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Flow and bedform dynamics in an alluvial channel with downward seepage

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ABSTRACT

In this paper, we report the findings from an experimental study on a parabolic cross-sectional sand bed channel with uniform fine sand under no seepage and downward seepage conditions. Through experiments, we observed that an alluvial channel, which remained at threshold condition of sediment movement during the no seepage experiment, started transporting sediments with the application of seepage in the downward direction. Shields stress of the threshold channel increased significantly from its critical value after the application of downward seepage, which led to the deformation of the cross-sectional shape and consequent development of the bedforms. The role of turbulence in the development of bedforms has also been analyzed. Measures of turbulent statistics show that the time-mean velocities and Reynolds stresses were increased significantly with the application of downward seepage. Under the action of seepage conditions, increase in the flux of streamwise turbulent kinetic energy in the streamwise direction was observed in the region close to the channel boundary. Also, quadrant analysis exhibited an increase in the contributions from all the bursting events and the thickness of the sweep-dominated zone in near-bed region after the application of downward seepage. A bedform tracking tool has been used to evaluate the variability in the geometry of bedforms. We have classified these developing bedforms as current ripples and linguoid ripples according to their evolution with time under the downward seepage condition. It has been further observed that the variation in Shields stress and corresponding bedform geometry reached an equilibrium state in the presence of downward seepage when the experiments were run over a longer period of time (24–31 h).

1. Introduction

Granular boundaries of sand bed channels are permeable in nature, which allow water to penetrate through them in the lateral directions. The difference among the groundwater table and flow level in an alluvial channel causes lateral flow (seepage) through the granular boundary. Exchange of water can take place either way, i.e., flow from the channel (downward seepage) or flow into the channel (upward seepage). The exchange of water between main channel discharge and seepage flows is of significant importance because of its role in the sediment transport and morphodynamics of alluvial channels. Consequently, seepage has the potential to influence the flow characteristics such as velocity profiles and bed shear stresses in the vicinity of the channel bed.

Lu et al. (2008) carried out an extensive review on the effects of seepage on the movement of sediment particles and they showed that effective weight of a sediment particle increases with the application of downward seepage. Also, they defined the stability of a sediment particle in terms of the equilibrium of forces, for example, if the effective weight of a sediment particle is less (more) than the force acting on it (by the flowing water) then greater (no) movement occurs. The existing analytical and experimental works indicate that downward (upward) seepage increase (decreases) shear velocity (Cheng and Chiew, 1999; Kavcar and Wright, 2009; Liu and Chiew, 2012, 2014; Antunes do Carmo, 2014). Increased time-mean streamwise velocities near the bed were observed in the presence of downward seepage in the plane bed channels (Oldenziel and Brink, 1974; Maclean, 1991a; Chen and Chiew, 2004). Several researchers (Watters and Rao, 1971; Willetts and Drossos, 1975; Maclean, 1991b; Rao and Sitaram, 1999; Sreenivasulu et al., 2010; Rao et al., 2011; Cao and Chiew, 2013; Patel et al., 2015; Deshpande and Kumar, 2016) have observed that the bed shear stress increases because of downward seepage, leading to increase in sediment movement.

Sand bed channel exhibits a variety of bedforms, whenever the bed shear stress exceeds from its critical value. Geometrical features of these bedforms are governed by the amount of increase in the bed shear stress. For example, the ratio of the bed shear stress to the critical shear stress for ripple formation varies from 2 to 10 (Kapdasli and Dyer, 1986). Several studies have been conducted to understand the linkage between the flow hydrodynamics and bedform characteristics over

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rough boundaries in alluvial channels (Simons and Richardson, 1961; Van Rijn, 1982; Coleman and Melville, 1996; Robert and Uhlman, 2001; Schindler and Robert, 2005; Venditti et al., 2005). In these studies, the development of bedforms was observed by increasing the inflow discharge, thus providing excess shear stress.

Bedform development is a function of the coherent turbulent flow structures in sedimentary environments, where sweeps (bursting events) govern the initiation of bed features in the near-bed region (Williams and Kemp, 1971; Raudkivi and Witte, 1990; Best, 1992; Nelson et al., 1995; Raudkivi, 1997). In particular, development of hairpin vortices near the channel bed causes the generation of multiple bursting events such as ejections and sweeps, moreover, impact of microturbulent sweeps ascribe to create flow parallel ridge or defects over the rough boundary (Best, 1992). Gyr and Kinzelbach (2004) and Langlois and Valance (2007) suggested that the turbulent instability is responsible for the formation of bedforms. Venditti et al. (2005) observed that the initiation of bed defects and their length are linked to an integral scale of flow. Nasiri Dehsorkhi et al. (2011) performed experiments to analyze the flow hydrodynamics over artificial bedforms with side bank vegetation. A large eddy simulation model was used by Frias and Abad (2013) to define the characteristics of turbulent flow before and after the development of bedforms. Additionally, some studies (MacVicar and Rennie, 2012; Fazlollahi et al., 2015) have been carried out to understand the turbulent flow characteristics on macroscale bedforms such as pools.

