

Comparison of flow turbulence over a sand bed and gravel bed channel

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ABSTRACT

Experiments were performed to examine the variations in flow turbulence with respect to sand and gravel bed channel. The 3D instantaneous velocity of water is measured by acoustic doppler velocimeter (ADV) at the test section, which will provide an important data related to the flow turbulence. The parameters of turbulence measured that the vertical profiles of longitudinal velocity in flows with a sand bed channel at the vicinity of the bed surface are higher by 2–6% than flow subjected to gravel bed channel, while away from the boundary surface, it decreases by 5–10%. The variations of Reynolds shear stress increase by 35–50% with gravel bed channel, indicating higher exchange of flow energy towards the boundary and vice versa. The higher value is obtained for shear velocities by 58.5% and the von Kármán's constant with gravel bed channel. The gravel bed channel influenced the turbulence intensities with higher magnitude in the streamwise and vertical direction. The present study also analysed the flow anisotropy, correlations coefficient and turbulence diffusivity and compared the results. The outcomes of the current work are beneficial for civil and hydraulic engineers, since the data of turbulence will advance the management of bed materials present in the river.

Key words: gravel bed, sand bed, turbulence, velocity time series

HIGHLIGHTS

- Water velocity is higher at the near bed in a sand bed channel.
- A gravel bed channel increases the velocity fluctuations.
- Flow momentum exchange is higher in a gravel bed channel.
- Riverbeds are usually composed of sand and gravel, therefore analyzing the turbulent characteristics of flow is important.
- There are benefits for the river engineer since the turbulence governs the morphological changes in the riverbeds.

1. INTRODUCTION

River beds are usually composed of either sand or gravel. Turbulent flow causing erosion and deposition of river beds is important to fluvial hydraulics. Large number of studies have been done by various researchers to know the characteristics of flow hydraulics in natural rivers. The relation of flow velocity with suspended sediment was examined by Bennett & Best (1995) who found that the time averaged velocity and the turbulence intensity in the distribution of vertical flow velocities near the bed is directly linked with the suspension of sediment. Best *et al.* (1997) worked on sediment transport in an alluvial channel composed of coarse sand and observed a lower mean longitudinal velocity and fluctuating component of velocity due to the sediment transport. The time-averaged longitudinal velocity decreases with the increase of flow resistance associated with apparent roughness in the observation of sediment transport (Bergeron & Carbonneau 1999). Bennett *et al.* (1998) conducted flow experiments on the smooth and transitional zones to investigate the von Kármán constant (k) and found that the value of k is more reduced than the universal value of 0.41 because of bed material transport. In a similar way, many previous researchers (Bennett and Bridge 1995; Gallagher *et al.* 1999) conducted flow experiments on the rough zone to investigate the universal value of k and found a reduction in k value from its universal value due to bed material transport. Gaudio *et al.* (2010) reviewed the non-universal value of k in a sand channel. The turbulent flow characteristics in a sand bed channel under the condition of a incipient motion discharge was investigated by the various researchers (Cao 1997; Dwivedi *et al.* 2010). Also, previous studies (Bennett and Bridge 1995; Venditti *et al.* 2005) investigated the turbulent flow characteristics in a sand bed channel under the condition of a mobile bed. Sharma *et al.* (2015) carried out the experiments in a curved

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cross section sand bed channel to investigate the turbulence parameters of flow under the condition of incipient motion discharge. *Devi et al. (2016)* studied the features of turbulent flow over a vegetated channel and compared with the flow characteristics over an alluvial channel without the presence of vegetation. The influence of sediment particles on the flow turbulence in the inner and outer layer was studied by *Saber et al. (2016)* and it was found that the increment of volume fraction of sediment particles affects the time averaged flow velocity and turbulence intensity. *Sharma & Kumar (2017)* analyzed the flow turbulence in a channel composed of non-uniform sand and related the bed material transport with the structure of turbulence. In a recent study, *Longo et al. (2017)* analysed the structure of turbulence in regular breaking waves and also proposed a relation between the components of the Reynolds stress tensor and of the dissipation tensor.

Turbulent flows in gravel beds are common in natural rivers. The sequence of research has been carried out to understand the turbulent flow in the near bed region of irregular rough beds and provided important information for flow turbulence over a gravel bed (*Kironoto & Graf 1994; Song et al. 1994; Dittrich & Koll 1997; Nikora & Smart 1997; Graf & Altinakar 1998; Nikora & Goring 2000; Smart & Habersack 2007*). In the flow over a gravel bed, the heterogeneity of bed topography composed of discrete particles of different shapes and orientations influences the flow turbulence (*Nikora et al. 1998; Nikora & Goring 2000; Nikora et al. 2001; Franca & Czernuszenko 2006*). Previous studies (*Drake et al. 1988; Robinson 1991; Khan & Sharma 2020*) undertook field studies on the gravel transport and also examined the turbulent structure on the gravel bed. They found the transport of gravel is mainly associated with turbulent event sweep. Study about gravel transport in a field canal by *Nikora & Goring (2000)* observed that the friction factor is reduced with the increase of time-averaged longitudinal velocity. The turbulent flow features on the coarse sand and fine sand were investigated by *Campbell et al. (2005)*. They observed that the time-averaged longitudinal velocity is higher for coarse sand and it becomes lower for fine sand. *Longo (2010)* conducted experiments to investigate the three-dimensional velocity of water in a stationary flow field generated by a Crump weir in a laboratory flume. *Cao et al. (2020)* conducted flume experiments to investigate the difference of hydrodynamics through a boulder array over impermeable and permeable beds.

