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Statistical description of morphological characteristics of bedforms in seepage affected alluvial channels

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Abstract

In this study, experiments were performed in a curvilinear cross-sectional threshold alluvial channel with no seepage and with seepage conditions in order to understand the influence of downward seepage in an alluvial channel. We observed that stable channel during no seepage condition started to reach in transporting stage with downward seepage. Increased value of Shields stress was observed after the application of seepage. In addition, this study deals with the effect of downward seepage on the evolution of alluvial bedforms. In this regard, multi-temporal bed elevation profiles were collected along the test section of channel, which are used to characterize migrating bedforms. Results reveal greater fluctuations and variability on the channel bed under the influence of increased seepage discharge. Slope of the power spectral density with wavenumber was significantly increased with an increment in seepage percentage, showing more inhomogeneous arrangement of bedforms and larger roughness over the channel boundary.

Keywords: turbulence; seepage; multi-scalar fluctuation; power spectral density; structure function.
1. Introduction

The intrinsic behavior of mobile beds in natural environments is complex if one attempts to understand their innate creation. Mobile beds transform themselves and evolve into different patterns such as sediment waves, which alter the flow and sediment transport. Understanding of these intriguing patterns is significantly important for river management, bed load transport, and structures in fluvial system. In this regard, the studies on fluvial bedforms are widely carried out to get an insight into physics behind the initiation of bedforms over rough beds in natural environments. In general, alluvial bedforms developed by unidirectional flow of water over rough beds in sedimentary environments. Sand bed channel exhibits a variety of bedforms, whenever the bed shear stress exceeds from its critical value. The most common features of bedforms are ripple and dunes, which are formed in tranquil (Froude number $< 1$) flow in the fluvial systems. Ripples are the small scale bed features that contribute to lesser turbulence, whereas, dunes are larger structures covering a significant part of the channel bed and result in macro disturbances in the flow (ASCE 2002). Best (1992) observed that ripples can only form on a finer sand (median diameter $< 0.7$ mm) bed and grow up to a maximum wavelength of approximately $0.3$ m. On the other hand, dunes occur on coarser sand (median diameter $> 0.7$ mm) bed and may grow in larger wavelength and amplitude (Allen 2009).

Earlier, experimental studies suggested that turbulence in the flows play an important role behind the development of bedforms (Best 1992; Robert and Uhlman 2001; Schindler and Robert 2005; Venditti et al. 2005). In addition to this, studies were carried out to understand the formation and migration of bedforms including their linkage with the flow structure by providing the excess shear stress over plane bed channels (Simons et al. 1965; Van Rijn 1982; Venditti et al. 2005). Some field studies on bedform dynamics such as flow structure, changes in bed level, and bed load transport are presented at large scale observations (Parsons et al. 2005; Kostaschuk et al. 2009; Shugar et al. 2010). Elegant work was presented by
Coleman and Nikora (2011) to investigate the nature of sand waves in terms of their development, characterization, statistics, and flow structure. Characterization of bedforms within a complex river flow system has always been a challenge to the researchers owing to their complicated geometry and dynamic interaction patterns. Previous studies on bedforms development and corresponding flow characteristics have shown the importance of evolution of bedforms and their dynamics by increasing inflow discharge over the plane sand-bed condition. However, they have not considered the cross-sectional profile of the channel and temporal changes in the length scale of bedforms. Thus, one has to describe the developing bedforms through statistical analysis of bed elevation series.

Singh et al. (2009) computed the power spectral density using data acquired from bed elevation profiles along the streamwise direction and showed that the spectral densities of the bed elevation time series and of spatial bed elevation transects are closely related to each other. In addition to this, Singh et al. (2010) experimentally verified that smaller bedforms move with a higher celerity the larger bedforms. Similar types of bedforms have been observed to possess significantly different physical properties such as size and shape (Hino 1968; Nikora et al. 1997; Van der Mark et al. 2008; Singh et al. 2011). In alluvial channels, spectral analysis of change in bed elevation profile (Nikora et al. 1997; Jain and Kennedy 1974; Nakagawa and Tsujimoto 1984; Nikora and Goring 2001; Aberle et al. 2010) affirmatively confirmed the existence of a wide range of scaling regimes (log-log linear power spectra) and a scale dependent celerity of migrating bedforms (Best 2005; Jerolmack and Mohrig 2005; Nikora et al. 1997; Raudkivi and Witte 1990; Coleman and Melville 1994; Schwammle and Herrmann 2004). In addition to this, Qin et al. (2013) discussed the equilibrium phase of ripples with the help of a digital elevation model, where they described the multi-scale behavior of sand waves by higher order structure function. Further, Singh et al. (2011) quantified the multi-scale statistical structure of migrating bedforms with the help
of a wavelet based cross correlation analysis for understanding the complicated dynamics of
bedforms. Guala et al. (2014) carried out experiments over a range of Froude numbers (0.2 -
0.5) under varying discharges and different bed material composition. They suggested that a
wide range of scale dependent convection velocities is one of the governing parameters for
adequately describing the spatial and temporal characteristics of migrating bedforms.

