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Turbulent characteristics and evolution of sheet flow in an alluvial channel with downward seepage

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ABSTRACT

Experimental investigation of the flow hydrodynamics and temporal changes in the cross-sectional profile of an alluvial channel has been studied in the present work. Experiments were carried out in a curvilinear cross-sectional shaped channel with no seepage and with a downward seepage condition to ascertain seepage effects on channel geometry and turbulent characteristics of flow. Measures of turbulent characteristics such as time-averaged near-bed velocities and Reynolds stresses were found to increase with the application of downward seepage. Stream power and the value of Shields parameter are increased under the action of downward seepage, causing bed particles to move in the form of a sheet layer. Integral scales of flow suggest that the size of eddies increases with the application of downward seepage, which is linked to the evolution of the sheet layer. Sheet development causes reduction in flow depth and rapid channel widening. Cross-sectional parabolic shape of the threshold channel is transformed into a trapezoidal shape with the presence of the sheet layer. With the passage of time (11 h), the channel attains another equilibrium geometrical state with the value of Shields stress around 0.074 from the no seepage value of 0.0399. An empirical equation for sheet flow rate is derived with the consideration of seepage in the downward direction.

1. Introduction

Alluvial channels often encounter permeable boundaries in natural environments such as porous boundaries consisting of sediment particles in natural rivers and in irrigation canals. Flow in natural channels is a complex interaction between surface and subsurface flows. Water is continuously seeping into or out of the channel bed and channel banks. Exchange of water (seepage) can occur in either way, flow from the channel (downward seepage) or into the channel, depending upon the difference of level between the water in the channel and the surrounding groundwater table. Earthen irrigation channels in permeable soils lose considerable amounts of water through the bed and sides of the canals resulting in low conveyance efficiency (Krishnamurthy and Rao, 1969; Sharma and Chawla, 1975; Raja et al., 1983; Yussuff et al., 1994; Berenbrock, 1999; Carlson and Petrich, 1999; Tanji and Kielen, 2002; Fipps, 2005; Kinzli et al., 2010; Martin and Gates, 2014). Apart from this, presence of seepage leads to increase in sediment transport and consequently changes the hydrodynamic characteristics of the channel (Rao and Sitaram, 1999). The study of the effect of seepage flows on the detachment of particles from the bed and further movement of the bedload is of great interest as this problem is related to the solution of important practical engineering problems. The majority of researchers (Watters and Rao, 1971; Willetts and Drossos, 1975; Maclean and Willetts, 1986; Maclean, 1991a,b; Prinos, 1995; Rao and Sitaram, 1999; Dey and Nath, 2010; Dey et al., 2011; Rao et al., 2011; Sreenivasulu et al., 2011; Cao and Chiew, 2014) are of the view that seepage in the downward direction increases the bed shear stress, which causes increased sediment transport. Alluvial channels are designed on the basis of the incipient motion condition of the particles resting on the bed, and banks of the channel are intended to have stable boundaries that do not exhibit appreciable erosion or deposition. Application of downward seepage to these channels increases the mobility of bed particles because of increased bed shear stress (Dey and Nath, 2010; Rao et al., 2011).

In an alluvial channel, sheet flow contributes significantly to sediment transport. Sheet flow occurs when tractive force is greater than resistive force and when the large amount of sediment is transported under sheet flow (Gotoh and Sakai, 1997). Sheet flow is the thin layer of high sediment concentration that occurs above plane, noncohesive, sediment beds. Available literature on laboratory and field observations of the sheet flow of bed material suggests that under sheet flow conditions the bed remains fairly plane where ripples and other bed topography features are absent and the bed material movement is restricted to a layer a few centimeters in thickness and composed of moving sediment particles (Dingler and Inman, 1976; Wilson, 1987; King, 1991; Conley and Inman, 1992; Ribberink and Al-Salem, 1994; Sumer et al., 1996).

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The sheet flow layer thickness is closely related to erosion depth. Many researchers (Wilson, 1989; Asano, 1992; Sumer et al., 1996) have observed an approximately linear relation between the nondimensional sheet flow layer thickness and the Shields parameter. Li and Sawamoto (1995) found that the sheet flow layer thickness also depends on the unsteadiness of the flow. Inman et al. (1986) performed measurements in the field and observed a significant increase in the thickness of the sheet flow layer because of turbulent bursting that occurred near the moment of maximum velocity. Field measurements of sand concentration in the sheet flow layer have been carried out in the swash zone on a beach on the island of Norderney by Bakker et al. (1988) and Yu et al. (1990). They measured maximal intrusion depth of sheet flow about 2 to 5 mm and the maximal moving layer about 8 mm. Flores and Sleath (1998) carried out an experimental study and proposed relations for the sheet flow layer thickness with Shields parameter and median particle diameter. Dohmen-Janssen et al. (2001) observed that turbulence damping and roughness height were increased in the presence of a sheet layer. Ahmed and Sato (2003) proposed a model to predict sheet layer movement through representative grain diameter of heterogeneous sediments. Dohmen-Janssen et al. (2002) and O'Donoghue and Wright (2004) utilized conductivity concentration meter (CCM) probes to measure the sheet flow layer thickness. Myrhaug and Holmedal (2007) developed analytical relations for characteristic statistical values of sheet flow layer thickness by considering a stationary Gaussian narrow-band random process. Dong and Sato (2011) used image analysis to predict maximum sheet layer thickness under asymmetric oscillatory flow in combination with the relatively strong opposite currents. Revil-Baudard and Chauchat (2013) proposed an analytical model by using the dense granular rheology and dilatancy law coupled with a mixing length approach and found the nondimensional relation for sheet flow layer thickness with Shields parameter, static friction coefficient, mean sheet flow layer concentration, and median particle diameter. Pitlick et al. (2013) observed the sheet layer caused by the increased Shields stress from its critical value under the condition of overbank flow. Lanckriet et al. (2014) used the conductivity concentration profiler (CCP) in their field study for quantifying the swash-zone hydrodynamics and sediment transport and evaluated the relationship for sheet layer thickness and sheet load as the function of mobility number.