The effect of the roughness on flow turbulence is nowadays mainly analysed using numerical simulations. *Longo (2005)* proposed the two phase flow model for sediment transport in sheet flows and found that the results are satisfied with experiments and previous models. *Benson et al. (2005)* conducted a series of experiments in smooth, rough development, and fully rough wall conditions to investigate the influence of roughness on particle velocities in a water channel. *Aghebatie & Hosseini (2016)* used the $k-\varepsilon$ turbulence model to simulate the turbulence in steep open channel flow. *De Marchis et al. (2017)* analysed the near-bed turbulence structures over irregular rough boundaries and relates with the dynamics of solid sediment transport in a water channel using Direct Numerical Simulations (DNS) and Lagrangian Particle Tracking (LPT). *De Marchis et al. (2019)* used Large Eddy Simulations (LES) to examine the effect of irregular rough surfaces on the turbulent flow structure.

The outcome of the literature review is that most of the studies either focused on the flow velocity and turbulence intensity in a sand/gravel bed channel or numerically analyzed the effect of roughness on the flow turbulence. The comparison of turbulent flow characteristics in between the fine sand bed and gravel bed channel with experimental observation remains unexplored, and the effects of fine sand and gravel on the turbulent flow characteristics are yet to be investigated. Therefore, the objective of the present study is to compare the turbulent flow characteristics in between the sand bed and gravel bed channel for a constant flow discharge. The three dimensional instantaneous velocity components of water were measured by using a probe named the Acoustic Doppler velocimeter (ADV) to order the flow characteristics over the sand and gravel bed channel. The experimental results will provide important information associated with the turbulent flow parameters, such as the time-averaged flow velocity, Reynolds shear stress, turbulence intensities, turbulent anisotropy, coefficient correlation, turbulence diffusivity and von Kármán constant.

2. MATERIALS AND METHODS

2.1. Flume experiments

The laboratory experiments were done in a 16 m long, 0.50 m wide and 0.50 m deep flume, to analyse the turbulence in a sand bed and gravel bed channel, as shown in [Figure 1](#). A series of pipe baffle were provided at the inlet of the flume to achieve a uniform flow. A discharge controlling system was used to measure the flow discharge, and the flow depth was regulated by a tailgate installed at the outlet section of the flume. The test section was 5 m in length and was located 8 m upstream of the flume entrance in order to avoid the effects of inflow and outflow in the test section of the channel. The 16 m flume

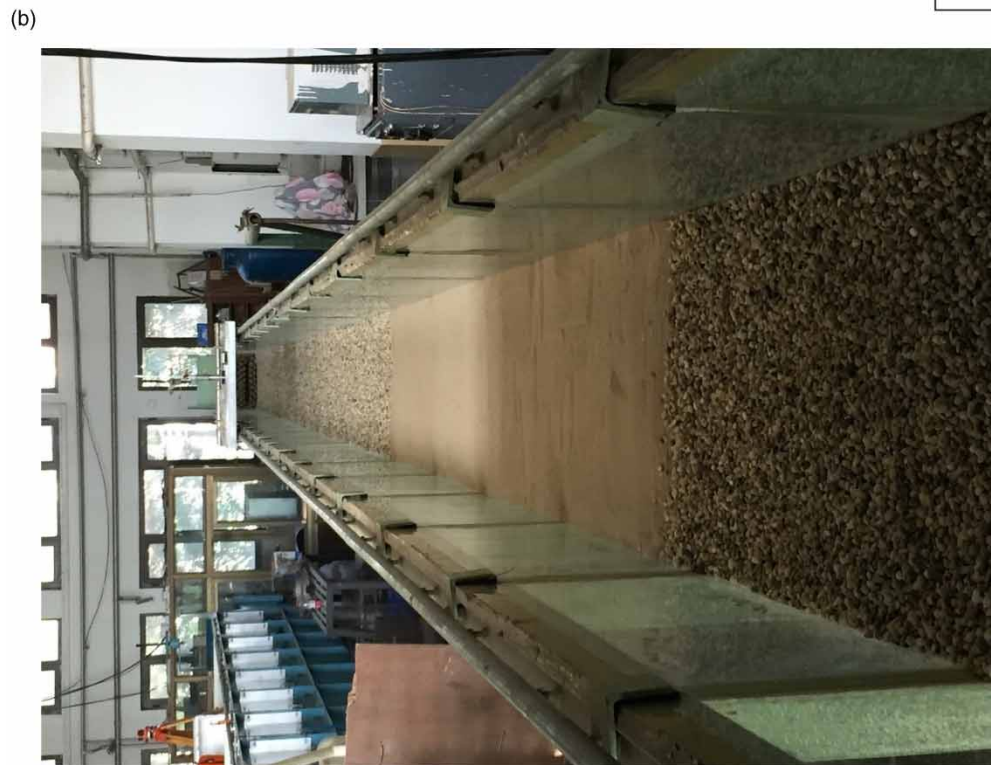
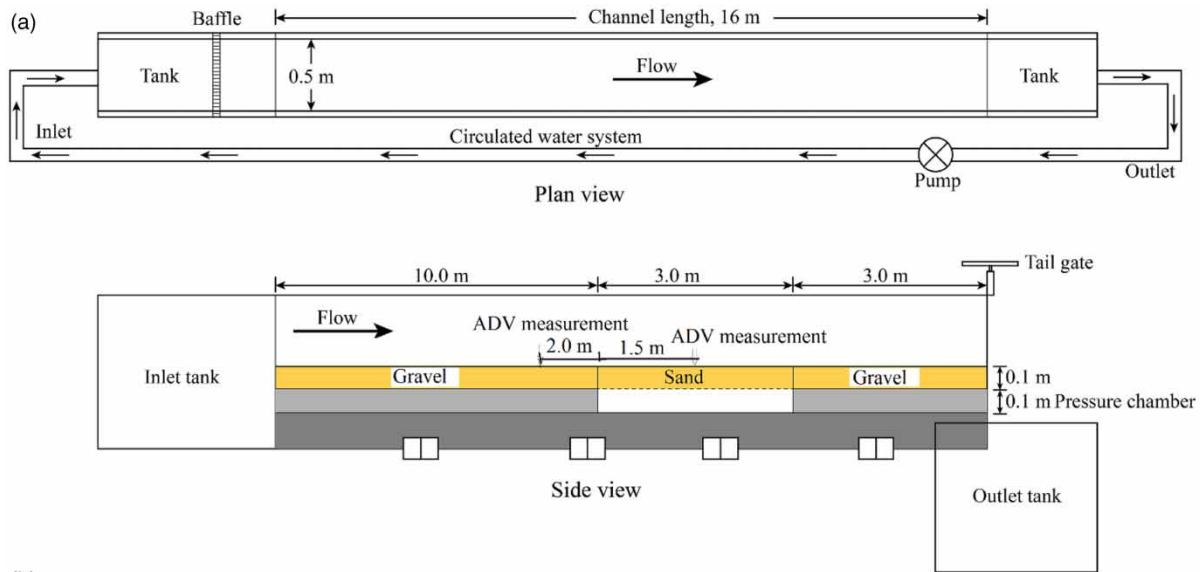


