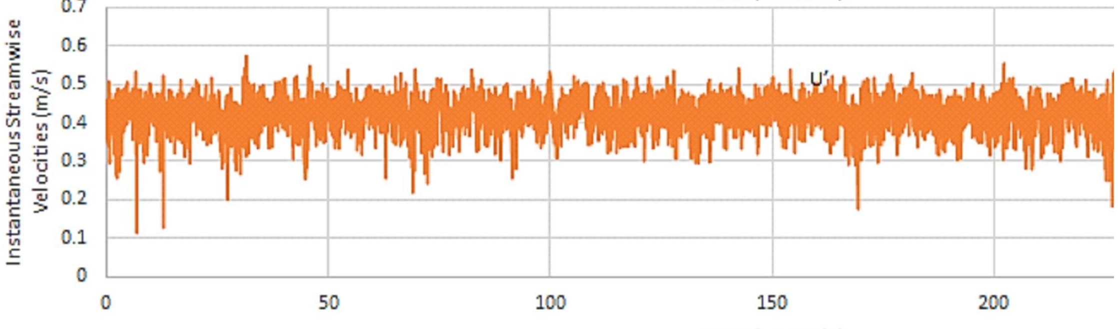
Time (seconds)


Instantaneous Streamwise Velocities (m/s)
0.7
0.6
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0.4
0.3
0.2
0.1
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100
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Time (seconds)

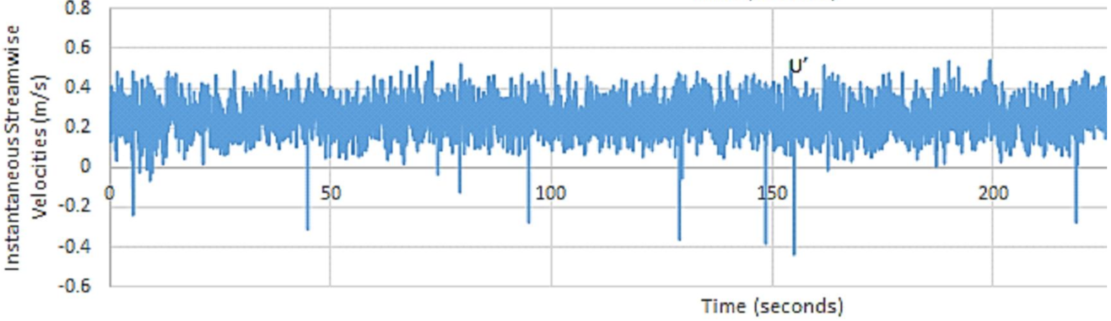
Instantaneous Streamwise Velocities (m/s)
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
0
50
100
150
200
U′
Time (seconds)

Figure 9: 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.

In figures 7 and 8, 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. Figure 9 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.

The outcome of this study is expected to provide a realistic model that can be used to predict and understand the relationship between sediment grain transport 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.

Conclusion

A series of laboratory flume experiments were undertaken to understand how bed surfaces of variable roughness may impact on turbulence generation and sediment grains transport. Beds comprising of fine sand and rough gravel surfaces were employed for this study.

This preliminary report demonstrates that bed surfaces with relatively higher degree of roughness (with ripples, mega ripples and individual sediment coarse grains) may significantly create more turbulence which could facilitate the suspension and transport of sediment grains.

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