Various researchers (Sutherland, 1967; Thorne et al., 1989; Clifford et al., 1991; Best, 1992; Cao, 1997; Dey and Raikar, 2007; Dwivedi et al., 2010; Dey et al., 2011) studied the turbulent structure of flow over bed particles that were on the threshold of motion. Williams and Kemp (1971) argued that the initiation of bed features is linked with the coherent structure of turbulent flow. In particular, sweeps dominate in the form of bursting events over flat surface that is envisioned to create bed defects (Best, 1992). Venditti et al. (2005) showed that initiations of cross-hatch patterns over the sand bed are associated with integral scales of flow. In previous studies, the effect of seepage through porous boundaries is clearly visible on the turbulent characteristics of flow (Oldenziel and Brink, 1974; Nezu, 1977; Antonia et al., 1988; Maclean, 1991b; Krogstad and Kourakine, 2000; Oyewola et al., 2004; Dey and Nath, 2010).

Existing knowledge on sediment transport in the form of sheet flow in alluvial channels involves the high bed shear stress, which could be achieved by increasing the flow discharge greater than some thresholds. However, downward seepage increases the bed shear stress if applied to the threshold channel with stable cross-sectional shape. Our goal is to describe how the downward seepage affects stable alluvial channels. Thus, the present work is conceptualized to attain the sheet flow condition with the application of downward seepage in an incipient or threshold channel. The discharge in the channel is kept in such a way that the particles on the entire cross section were on the condition of incipient motion throughout the test reach and that 30% of the main channel discharge was applied in the form of downward seepage. This resulted in greater Shields stress from its critical value, which is responsible for initiation of the sheet flow layer. Also, integral scales and turbulent flow structure are documented in the near-bed region to understand the linkage between flow and evolution of the sheet layer. The flow in an alluvial channel is significantly affected by the presence of the sheet flow layer as a large amount of sediment is transported, which affects the morphological processes such as erosion and disposition in canal or alluvial river systems. Thus, the aim of this paper is to observe the hydraulics of sheet flow and its propagation over time and space by doing experiments on a threshold channel with downward seepage.

2. Experimental setup and procedure

In the present study a glass-walled tilting flume of 20 m length, 1 m width, and 0.72 m depth was used for conducting the experiments in the laboratory (Fig. 1). A collection tank of dimensions 2.8 m long, 1.5 m wide, and 1.5 m deep was provided at the upstream end of the flume with a couple of wooden baffles installed in it to prevent highly turbulent flow from entering the channel. The entire length of the main channel bed, except a 2-m length at the upstream limit, was made porous by covering it with a fine stainless steel mesh (0.1 mm) supported by a steel tube structure of 0.22 m height, 1 m width, and 15.20 m length, which was placed on the bottom of the flume. A bottom pressure chamber was formed by the area between the bottom of the flume and the fine mesh. Uniform river sand of median particle diameter $d_{50} = 1.1$ mm was used as bed material in the experiments. Sand can be considered uniform if the value of geometric standard deviation (σ_g) is <1.4 (Marsh et al., 2004), which has been found to be 1.03 for the sand used in the present study. Bed material was placed on the fine mesh in order to prevent the entrance into the bottom chamber. Angle of repose for the dry sand was $\varphi^\circ = 31.154$. Three pumping units (10 HP each) were used to supply discharge to an overhead tank and then supplied to the main channel. An adjustable tail gate was provided at the downstream end of the flume to maintain the required depth of flow in the channel during experiments. The bottom pressure chamber was used to extract water from the main channel through the sand bed in a perpendicular direction in the form of downward seepage. The amount of downward seepage was controlled by a couple of valves connected to the bottom pressure chamber at the downstream end and was measured with the help of two electromagnetic flow meters. Flow discharge from the main channel was measured by recording the depth of flow over the rectangular notch provided at the downstream collection tank. Pitot tubes attached to a digital manometer and a digital point gauge were used to measure water surface slope and flow depth in the channel, respectively. To minimize the effects of flow entrance and exit conditions in the channel, the test section in the present experiments was considered as 8 m in length in the middle of the flume (4–12 m from the downstream end).

2.1. Preparation of the cross-sectional bed profile

Previous literature implies a trapezoidal cross-sectional shape of the channel for the study of sheet flow development. Most of the stable channel shape predictors in terms of width, depth, and slope are empirical or semiempirical in nature except the one proposed by Lane (1953). Various researchers (Griffiths, 1983; Hey and Thorne, 1986; Millar and Quick, 1993) have argued that natural channels have curved cross-sectional profile. The theoretical regime equation developed by Lane (1953) fulfills the criteria contrary to the other empirical predictors. Mahmood et al. (1988) also stated that Lane's (1953) formulation of alluvial channel response is well suited for trend analysis.

Lane (1953) proposed the parabolic shape of a stable channel that is derived on the basis that the tendency to motion of a particle in the direction transverse to the flow is proportional to the slope of the stream bed, as measured by the tangent of the angle with the horizontal, and the direction of flow is proportional to the depth of the stream. In Lane's (1953) geometric profile, at and above the water surface, the maximum angle of the sideslope approaches the angle of repose of the