Figure 1 | (a) Plan and side views of the tilting flume; (b) sand and gravel bed channel.

length is enough to achieve a fully developed flow condition in the test section. The bed slope of the channel was maintained as 0.0025 throughout the experiments. The pump system was used for the recirculation of water in the flume. The ratio of flume width to flow depth (the aspect ratio) for all experiments was higher than 6; therefore, the side wall effect on the turbulent flow was not considered in the present study (Yang *et al.* 2004), and ultimately, the turbulent flow was not influenced by three-dimensional effect.

The present experiments used fine sand and gravel as the bed material. The sieve analysis was done to calculate the grain size distribution of the sand and gravel. The grain size distributions of the fine sand and the gravel is displayed in Figure 2. The

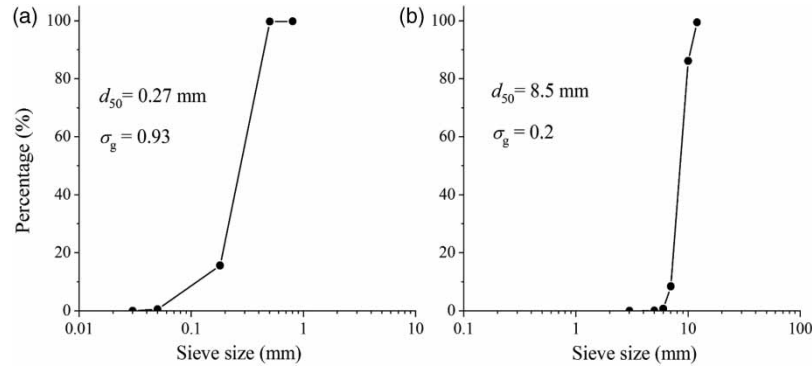


Figure 2 | Grain size distributions of (a) fine sediment and (b) gravel.

geometric standard deviation $\sigma_g = (d_{84.1} - d_{15.9})/d_{50}$ of the used sand material was 0.93, where d_x represent the size at which the percentage of finer particles is x, which signifies that the fine sand used as a bed material is uniform sand because $\sigma_g < 1.4$ (Marsh *et al.* 2004). The details of the bed materials and flow parameters are shown in Table 1. The thickness of the sand bed and the gravel bed channel in the flume is 10 cm. The water tanks were fixed at both the entrance and exit ends of the flume to avoid the recirculation of the eroded bed material in the channel.

