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Structure of turbulence over non uniform sand bed channel with downward seepage

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ABSTRACT

Experimental investigations were carried out to investigate turbulent flow characteristics in non-uniform sand bed channels for both no seepage and seepage flow. Steady flows over non-uniform sand bed channel were simulated experimentally with downward seepage applied through the boundary. Measures of turbulent parameters such as velocity, Reynolds shear stresses, thickness of roughness sub layer and shear velocities were found increasing with seepage. The turbulent diffusivity and mixing length decrease in presence of seepage. The quadrant analysis suggests that the relative contributions of bursting events increased throughout the flow layer and the thickness of the zone of dominance of sweep event increases with seepage which is responsible for increment in bed material transport. The mean time of occurrence of ejections and sweeps in downward seepage are more persistent than those in no seepage. The analysis of third order moments states that an upward downstream flux of turbulent kinetic energy is observed over the near bed surface giving rise to sweeps with seepage. The turbulent kinetic energy fluxes increase in presence of seepage within the near bed flow. The increased in bed load transport with seepage associated with an increase in flow turbulence production corresponds with decrease in turbulent kinetic energy dissipation, pressure energy diffusion and turbulent diffusion. The traversing length decreases and size of eddies increases with seepage.

1. Introduction

Flow over sand bed occurs frequently in nature. Riverbeds are usually comprised of non uniform sediment mixtures and the respective particle size distribution of sediment in transport is generally finer than the distribution of bed material because of selective transport. Most of the early experiments on sediment transport and deposition were confined to the homogeneous sediment mixture [1–8]. Deigaard and Fredsøe [9] investigated the sorting of longitudinal grain size due to flowing water in alluvial channels, and observed that the mean grain size reduce in the downstream direction with the decrease of slope of the river. Recent years experimental studies have been attempted to understand the basic grain-sorting process during sediment transportation and deposition in heterogeneous sediment mixtures [10–14]. For the beds of composed of sand–gravel mixture, all sand sizes showed essentially a constant relationship between the grain sizes and critical shear stress whereas for the gravel fraction the critical shear stress increased with increase in size. Most of the studies on the non-uniform sediment transport are based on introducing correction factors to understand this hiding and exposure effect and use these factors to modify the existing formula for uniform sediment transport [15–19]. Fractional sediment transport was calculated for non uniform sediment based on correction factors related to bed material sizes [20–23]. On transport of sediments mixture, the effect of sand and gravel contents on overall transport rate was studied in the laboratory flume [24–26]. The movement of gravel fractions in stream bed is increased due to increase in sediment which can lead to bed degradation and preferential evacuation of sediment from the river bed [12]. Frostick et al. [27] conducted series of flume experiments to study the effects of fine materials to the mobility of coarse sand, and they suggested that the presence of sand materials increased the movement of gravels and run to a distinctive patchiness in bed break-up which supported the development of bedforms.

The important hydraulic nature of sand bed in natural channel is that it provokes lateral flow as seepage. Water in sand bed continuously seeps into or out of the channel bed and banks [28]. Depending on the difference in water level in the channel and the surrounding groundwater table, seepage can occur either flow from the channel (suction) or flow into the channel (injection). Due to application towards the contaminant and sediment transports preserving a hygienic stream ecosystem, the flow interactions between no seepage and seepage flows are of significant importance.

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The important features is that the seepage influence the main stream flow characteristics in the wall shear layer as well as the outer-flow layer [29–33]. Since seepage affects the hydrodynamic characteristics of alluvial channels by detachment of particles from the channel bed, hence sediment transport rate is increased with seepage [30]. This problem is related to the solution of important practical engineering issues such as stability of hydraulic structures, which is highly affected by the groundwater movement.

The considerable amounts of water loss through the bed and sides of the irrigation canals results reduced conveyance efficiency. Researchers [34–42] predicted that low conveyance efficiency is mainly due to the loss of water through the bed and sides of the irrigation canals. Based on site specific condition, the quantity of seepage losses in alluvial channel is about 45% of the water supplied at the head of the canal and fluctuates from 0.3 to 7 m^3/s per million square metres (Mm^2) of wetted area [43]. The quantity of water losses in semi-arid zones due to downward seepage is about 20%–50% of the total volume of flow in unlined earthen canals [44]. Kinzli et al. [37] investigated the seepage loss in earthen canals which is located in Middle Rio Grande Valley of New Mexico and observed that more than 40% of water volume is diverted to downward seepage. Martin and Gates [39] quantified loss of around 15% of the main flow rate due to downward seepage in an unlined irrigation canals.

Many elegant researchers [29,30,45–48] observed that downward seepage increased stream wise velocity near the bed resulting in the formation of a more uniform velocity distribution. Previous Researchers [31,49–51] observed that departure in velocity profiles over a rough bed is higher with downward seepage as compared to that with no seepage. Turbulent flow is strongly anisotropic in suction affected flows [52–54]. The bed shear stress increases with downward seepage which caused increased sediment transport with seepage [55–58]. Presence of downward seepage reduced the momentum transfer across the flow bed interface results slip velocity [50,51]. Turbulent intensities decrease in the presence of downward seepage [30,49,52,59,60]. In recent studies [30] the effect of downward seepage through porous boundaries is clearly visible on the time averaged turbulent characteristics of flow.