In the present day scenario, ground water table is depleting because of the excessive use of
tube-wells. Therefore, the difference in ground water table and flow level in an alluvial
channel varies. If the level of ground water table is lower than the flow level in the channel,
water seeps in the downward direction causing downward seepage. The conveyance capacity
of the channel is reduced because of the presence of seepage (Kinzli et al. 2010; Martin and
Gates, 2014). Earlier studies (Chen and Chiew 2004; Patel et al. 2015; Deshpande and
Kumar 2016; Patel et al. 2017; Patel and Kumar 2017) observed that time-mean velocities
and Reynolds shear stresses are increased because of downward seepage in the alluvial
channels. Bedform dimensions were increased owing to the effect of seepage by considering
small test section in alluvial channel as discussed by Lu and Chiew (2007). Patel et al.
(2015) investigated that downward seepage caused deformation of banks and development of
a sheet layer because of increased Shields stress (bed shear stress) over coarser sand bed
channel.

Aforementioned studies have focused either on the time dependent evolution of bedforms at a
single point within the test section or the variation of the bed load transport rate with
increasing discharge. However, to the best of our knowledge, none of the earlier studies have
addressed the effect of seepage on the physical properties of bedform and their evolution
mechanism. Seepage occurs through the porous boundary of natural channels causing an
extra downward force to the boundary particles as well as a downward shift of the velocity
profile of the channel bed. Thus, seepage must be taken into account as an interfering factor,
while considering the phenomenon of bedform evolution and their characteristics, especially in alluvial channels. In addition to this, the study on bedform genesis, their complex interaction and migration patterns has not been carried out in the previous literature. Taking all these probable deficits under consideration, the main objective of this study is to quantify the effect of seepage on the physical characteristics and the evolution mechanism of bedforms. Thus, in the present study, statistical analysis has been carried to characterize the developing bedforms at different percentages of seepage.

2. Experimental setup and methodology

Experiments were conducted in a 20 m long, 1 m wide and 0.72 m deep glass-sided large tilting flume with an adjustable bed slope as shown in Figure 1. Flow in the channel was straightened before entering in the main channel by a 2.8 m long, 1.5 m wide, and 1.5 m deep tank provided at the upstream of the flume. Three pumps of 10 HP capacities each were deployed to supply the water in the overhead tank. A control valve was installed at the overhead tank, which was used to regulate the flow in the main channel. The test section was considered from downstream 4 m to 12 m to ensure the measurements free from any upstream or downstream disturbance. A seepage chamber of 15.2 m length, 1 m width and 0.22 m height was located at the bottom of the main channel, which collects and allows the seepage through the sand bed in the downward direction. Two meters of 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 x 0.1 mm aperture size), which was supported with the help of steel tube structure of 0.22 m height, placed on the bottom of the channel. The void space between the bottom of the channel and the mesh forms a seepage chamber. The mesh hinders the bed materials from entering into the chamber. Couple of electromagnetic flow meters was installed at the downstream end of the chamber to measure and control the seepage discharge.
A tail gate, which was operated manually by a geared mechanism with edges allowing precise positioning of the gate, was used in controlling the flow depth in the channel. A rectangular notch with coefficient of discharge ($C_d$) 0.82 was evaluated at the downstream end of the collection tank to measure the main channel discharge. Water surface slope was measured by using a pitot tube connected to a digital manometer, which was assembled on a moving trolley. Bed slope of the flume was measured with the help of total station.