2.2. Measurement of hydrodynamics

The instrument named the ADV was used to measure the instantaneous 3D water velocities at the centerline of the test section. The ADV collects the data with a sampling frequency of 100 Hz, and an acoustic frequency of 10 MHz. The velocity data is collected in a cylindrical sampling volume whose diameter is 6 mm and with the height varying between 1 and 4 mm. The sampling volume position is 5 cm below the central transmitter; therefore, it is not possible to measure the velocity data at a distance of 5 cm from the water surface. In the meantime, the height of the sampling volume was set as 4 mm for the collection of velocity data at the outer layer of flow. The height of the sampling volume was set as 1 mm when data is collected near the bed surface so that the bed materials did not collide with the sampling volume. The sampling height of 1 mm was enough to obtain the actual velocity distributions in the vicinity of the bed region (Sharma & Kumar 2018). The 300 sec time duration was set to collect the instantaneous velocity data with the ADV, which was enough to achieve the time-independent time-averaged velocity.

The uncertainty of the ADV data was measured by collecting 10 samples of instantaneous velocities at a distance of 12 mm in the vicinity of the bed region. The uncertainty of the ADV data is shown in Table 2, where, \bar{u} , \bar{v} , and \bar{w} are the mean velocity in the streamwise, widthwise, and vertical directions, respectively, u' , v' and w' are the corresponding components of velocity fluctuations, and $(\overline{u'u'})^{0.5}$, $(\overline{v'v'})^{0.5}$ and $(\overline{w'w'})^{0.5}$ are the turbulence intensity. The standard deviation of the time

Table 1 | Details of the sediment and the flow parameters involved in the experiments

Bed materials	Median size, d_{50} (mm)	Geometric standard deviation, σ_g	Equivalent grain roughness (mm)	Discharge, Q (L/s)	Flow depth, h (cm)	Flow Reynolds number, Re	Flow Froude number, F_r
Sand	0.27	0.93	0.54	14	11.2	28,000	0.238
Gravel	8.5	0.2	8.5	14	11.2	28,000	0.238

Table 2 | Uncertainty associated with ADV data

	\bar{u} (m/s)	\bar{v} (m/s)	\bar{w} (m/s)	$(\overline{u'u'})^{0.5}$ (m/s)	$(\overline{v'v'})^{0.5}$ (m/s)	$(\overline{w'w'})^{0.5}$ (m/s)
Standard deviation	4.76×10^{-5}	8.95×10^{-4}	5.30×10^{-4}	1.34×10^{-5}	9.76×10^{-4}	3.54×10^{-4}
Uncertainty (%)	0.15	0.028	0.016	0.424	0.03	0.11

averaging of numerous frequent samples of instantaneous velocities is defined as the standard uncertainty. The standard uncertainty, S_u , is defined as:

$$S_u = \frac{S_d}{\sqrt{n}} \quad (1)$$

where S_d and n respectively indicate the standard deviation and the number of samples of instantaneous velocities (i.e. $n = 10$). Table 2 shows that the uncertainty of mean velocities and turbulence intensities are lower than $\pm 5\%$, which specifies the correctness of the ADV data (Sharma *et al.* 2018).

The instantaneous velocity measured by the ADV has spikes because of correlation between the reflected and transmitted pulses. An acceleration threshold method is used to remove the spikes from the ADV data (Goring & Nikora 2002). In this method, the signal to noise ratio (SNR) and the correlation value are maintained as 15 and 70, respectively. According to Sharma & Kumar (2018), the value of correlation can be set as 65 in the vicinity of the bed surface. The acceleration threshold value was maintained at between 1 and 1.5; as a result, the velocity power spectra of the filtered ADV data should satisfy Kolmogorov's $-5/3$ scaling law in the inertial sub-range (Lacey & Roy 2008). The discrete fast Fourier transform method was used to calculate the velocity power spectra $F_{uu}(f)$ at a distance of 12 mm from the bed surface ($z = 12$ mm), and the distributions of $F_{uu}(f)$ with the frequency, f , are shown in Figure 3. It is seen from Figure 3 that the velocity power spectra of filtered ADV data match with Kolmogorov's $-5/3$ law in the inertial sub-range of frequency that occurs for frequencies $f > 1$ Hz.

3. RESULTS AND DISCUSSION

In order to know the difference in hydrodynamics with sand and gravel bed channels, turbulent flow parameters including the time-averaged velocity, Reynolds shear stresses (RSS), turbulence intensity, flow anisotropy and turbulent diffusivity, are measured at the centerline of the channel. Consequently, the structure of turbulence is determined based on the ADV data.

3.1. Time averaged velocity

The time-averaged (mean) streamwise velocity was measured as

$$\bar{u} = \frac{1}{n} \sum_{i=1}^n u_i \quad (2)$$

where, u_i and n represent the streamwise instantaneous velocity and the samples number respectively. Figure 4 displays the profiles of time-averaged velocity with non-dimensional flow depth, z/h , (where z is the distance from the bed surface and h is the flow depth) for all the experiments where the solid and open circles signify the sand bed and gravel bed runs, respectively.