Although many studies have investigated flow hydrodynamics or turbulent characteristics with seepage in case of uniform sand, the flow characteristics of flat sand bed composed of non-uniform sediment with downward seepage remain unexplored. Since riverbeds are usually composed of non-uniform sediment mixture [61], the present study therefore focuses on the influence of downward seepage flow on the turbulent flow characteristics over a mobile rough boundary (made of non-uniform sand of size 0.5 mm). Experiments were conducted for free-surface flows subjected to downward seepage from the boundary. Acoustic Doppler Velocimeter measurements were undertaken at a location where flow and turbulence quantities were uniform over a horizontal range. The experimental result will deliver important information related to the turbulence characteristics, such as velocity, Reynolds shear stress, anisotropy, correlation coefficient, turbulence diffusivity, mixing length, von Kármán constant, third order correlations, fourth order correlations, turbulent energy budget and conditional Reynolds shear stresses.

2. Experimental setup and programme

In the present work, experiment was conducted in a large tilting flume with dimensions of 17.24 m in length, 1 m in width, and 0.72 m in deep (Fig. 1) at a bed slope (S) of 0.1%. A tank of dimensions 2.8 m long, 1.5 m wide and 1.5 m deep is provided at the upstream of the flume which straightens the flow before its introduction into the flume. A control valve was located at the overhead tank and was used to regulate the flow in the main channel. A wooden baffle was installed at the upstream tank to prevent turbulences in the water coming from the overhead tank to enter the main channel. A tail gate provided at the downstream end of the main channel to control the flow depth. The tail gate was operated manually by a geared mechanism with edges that allow precise positioning of the gate. A tank was provided at the downstream end of the flume to collect the water coming from channel and discharge it to the underground trench that delivers it to an underground tank from where the water is pumped into the overhead tank. This way the water is recirculating in the experiment. The aim of the present study is to experimentally investigate the effect of the seepage on the turbulence nature of free-surface flow mainly in the wall shear layer (logarithmic layer) that exists near to the boundary. Initially, a zero pressure gradient flow was simulated over a mildly sloping sand-boundary and then downward seepage flow was applied through the boundary. The flume is having seepage chamber of 15.2 m long, 1 m wide and 0.22 m deep located at 2 m from the upstream end of the flume that collects water and allows free passage of water through the sand bed. Non-Uniform river sand of particle sizes $d_{50} = 0.5$ mm was used as bed material in the experiments that was kept on the fine mesh in order to prevent the entrance into the bottom chamber. A bottom pressure chamber was formed between the bottom of the mesh and the channel. The bottom pressure chamber was used to absorbed water from the channel through the sand bed in a perpendicular direction in the form of downward seepage. The seepage flow rate that was measured by an electromagnetic flow metre (accuracy of $\pm 0.5\%$) could be controlled by a valve which is installed at the downstream end of the flume. The flow depth in the channel was measured with digital point gauge attached to a moving trolley. Water surface slope is measured using a Pitot static tube connected to a digital manometer attached to a moving trolley. Main Flow discharge in channel was measured by using the flow depth over the rectangular notch at the downstream collection tank. To minimise the effects of flow entrance and exit conditions in the main channel, the test section in the experiments was considered as 5–10 m length from the downstream end of the flume. The length of the flume (17.24 m) is enough large to achieve the fully developed flow condition at the test section which is 5 m long in the stream wise direction. Further, as far as the flow three-dimensionality is concerned, considering to the fact that the aspect ratios were greater than 6, the flows in the experiments were free from 3D (Three dimensional) effect provided by the side-walls [62]. Bed load sampler was placed at downstream end of the flume to collect the transported bed material.

The grain size distributions of non-uniform sediment used in present study are shown in Fig. 2. Non-uniformity in the particle size distribution for the sand was confirmed with the value of geometric standard deviation (σ_g) greater than 1.4 [63]. The characteristics of sediment mixture and flow parameters used in study are shown in Table 1. In Table 1, d_{50} is the median size of sediments, M = Kramer's uniform coefficient of sediment mixture, $M = \sum_0^{50} d_i \Delta p_i / \sum_{50}^{100} d_i \Delta p_i$ where d_i is the geometric size of two consecutive size fractions and Δp_i is the percentage of material present in the sediment mixture, σ_g = geometric standard deviation of sediment mixture, $\sigma_g = \sqrt{d_{84}/d_{16}}$ where d_{84} and d_{16} represent sieve sizes such that 84% and 16% materials are respectively finer than these sizes. In the no seepage (NS) run, Water is introduced to the channel by gradually opening a valve located at the overhead tank till required discharge Q and corresponding flow depth y are registered. Consequently after conducting the experiment with no seepage, different downward seepage discharge of 10% and 15% of the main flow discharge were applied by controlling the electromagnetic flow metres installed at the downstream section of the flume.