River sand was used for all the experimental runs. Median diameter ($D_{50}$), geometric standard deviation, and angle of repose ($\phi$) were evaluated as 0.41 mm, 1.17, and 32.55°, respectively, for the sand used in this study. Previous researchers suggested that the shape of the natural channels is curved cross section or trapezoidal (Griffiths 1983; Hey and Thorne 1986; Millar and Quick 1993). Various studies evaluated the stable shape in terms of width, depth, and slope, which was empirical or semi-empirical in nature except one proposed by Lane (1953).

In the present study, a parabolic cross-sectional profile of the channel was made based on the Lane’s (1953) theory, importance of which was to design the stable channel at incipient motion condition. Lane (1953) derived the equation to design of threshold channel by considering balance between the forces acting on a particle resting on the channel boundary.

$$y_0 = h \cos \left\{ \left( \frac{\tan \phi}{h} \right) x \right\}$$

Where $h$ is centre line depth, $y_0$ is lateral bank zone depth, and $x$ is transect distance. Cross section profile of channel has been obtained by given using. For top width 0.7 m, maximum depth of flow is calculated as 0.14 m by using equation (3) (see X-X section of Figure 1).
2.1 Data collection

In order to understand the flow hydrodynamics, instantaneous velocity measurements were taken at the centre line of flume by the Vectrino+ Acoustic Doppler Velocimeter (ADV). Velocity samples were collected in the vertical direction for no seepage and seepage experiments (immediately after the application of downward seepage). In the no seepage experiment, when channel remained in stable condition after running several hours (10-12 h), around 20-25 velocity samples were collected at center of the cross-section 8 m from the downstream reach end. After the application of downward seepage, when measuring location of the channel was not distorted until 3 h of run, velocity measurements were taken during this period for determining the influence on flow structure caused purely by the presence of downward seepage at the same location. Once the deformation starts after 2-3 h of downward seepage, this would have an effect of the flow structure. At each vertical location instantaneous velocity samples were recorded for five minutes duration at a sampling rate of 100 Hz. Ten pulses of instantaneous velocities were recorded at 10 mm above the bed to obtain the uncertainty associated with the measured data (Table 1).

Geometric observations in the channel were recorded with the help of SeaTek 5 MHz Ultrasonic Ranging System that contained eight transducers. The distance between each adjacent transducer was approximately 25 mm c/c in transverse direction. The whole system was run from the upstream to the downstream of the test section for several times during experimental run of almost 31 h. The measured data of bedforms development are the streamwise spatial bed elevation profiles with the resolution of 7.8 mm in longitudinal transect. Two time intervals 9 h and 21 h are considered to analysis these recorded bed elevation profile in accordance with developing stage of bedforms. A summary of
experimental conditions is given in Table 2. Analysis of bedforms characteristics has been carried out under both the seepage discharges (15% and 20%) at slope 0.00176 to avoid the duplicity and conjunctions in the results.

[Insert Table 2]

3. Investigation of Shields stress

For validating the incipient motion condition during the no seepage run, results were plotted on a Shields curve as shown in Figure 2. Mean line in Figure 2 represents the Shields curve, which has been plotted by using the empirical formulation of Paphitis (2001).

[Insert Figure 2]

Shields stress provides the information regarding characteristics of bed shear stress on the sediment particles. Figure 2 shows that the value of Shields parameters falls within the band of Shields curve, suggesting incipient motion condition of sand particles during no seepage run. Few researchers (Liu 1957; Bogardi 1959; Southard and Dingler 1971; Venditti et al. 2005) reported stable beds with little sediment transport and no signatures of bedforms were seen. In the present experimental study, the parabolic cross-sectional shape remained stable i.e. in the threshold of sediment movement for several hours (10-12 h) during the no seepage run, although sediment movement was sporadic along the channel. However, when downward seepage was applied to the channel, bed shear stress was increased by ~27-30% from its critical values. This increase in shields shows the higher bed shear stress, resulting in sediment transport and consequent deformation of cross-sectional shape of the channel. Through experiments, we observed that sediment particles were detached from the channel banks and collected in the form of bedforms at the center of channel. Those bedforms were
prograded from the upstream to the downstream end of the channel and resulted in the complete distortion of the cross-sectional shape of the channel.

4. Results and outcomes

Understanding of the influence of downward seepage on the turbulent flow structure is necessary for the assessment of changes in the morphodynamics of the channel. Also, statistical analysis has been carried out to quantify the effect of seepage in bedform dynamics.

