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Original Research

Experimental study of depth-limited open-channel flows over a gravel bed

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ABSTRACT

Laboratory experiments of depth-limited open-channel flows over a gravel bed were conducted in the study. Two gravel patches with identical individual element size and different lengths (3.81 m and 7.5 m) were tested. The depth-limited uniform flow regime with relative submergence S_r ($=D/k_s$) ranging from 2.68 to 5.94 was produced by adjusting the tailgate weir. The velocity profiles were measured by using both an ultra-sound velocity profiler (UVP) and an acoustic Doppler velocimeter (ADV). The conventional methods used to determine the zero-plane displacement and estimate the bed shear velocity were then reviewed and compared. The measured double-averaged (DA) velocity profiles were found to fit well with the log law and defect law with a non-universal Karman constant κ. κ-value remains nearly constant and in the range from 0.2 to 0.3 for the long patch (LP) cases and κ-values are scattered within a wider range from 0.3 to 0.5 for the short patch (SP) cases. While the *Br*-value in log law remains constant and equal to 8.5 for LP cases, the *Br*-value was found to decrease with the increase of the dimensionless roughness height k_s^+ for SP cases. The streamwise turbulence intensity distributions were found to be independent on the patch length and agree well with the available experimental data in the intermediate region and wall region. The Manning resistance coefficient and Darcy–Weisbach friction factor were analyzed. The κ-value decreases to 0.22 for the fitting of the logarithmic flow resistance law under small relative submergence. The value of the integration constant *Ar* in the logarithmic law falls within the normal range between 3.25 and 6.25.

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1. Introduction

The mean flow and turbulence characteristics of open-channel flows over hydraulically smooth surfaces have been extensively studied in the last 20–30 years. Progress was also achieved in understanding the mean flow and turbulence structure in flows over hydraulically rough beds with high relative submergence (Kironoto & Graf, 1994). Knowledge of mean velocity and turbulence characteristics of open-channel flow over gravel bed with small relative submergence (e.g., mountain streams and floodplain rivers) remains incomplete and needs to be further studied.

One of the main topics in the study of turbulent geophysical flows is the form of the streamwise velocity profile. In shallow gravel-bed rivers the mean velocity profiles, which are greatly affected by the macro-rough beds, have two kinds of shapes, i.e., logarithmic and S-shaped. As mentioned previously, the S-shaped velocity profile is a consequence of local protrusions and simultaneously exists with the logarithmic velocity profile in gravel-bed river flows (Franca & Lemmin, 2009). Thus for most cases in gravel-bed open-channel flows, especially under the well-sorted condition, the streamwise mean velocity might still follows the logarithmic distribution. However, due to the low relative submergence, the Karman constant κ appears to be non-universal (Rand, 1953).

The Karman constant κ, which is defined as the ratio of the mixing-length to the vertical distance from the wall, is a crucial parameter to describe the time averaged streamwise velocity profile along the vertical axis in a wall-bounded shear flow based on the log-law. There have been many attempts to accurately determine κ for an idealized flow over a smooth wall or for homogeneous turbulence. Based on systematic velocity measurements with an LDA-system, Nezu and Rodi (1986) obtained a universal value for κ ($=0.412$) for fully-developed open-channel flows over smooth beds. This value has been confirmed extensively in the subsequent experimental and numerical studies. On the contrary, the value of κ for rough-bed flows with low submergence still remains unclear. By performing laboratory experiments on an

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open-channel flow with artificial bottom roughness, Rand (1953) reported a value of $\kappa=0.3$ for the open-channel flow with relative submergence $S_r=3.3$. Dittrich and Koll (1997) demonstrated that κ is non-universal and dependent on both the bed roughness and S_r. Their experimental results indicated that the vertical velocity distributions can be described by the logarithmic relationship with modified κ values in the order of 0.18. In addition, they also claimed that the value of κ strongly depends on the chosen reference level. Koll (2006) also reported that κ is non-universal but depends on the irregularity of the bed roughness as well as the S_r. For regular surfaces and large relative submergences, κ approaches a value of 0.4. The κ-value decreases significantly as the bed roughness becomes more irregular or the values of S_r decrease. Furthermore, he suggested that the κ-value reaches a minimum within the range $4<S_r<7$ and increases again as S_r further decreases. Cooper (2006) also reported values of $\kappa<0.41$ when $4<S_r<13$. Gaudio et al. (2010) summarized the existing experimental data and suggested a non-monotonic dependency of κ on S_r: κ-value decreases as S_r increases if $S_r>2$, reaches a minimum value of 0.27 at $S_r=7.5$, and becomes universal for $S_r>15$. Nevertheless, the cause of the non-monotonic dependency still remains unexplained.

In this study, a series of laboratory experiments were conducted to further investigate the mean velocity and turbulence intensity distribution, as well as the friction factors in gravel-bed open-channel flows under small relative submergence. The primary objective was to explore how the mean and turbulence characteristics respond to the reduced relative submergence by comparing the measurements to the existing achievements under large relative submergence.