The maximum value of streamwise velocity is obtained at the water surface and slowly reduced towards the boundary wall because of the impact of bed materials resulting in the decrease of momentum. This observation is in conformity with

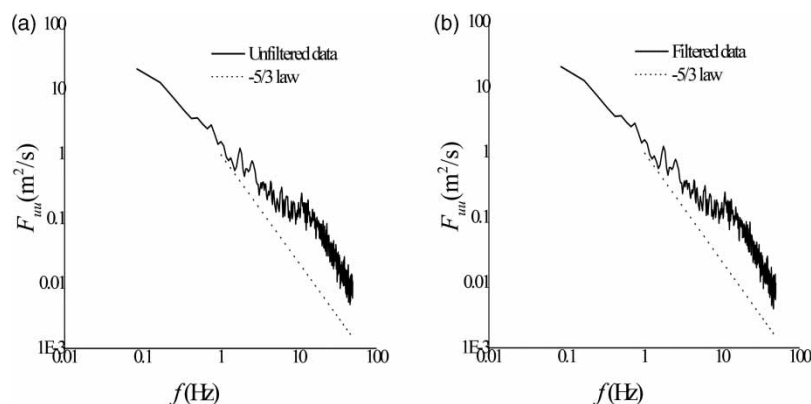


Figure 3 | Velocity power spectra for unfiltered and filtered data of sand bed channel law at $z = 12$ mm for streamwise velocities.

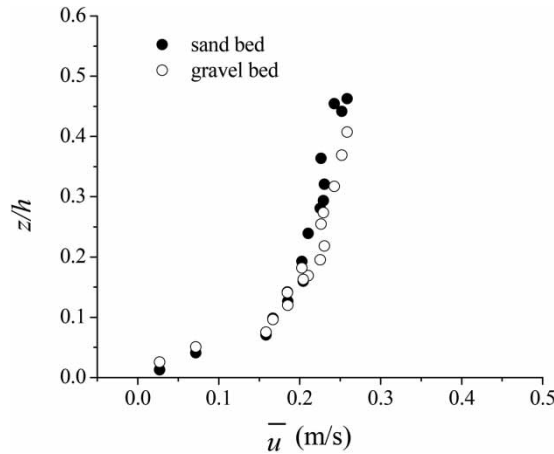


Figure 4 | Vertical distribution of time-averaged velocity.

previous researchers (Nezu 1977; Penna *et al.* 2018). The near bed streamwise velocity is increased with the sand bed channel because of lower flow resistance as compared to the gravel bed channel. However, the velocity is increased near the water surface with the gravel bed. The near-bed velocity increased by 2–6% with the sand bed channel, but the magnitude is decreased by 5–10% in the outer layer of flow as compared to gravel bed channel.

Sharma & Kumar (2017) log law is fitted to the present experimental data as per Equation (3). As the flow regime was rough-turbulent flow, it was expected to use d_{50} to scale z . Moreover, the Reynolds shear stress (RSS) distributions provide the truly available turbulent shear stress in the flowing fluid and so u_* obtained from RSS is chosen as the shear velocity, which is used to normalise the time-averaged velocity in Equation (3).

$$\frac{\bar{u}}{u_*} = \frac{1}{k} \ln(z^+ + \Delta z^+) - \frac{1}{k} \ln(\varepsilon^+) \tag{3}$$

where, $z^+ = z/d_{50}$, $\Delta z^+ = \Delta z/d_{50}$, $\varepsilon^+ = z_0/d_{50}$, where Δz and z_0 are the virtual bed level and zero velocity level respectively, u_* and k are the shear velocity and von Karman constant respectively. Nezu (1977) developed the equation for the bed shear stress, $\tau_0 = (\tau_{uw})_{z=0}$ where, $\tau_{uw} = -\rho \overline{u'w'}$ is the Reynolds shear stress. The bed stress is estimated by the linear projection of the RSS distributions on the boundary surface. The shear velocity is calculated as $u_* = (\tau_0/\rho)^{0.5}$. It is clear that a prior calculation of Δz^+ was a crucial criterion to plot the data, and consequent estimation of κ and ζ^+ was essential to fit the data in the log-law given by Equation (3). The calculation of these parameters was done individually. The shear velocity for sand and gravel bed channel is measured as 11.62 mm/s and 18.42 mm/s respectively. The shear velocities increased by 58.50% in the case of the gravel bed compared to those of the sand bed channel. The logarithmic equation for the experimental data is shown in Figure 5 subjected to the sand and gravel beds used in the present study.

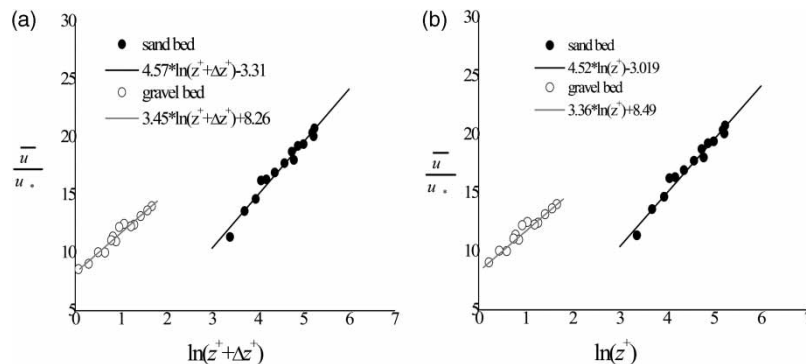


Figure 5 | (a) Velocity log law; (b) velocity log law without virtual bed level.