4.1. Turbulent fluvial flows

In order to understand the changes in hydrodynamics of channel for no seepage and with scenarios turbulent flow parameters such as time-mean velocities, Reynolds shear stresses (RSS), turbulent production, and turbulent dissipation are evaluated in the middle of the test section (8 m from downstream end). Figure 3 (a) shows the distributions of time-mean velocities against dimensionless depth ($z/h$, where $z$ is distance from channel bed and $h$ is the depth of flow) for all the runs. We can observe that time-mean velocities are increased significantly with the application of seepage. These increased velocities cause increase in sediment movement along the flow in the channel.

[Insert Figure 3]

RSS defines the real time momentum flux of the streamwise velocity in the vertical direction caused by the fluctuating velocity field. RSS has been obtained for all the runs and the vertical distributions are shown in Figure 3 (b). Careful observation from Figure 3 (b) shows that Reynolds shear stresses are increased by ~25-40% from their no seepage values with the application of seepage, confirming increased momentum transfer toward the channel boundary in the presence of seepage. In the previous study, Patel et al. (2015) observed a
sheet layer because of increased Reynolds shear stresses in the presence of downward seepage over coarser \((D_{50} = 1.1 \text{ mm})\) sand bed with curvilinear cross section channel. Here, we observed increased sediment transport and consequent development of bedforms over the finer sand-bed channel with the application of seepage.

Figure 4 depicts the Profiles of turbulent production and turbulent kinetic energy dissipation for experiments on both sands under no seepage and with seepage conditions, which can be evaluated as calculated by Krogstadt and Antonia (1999).

\[
t_p = -uw \frac{\partial u}{\partial z}
\]

\[
e_d = \frac{15\nu}{u^2} \left( \frac{\partial u'}{\partial z} \right)^2
\]

where \(\nu\) is the kinematic viscosity. Quantities \(t_p\) and \(e_d\) are normalized by multiplying with \(h/u'^*\), and are expressed as \(T_P\) and \(E_D\), respectively. Shear velocity \(u_*\) is obtained by the linear projection of the RSS profile to the channel bed \(u_* = (u'w')^{0.5} \text{ at } z=0\) for all the runs. Turbulent production comes from the interchange of mean flow energy to fluctuations. Here, \(T_P\) and \(E_D\) are shown for no seepage and 15% seepage at slope 0.00116 in order to avoid duplicity and to show the trend adequately in both scenarios (see Figure 4). We can observe from Figure 4 that the turbulent production is increased when the downward seepage is applied to the channel. This increased \(T_P\) is in agreement with the higher momentum transfer under the seepage condition. Also, it can be implied that larger roughness over the boundary of the channel with the application of seepage, causes more turbulent production in the flow. Further, we can observe that the turbulent dissipation is reduced when water is extracted in the vertically downward direction through the sand bed. Under the action of
downward seepage, more energy is converted to turbulent fluctuations in the flow, resulting
in the reduced dissipation of the turbulent kinetic energy.

4.2. Scale dependent statistical analysis of bed elevation increments

For quantifying the effect of seepage on the bed elevation profiles as well as local
fluctuations, multi scale statistical analysis has been carried out. In this analysis, wavelet
coefficients, derived from Mexican hat wavelet as mother wavelet, at different length scales
are obtained in accordance with Patel at al. (2017). Wavelet coefficients (fluctuations of bed
elevation) can be computed as:

\[ WC_f(a,b) = \frac{1}{\sqrt{a}} \int_R \psi \left( \frac{x-b}{a} \right) f(x) dx \]  

Where \( a \) is defined as the scaling parameter, \( b \) is defined as the location parameter, and \( R \) is
the set of real number. The factor \( \frac{1}{\sqrt{a}} \) is scaling factor of mother wave as discussed in
earlier studies (Mallat 1999; Kumar and Fououlia-Gerojiu 1997). Some predetermined
scales were chosen and the elevation series were transformed with a Mexican hat wavelet at
those particular scales. For example, Figure 5 shows the wavelet coefficient computed at 20
mm and 10 mm length scales after 21 h of run for 15% seepage case.