2. Experimental setup and procedure

2.1. Experimental setup

The laboratory experiments in this study were conducted in a 12.5 m long, 0.31 m wide, and 0.4 m deep tilting flume. Its longitudinal bed slope can be varied from −0.83% to 2%. The sidewalls and the bottom of the flume were made of glass and steel, respectively. A series of honeycomb grids were installed at the entrance of the channel to straighten the flow and prevent the formation of large-scale flow disturbances. The flume received a constant supply of water from a head tank and had an adjustable tailgate at the downstream end of the flume to regulate the flow depth. Water leaving the flume entered a large sump under the flume, where it was recirculated to the constant head tank with a pump. Two wheeled trolleys, which can be moved along the double-rail track on the top of the flume, were used to mount the point gauge and velocity measuring instruments (i.e., UVP and ADV). Fig. 1 shows the schematic diagram of the laboratory setup.

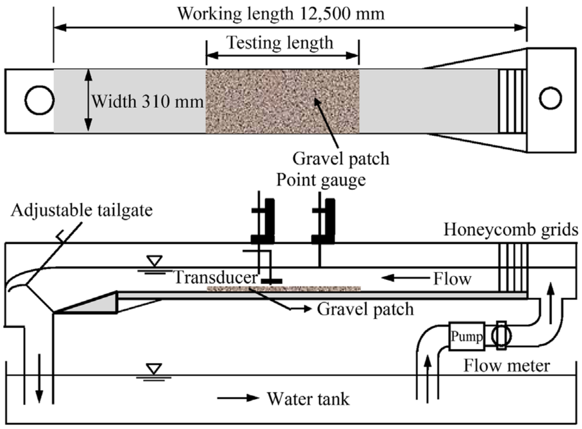

Fig. 1. Schematic of laboratory setup (not to scale).

Flow velocity and turbulence measurements were collected by using both the UVP and ADV. The UVP measured the instantaneous velocity profile along a line. The transducer of the UVP was placed horizontally inside the water body (as shown in Fig. 1) and measured the longitudinal profile of the centerline velocity. The uniform flow condition is reconfirmed by checking the uniformity of the longitudinal velocity profiles. The vertical profiles of the centerline velocity were obtained by measuring the longitudinal velocity profiles at different levels. The vertical measurement interval was 0.5 cm. At each level, the UVP sampled for 252 s, yielding 4000 records. For the use of Vectrino ADV, the height of the sampling volume was set to 7 mm and the sampling rate was set to 75 Hz according to the sampling frequency criteria suggested by Nezu and Nakagawa (1993). Centreline velocities were measured every 0.5 cm in the vertical direction except for the uppermost 5 cm layer where measurement cannot be performed. At each point, the Vectrino ADV sampled for 107 s, yielding 8000 records. Since the water depth is limited in the study, fewer measurement points were used for a single vertical profile. Thus the experimental data measured by ADV were mainly used to estimate the bottom shear stress and recheck the measuring accuracy of UVP.

Natural gravels were used to roughen the flume bottom in the testing section. A sample of the gravels were sieved and weighted to obtain the grain size distribution. The sieving was performed using the following set of sieves: 9.5, 13.2, 19.0, 25.4, 38.1, 50.0 mm. All the gravels were shaken through the sieves from coarser to finer in a mechanical shaker for 10 min. Table 1 illustrates the grain size distribution of the gravels. It can be seen that the diameters of most of the particles range from 19.0 mm to 38.1 mm (over 96.7%). Thus the gravels are quasi-uniform with median diameter approximately equal to 23 mm. These gravels were densely and randomly deployed into plates which were then placed consecutively on the flume bottom. The armored bed was considered fixed since no motion of the gravels was observed throughout the experiments.

Two gravel patches with different lengths were tested under the uniform flow condition. Throughout the flume experiments, the water depths along the testing area were monitored. We consider the uniform flow state is reached within the testing area as long as the water depths are identical. The testing lengths of the short patch (SP) and long patch (LP) were 3.81 m and 7.5 m, respectively. The gravels used in the SP and LP are also slightly different. While the original gravel pack, which is quasi-uniform, was used in the SP, the uniform gravels with very narrow size distribution (19.0–25.4 mm) were used in the LP. By using uniform gravels, it can be more effective to control the uniformity of a relatively long patch. The width and thickness of these two gravel patches are the same with values of 0.3 m and 35 mm, respectively. The length and median diameter are different with values of 3.81 m and 23 mm for SP and 7.5 m and 22.2 mm for LP, respectively. These two gravel patches were both well sorted with low protrusion.

Table 1
Grain size distribution for the original material.

Cumulative finer [%]	100	99.3	83.1	2.6	0.2	0.0
Maximum diameter [mm]	50.0	38.1	25.4	19.0	13.2	< 9.5

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