It is observed from Figure 5 that the logarithmic law is well fitted to the experimental data sets. The calculated value of the von Kármán constant for the sand and gravel beds is 0.22 and 0.29 respectively. The velocity logarithmic law without virtual bed level is shown in Figure 5(b). It is seen from Figure 5(b) that the von Kármán values achieved were 0.221 and 0.297 for the sand and gravel bed respectively, which is approximately the same as observed from Figure 5(a). The value of k for the sand and gravel beds is observed to be less than the universal value. The bed material is transported quickly in the case of the sand bed channel because of the higher velocity at near bed compared to the gravel bed; therefore, the value of k decreases with the sand bed. With the application of flow discharge in the channel, it is seen from the experiment that the sediment particles start to move in the sand bed channel, whereas the gravel particles remain stationary in the gravel bed channel; eventually, the value of k drastically decreased in the case of the sand bed channel. Further, the decreased value of k with the sand bed suggests an exposure of increased velocity component in the streamwise direction to the particles on the bed surface.

3.2. Reynolds shear stress (RSS)

RSS indicates the transfer of mass and momentum in between the flow and bed materials. It is, therefore, an important parameter governing the bed material erosion and transport. The RSS is measured as

$$\overline{u'w'} = \frac{1}{n} \sum_{i=1}^n (u_i - u)(w_i - w) \quad (4)$$

$$\tau_{uw} = -\rho \overline{u'w'} \quad (5)$$

RSS is measured for both the sand bed and gravel bed runs, and the vertical distributions of RSS against the non-dimensional flow depth z/h are shown in Figure 6, where the RSS magnitude for the sand and gravel beds is represented by solid and open circles, respectively. RSS is increased towards the bed surface, which indicates the exchange of higher momentum in between the flow and the bed materials. As a result, the bed shear stress becomes higher and, therefore, the flow would be able to sustain the movement of bed materials, overcoming the grain resistance. The RSS attained maximum value in the vicinity of the inner region and then was reduced in the direction of the boundary wall due to the existence of a viscous force or roughness sub-layer in the boundary zone. The damping in RSS distributions close to the rough bed is a common feature due to the formation of a roughness sub-layer that gives rise to form-induced stress (Dey *et al.* 2012). The vertical distribution of RSS is determined in order to define the momentum diffusion mechanism. The vertical distributions of RSS are similar for sand bed and gravel bed runs with varying magnitude. Mainly, the RSS magnitudes with the sand bed are reduced by 35–50% compared to those of gravel bed runs, indicating the lower momentum exchange in between the flow and bed materials. As a result, turbulence decreases with the sand bed. The reduction in magnitude of u^* and thus in RSS distributions with the sand bed channel can also be clarified, observing that the bed materials are associated with the momentum provided from the flow to maintain their motion.

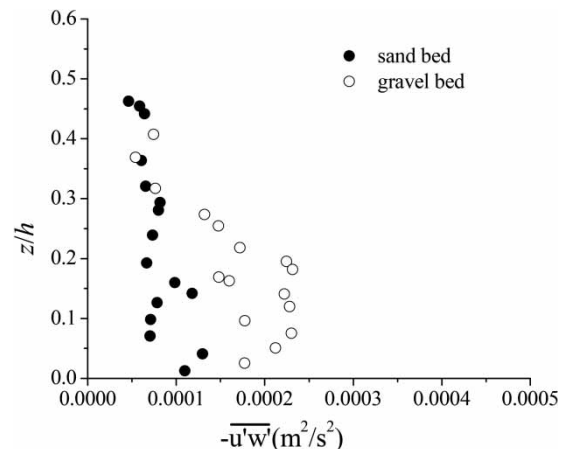


Figure 6 | Reynolds shear stress profiles of flow.

3.3. Turbulence intensity

The root mean square (rms) of the velocity fluctuation is called turbulence intensity. Turbulence intensity is the result of the differences in instantaneous velocity at a point, which can be influenced by the magnitude of the velocity, bed roughness, etc. The turbulence intensity in the streamwise direction, σ_u , and vertical direction, σ_w , was calculated as

$$\sigma_u = \sqrt{\frac{\sum_{i=1}^n (u_i - \bar{u})^2}{n}} \quad (6)$$

$$\sigma_w = \sqrt{\frac{\sum_{i=1}^n (w_i - \bar{w})^2}{n}} \quad (7)$$

The streamwise turbulence intensity, σ_u and σ_w , represents the fluctuating component of velocity or the level of turbulence in the stream and vertical direction respectively. The vertical distributions of σ_u and σ_w for the sand bed and gravel bed channel are shown in Figures 7 and 8 respectively. The σ_u and σ_w for the sand bed and gravel bed runs are represented by solid and open circles, respectively. The peak value of σ_u and σ_w is achieved in the near-bed zone, and the least value is achieved at the

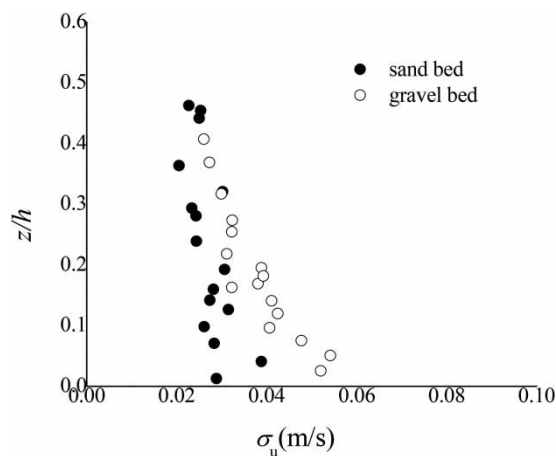


Figure 7 | Vertical distribution of streamwise turbulence intensity.