At length scale \( a \), \( q^{th} \) order statistical moments of the absolute values of the increments can be
obtained as:

\[ M(q,a) = \frac{1}{N} \sum_{i=1}^{N} |dh(x,a)|^q \]  

Where \( N \) is the number of data points of the bed elevation series at scale \( a \). The term \( M(q,a) \)
is defined as the structure function or statistical moments. The statistical moments for all \( q \)
values completely depict the shape of the probability density function of the bed elevation
increments at scale $a$. Scale invariance ensured that it varies with the following power law with scale $a$

$$M(q,a) \sim a^{\tau(q)}$$  \hspace{1cm} (6)

Where $\tau(q)$ represent the scaling exponent function. In general, $\tau(q)$ follows a nonlinear relationship with $q$. Therefore, the following quadratic equation is used to evaluate the $\tau(q)$

$$\tau(q) = c_1 \times q - \left( \frac{c_2}{2} \right) \times q^2$$  \hspace{1cm} (7)

Where $c_1$ and $c_2$ are defined as average roughness of the wave series and intermittency parameter, respectively. The parameters ($c_1$ and $c_2$) signify the variations in probability distribution function of bed elevation increment over a range of length scales. From following geometrical interpretation of the statistical scaling (Frisch 1995; Venugopal et al. 2006), the parameter $c_2$ is related to the local roughness or degree of differentiability of the bed elevation signal. A non-zero value of $c_2$ symbolizes a temporally non-stationary or spatially inhomogeneous arrangement of spikes or abrupt changes along the channel. In this study, structure function has been analysed on the bed elevation spatial series after 9 h and 21 h run for both the seepage amounts (15% and 20%). Figures 6 (a) and (b) show the scaling of the statistical moments of the bed elevation variations $dh(x,a)$ as a function of scale $a$ after 9 h run and 21 h run, respectively for 15% seepage. These plotted moments are offset vertically (along the $y$-axis) to get better visualization. Figures 6 (c) and (d) show the $\tau(q)$ curves obtained from the slopes of the statistical moments within the scaling range for 15% seepage. Similar explanation hold true for Figures 7 (a) to (d) for 20% seepage. From Figures 6 and 7, we can observe that the structure function follows power law in the scaling range from approximately 50 mm to 400 mm for both the seepage experiments. Additionally, the $\tau(q)$
curves have exhibit a nonlinear relationship with $q$, indicating the presence of multifractality
in both of the seepage experiments.

[Insert Figure 6]

[Insert Figure 7]

The value of the intermittency parameter $c_2$ is higher for 20% seepage experiment than the
value obtained for 15% seepage experiment after the 9 h run. This suggests that after
increasing the seepage discharge more inhomogeneous arrangement of abrupt bed elevation
fluctuations was found during developing bedforms (after 9 h run). While, the value of $c_2$ is
nearby equal after 21 h run for both the seepage discharges, indicating bedforms
arrangements achieve an equilibrium state after longer period of the seepage runs. In
addition, the parameter $c_1$ defines the characteristics of the bed elevation fluctuation, in
which greater value corresponds to smoother bed elevation. In the present study, we observe
that the value of $c_1$ is higher after 9 h as compared with 21 h run for both the seepage
discharges. This suggests that the bed elevation fluctuation is smooth in the beginning (after 9
h run) of seepage run. However, value of $c_1$ increases with the passage of time (after 21 h
run), implying an increase of bed elevation fluctuation because of greater variability in
bedforms dimensions. Therefore, the results show larger bed roughness on the channel bed at
the end of seepage experiments.

4.3. Probability distribution function (pdf) of dimensionalized bed elevation increments
as a function of scale

In the previous study, Wong et al. (2007) suggested that mean-removed bed elevations in
plain bed channel shows nearly Gaussian distribution. For understating the patterns of bed
Figure 8 shows the semi-log pdfs of the bed elevation increments for 15% and 20% seepage experiments after 9 h run and 21 h run, respectively. Careful observations of Figure 9 reveal that the pdfs at different scales are asymmetric to each other. As the scale is increased, the width of the pdfs increases and they become more skewed to the right signifying a higher probability of occurrence of higher positive bed elevation fluctuations or increments. The pdfs also show a significant increase in width with an increase in seepage amount, suggesting larger elevation fluctuations or larger bedforms under the influence of increased seepage amount. It is very important to note that earlier in the structure function analysis; we have seen that the value of the roughness parameter increases with the increment in seepage discharge. Further, pdf of bed elevation increments is normalized to understand the variations adequately for both the seepage discharges as shown in Figure 9. We can observe that pdfs are getting thinner tailed at larger length scale, which can be seen from the log-log plots of the scale dependent probability of exceedance of the positive bed elevation increments. Results show that the exceedance probability curves more upwards in the case of 20% seepage experiment as compared with 15% seepage experiment. This suggests that the existence of larger bedforms is more likely for the case of higher seepage discharge.