Previous studies have shown that the prediction of variability in the bedform geometry plays an important role in the morphology of alluvial channels, which is stochastic in nature (Wang and Shen, 1980; Gabel, 1993; Van der Mark et al., 2008). Knowledge of the geometric variability of bedforms is important in the field applications such as dredging (a process necessary to keep a navigational channel sufficiently deep), which requires information on the highest crest elevations. Jerolmack and Mohrig (2005) used the time-lapse photography to visualize the evolution of bedforms for the characterization of their size, shape, and spacing, according to the imposed flow. They observed that the variability in bedforms is dependent on the interaction among bedform development and unidirectional flows. Nelson et al. (2013) developed a model by using data from field and flume experiments to predict the dimensions of ripples. However, sediment movement from the channel banks also influences the morphology of an alluvial channel. These studies have mainly focused on the plane bed channels while little attention has been devoted to study the curvilinear or other cross-sectional shape in the presence of seepage.

Shapes (plane and curvilinear bed in cross-sectional view) of threshold alluvial channels have been the subject to many investigations, as reported by the ASCE Task Committee (1998). The cross-sectional shape of an alluvial river is governed by the interrelationship among water discharge, channel width, flow depth, velocity, channel slope, channel alignment, bed roughness, and sediment gradation of the alluvial soil. In natural rivers, cross-sectional shape controls the bed morphodynamics in terms of sediment transport from upstream and eroded from its bed and banks (Wobus et al., 2008). In this regard, Wolfert et al. (2006) have discussed the deformation of cross sectional shape and failure of banks during peak flows that cause widening of the river width and formation of depositional bedforms in natural streams. Many researchers have suggested that the natural stable streams are curved in their cross-sectional profile (Hey and Thorne, 1986; Millar and Quick, 1993). Existing literature seems to neglect the cross-sectional profile of the experimental channel bed before the development of bedforms.

A wide range of aspects of the alluvial channels with deformable boundaries are still active areas of research, where the variability in bedform geometry is influenced by the material transport from the channel banks. As has been discussed earlier, there is a significant scope for exploring the effects of the downward seepage in an alluvial channel, having a parabolic cross-sectional profile. Very few studies with flow variations over the bedforms subjected to seepage have been reported. For example, Harrison (1968) carried out experiments on the artificial bedforms with downward seepage and observed that the angle of the lee face of bedform increased by 10°. Lu and Chiew (2004) and Lu (2005) found that the downward seepage affects the height of the dunes. Lu and Chiew (2007) carried out measurements on fixed bedforms with downward seepage and found reduction in the separation length. Recently, Patel et al. (2015) have observed sediment transport in the form of a thin sheet layer because of the increased bed shear stress after the application of downward seepage to a coarser sand bed channel (median diameter = 1.1 mm).

To the best of our knowledge, none of the earlier studies have addressed the development of bedforms in an alluvial channel caused by the presence of downward seepage on a fine sand bed. The present study examines the role of turbulent flow in the bedform development after the application of downward seepage to an otherwise threshold channel. The objectives of this study are:

1. To analyze the temporal variation in Shields stress in the presence of downward seepage.
2. To investigate the turbulent flow structure with and without seepage in a curvilinear cross-section channel using fine grained sand (median diameter = 0.41 mm).
3. To observe the evolution of bedforms under the action of downward seepage in an otherwise threshold alluvial channel.
4. Quantification of the variability in the bedform geometry.
5. Classification of the physical characteristics of bedforms in the presence of seepage.

The experimental investigations of Shields stress and turbulent flow characteristics are performed on a threshold alluvial channel in no seepage and with seepage scenarios, additionally, bedforms are observed on the periphery of the channel bed in seepage conditions. Further, temporal quantification and classification of evolving bedforms are carried out in the presence of bedforms.

2. Experimental set-up and methodology

The experiments were performed on a 20 m long, 1 m wide, and 0.72 m deep recirculating transparent plexi-glassed tilting flume. The seepage facility was provided beneath the main channel as shown in Fig. 1. Length, width, and depth of seepage chamber were (measured from the downstream end of the flume) 15.2 m, 1 m, and 0.22 m, respectively. Two meters of the upstream length of the main channel bed was made non-porous and the remaining length of the channel was made porous by covering with a fine mesh (0.1 mm × 0.1 mm aperture), which was supported with the help of a steel tube structure placed on the bottom of the channel (0.22 m high). The void space between bottom of the channel and the mesh formed a seepage chamber. This mesh hindered the sediment particles from entering into the chamber. The seepage chamber was used to extract water through the sand bed in the form of downward seepage. Amount of seepage was controlled with the help of gate valves connected with the seepage chamber at the downstream end of the flume. Two electromagnetic flow meters were installed at the downstream end of the seepage chamber to measure the seepage discharge (accuracy ± 0.5%). A tailgate was provided at the downstream end of the main channel to maintain flow depth in the channel. The water surface slope was obtained by using a pitot tube and a digital display manometer attached on a moving trolley. Three pumping units (10 HP each) were deployed to supply water into the overhead tank. A regulating valve was used to supply a controlled amount of water in the main channel connected with the overhead tank. Main channel discharge was measured using a rectangular notch provided at the downstream collection tank. Two baffles wall were installed in the upstream tank in order to ensure smooth entry of flow in the flume. The test section of 8 m long was