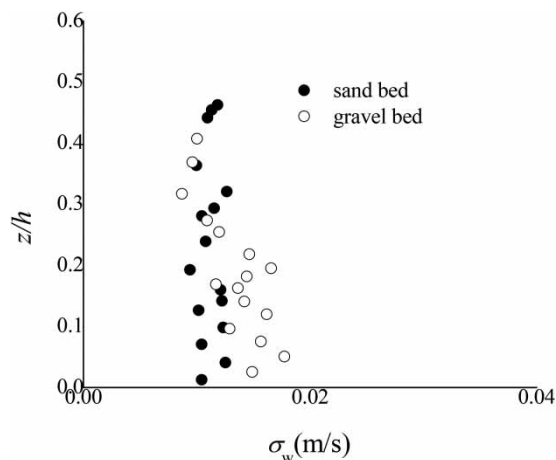


Figure 8 | Vertical distribution of vertical turbulence intensity.

water surface due to the reducing nature of RSS. This observation is in conformity with previous researchers (Nezu 1977; Sharma & Kumar 2017). The σ_u and σ_w reduced with the sand bed channel, which indicates that the sand bed reduced the velocity fluctuation that helps in decreasing the turbulence in the flow. The profiles of turbulence intensity are significant in the inner region of the flow, and the magnitude of streamwise and vertical turbulence intensity decreased by 30–35% and 5–15% respectively with the sand bed. It can be concluded that turbulence intensity generated large fluctuations in the presence of a gravel bed, which means that flow velocities induce strong fluctuations over the gravel bed.

3.4. Turbulent anisotropy

Turbulent anisotropy is the ratio of vertical turbulence intensity to streamwise turbulence intensity. The characterization of turbulent flow requires knowledge of the departure from isotropy. In order to calculate the turbulence anisotropy, the σ_u and σ_w are changed to a dimensionless form with u_* as the denominator, $\hat{\sigma}_u = \sigma_u/u_*$ and $\hat{\sigma}_w = \sigma_w/u_*$. Figure 9 shows the turbulence anisotropy ($\hat{\sigma}_w/\hat{\sigma}_u$) with z/h , and it has been observed that the flow is highly anisotropic as $\hat{\sigma}_w/\hat{\sigma}_u < 1$. The $\hat{\sigma}_w/\hat{\sigma}_u$ is nearly 0.36 and 0.28 in the vicinity of the bed region for the sand bed and gravel bed respectively, fluctuating linearly towards the water depth. Previously, the universal value (0.55) of turbulent anisotropy was obtained throughout the water depth for the smooth boundary (Nezu & Nakagawa 1993), while Sharma & Kumar (2017) found the near-bed magnitude of 0.28 for a non-uniform sand bed channel. However, the magnitude of turbulent anisotropy obtained in the present study does not correlate with past studies (Nezu & Nakagawa 1993; Sharma & Kumar 2017). Also, it is observed that the turbulent flow is highly anisotropic in flow subjected to a sand bed channel compared to those of the gravel bed condition.

3.5. Correlation coefficient

The correlation coefficient is used to measure the degree of relationship between the Reynolds shear stress and turbulence intensity. The correlation coefficient $r_{uw} [= -\overline{u'w'}/(\overline{u'u'} \times \overline{w'w'})^{0.5}]$ is the ratio of RSS to the product of the σ_u and σ_w . The profiles of r_{uw} are shown in Figure 10. It is observed that r_{uw} varies with the water depth for both the sand and gravel bed runs. The peak value of the correlation coefficient is observed near the inner layer ($z/h \sim 0.14$) and thereafter the magnitude is reduced within the inner layer ($z/h < 0.14$) and outer layer ($z/h > 0.14$) of turbulent flow. Thus, a strong level of correlation is observed in the vicinity of the flow inner layer. In the sand bed experiment, the r_{uw} increases with the increase of z/h changing from $r_{uw} \sim 0.16$ near the bed surface to $r_{uw} \sim 0.35$ at $z/h = 0.14$. The observed magnitudes of r_{uw} in the present experiments are lower than the previous studies (Hinze 1975; Schlichting 1979). Hinze (1975) and Schlichting (1979) achieved $r_{uw} = 0.4$ – 0.5 over the smooth and rough boundaries, while Dey & Raikar (2007) achieved the universal value of r_{uw} (0.43) for $z/h < 0.6$ in case of a mobile gravel bed, but it reduced in the direction of the water surface. The effect of a gravel bed on r_{uw} is noticeable as r_{uw} with a gravel bed is increased compared to those of the sand bed condition. Alteration of r_{uw} with the gravel bed is because of comparative variation of $-\overline{u'w'}$ over $(\overline{u'u'} \times \overline{w'w'})^{0.5}$ in the gravel bed channel. It can be concluded that the degree of correlation between the RSS and turbulence intensity is higher in the presence of a gravel bed, which means that flow velocities induce strong correlations over the gravel bed.

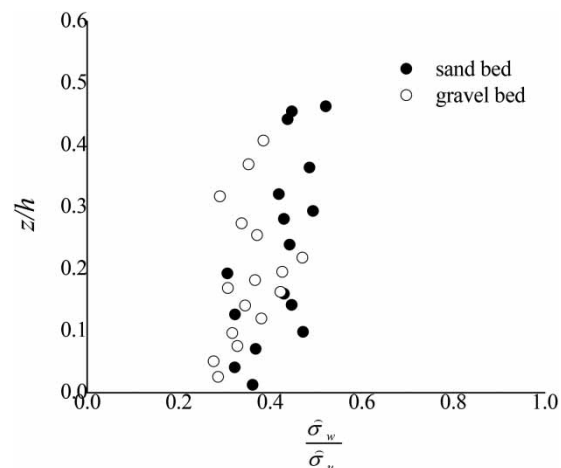


Figure 9 | Turbulent anisotropy.

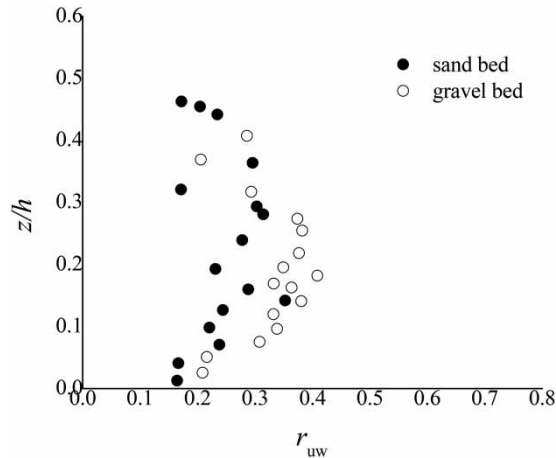


Figure 10 | Vertical profiles of correlation coefficient.

3.6. Turbulence diffusivity

The turbulence diffusivity is defined as the ratio of RSS to the velocity gradient and it is represented by the equation $\varepsilon_f \left[= -\overline{u'w'} / \left(\frac{du}{dy} \right) \right]$. The turbulence diffusivity for the sand bed and gravel bed runs are shown in Figure 11. For both the sand and gravel bed runs, the turbulence diffusivity is increased with the water depth in response to the turbulent formation and achieved the peak value at $z/h \sim 0.16$, after which it reduces with the water depth. At $z/h \leq 0.16$, ε_f increases because of the reduction in the velocity gradient and at $z/h > 0.16$, ε_f decreases because of the formation of larger eddies. The magnitude of ε_f gradually reduces in the vicinity of the bed region ($z/h \leq 0.1$) for the sand bed channel. This happens because of the increase in the velocity gradient du/dy in flows induced by the sand bed.

4. CONCLUSIONS

A series of experiments based on the laboratory flume is conducted to measure the turbulent parameters of the flow over sand and gravel bed channels. In this work, the turbulent flow features of a sand bed channel are compared with the flow characteristics over a gravel bed channel. Hence, an Acoustic Doppler velocimeter was used to measure the water instantaneous velocity data in order to find the variation in turbulent structure of the flow. The results of turbulent parameters with sand bed and gravel bed channels, proceeds to the various conclusions. The study of the mean velocity profile exposes that the near-bed velocity was higher by (2–6) % with the sand bed channel than the velocity for the gravel bed channel, which caused the bed particles to transport speedily. In this work, the reduction of von Kármán's constant recommends the occurrence of sediment

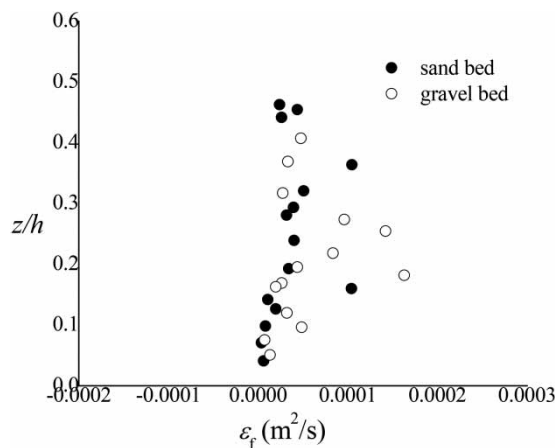


Figure 11 | Vertical profiles of turbulence diffusivity.

transport in the sand bed run. The profiles of RSS are slightly scattered in general and decreased with the sand bed channel. The profile of RSS is reduced in the near bed region because of the reducing nature of turbulence fluctuation. The decrease in Reynolds shear stress by (35–50) % with the sand bed tends to decrease in shear velocity by 36.9%, thus indicating a lower exchange of momentum towards the bed region in sand bed runs, where lower turbulence intensities were also found than those of gravel bed runs. The turbulence is strongly anisotropic in flow subjected to the sand bed channel and changing almost linearly with the water depth. The correlation coefficient reduces approximately linearly with the flow depth. The vertical distributions of correlation coefficient are lower in the sand bed runs than the gravel bed runs. The turbulent diffusivity decreased with the sand bed channel compared to gravel bed runs.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

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