4.4. Spectral analysis

Power spectral density function (PSD) represents the strength of the energy as a function of frequencies (or scales). In other words, it shows whether the energy is strong or weak at any
particular frequency. The PSD is the average of the Fourier transform magnitude, squared over a large time interval. The PSD, \( S_x(f) \) of a random time signal \( x(t) \) in the interval \((-T, T)\) can be expressed as

\[
S_x(f) = \lim_{T \to \infty} E \left\{ \frac{1}{2T} \left| \int_{-T}^{T} x(t) e^{-j2\pi ft} dt \right|^2 \right\}
\]  

(8)

Similarly, the \( S_x(f) \) can also be defined as the Fourier transform of the auto-correlation function

\[
S_x(f) = \int_{-\infty}^{\infty} R_x(\tau) e^{-j2\pi ft} d\tau
\]  

(9)

Where \( \tau \) is the time lag and the auto-correlation function \( R_x(\tau) \) is defined as:

\[
R_x(\tau) = \frac{E[(x(t)-\mu)(x(t+\tau)-\mu)]}{\sigma^2}
\]  

(10)

Where \( \mu \) is the mean and \( \sigma \) is the standard deviation of the data series. For time series signals, the unit of the frequency response is in hertz (cycles/sec). In the present experiments, we have collected spatial data after 9 h and 21 h of seepage runs. Therefore, the representative unit of frequency is defined in terms of wave number (number of waves per unit length). Wavenumber \( \omega \) is defined as the inverse of the spatial resolution (=2\( \pi/\Delta x \), where \( \Delta x = 7.8 \) mm). It is important to note that the length scales are proportional to inversely of the wavenumbers, obtained from the PSD plots. In the spectral density plots the power spectra saturates near 1000 mm or 1 m for both the seepage experiments. This suggests that the largest amount of variance is associated with this particular length scale.

Figure 10 shows to the PSD versus wavenumber plots obtained from bed elevations series after 9 h and 21 h of run for 15% and 20% seepage. We can observe that the slopes of the
PSD plots are nearly equal after 9 h run for both the seepage percentages. While after 21 h, slope of the PSD for 20% seepage experiment is increased to -2.0 from -1.86 of the 15% seepage experiment. In the study of Singh et al. (2010) on a gravel bed channel, they observed that slope of the power spectra versus wavenumber increased from -1.87 to -2.06 after increasing the inflow discharge from 2 to 2.8 m$^3$/s. In the present study, increment in the PSD slopes suggests the development of larger bedforms and more inhomogeneous arrangement of bed elevation series with the increase in seepage discharge after 21 h run.

5. Discussion

This study shows the influence of downward seepage on a threshold alluvial channel. In this regard, to understand the effect of seepage experiments were performed in no seepage and with seepage scenarios over sand bed channel. It was observed that the threshold channel remained in stable condition, while running several hours at no seepage condition (see Figure 11a). Stability of the cross-sectional shape of the channel was validated by using Shields curve as presented in Figure 2. However, with the application of downward seepage, an increased Shields stress was observed, indicating higher bed shear stress on the bed particles. Existing studies suggested that sediment transport increases when Shields stress reach towards ~20% higher than its threshold value (Diplas 1990; Ikeda et al. 1988). Bed features on the channel bed were observed when shear stress was increased from its threshold value (Kapdasli and Dyer 1986; Best 1992; Venditti et al. 2005). In recent experimental study, Pitlick et al. (2013) observed that the overbank flow caused the bank distortion because of the high Shields stress associated with it. In addition, Patel et al. (2015) observed that Shields stress increases after the application of downward seepage, causing the development of sheet flow of sediment particles. In the present study, stable particles during no seepage experiment started to detach from the banks and deposited at adjacent section because of increased Shields stress after the application of downward seepage. This process continued till the cross
section of channel distorted fully, resulting development of bedforms. Snapshots of the channel cross section obtained at the end of 15% and 20% seepage experiments are shown in Figures 11 (b) and 11 (c), respectively. Figure 11 (a) shows snapshot of the channel cross section after running the experiment for several hours under no seepage condition, where no signature of bed or bank deformation was seen. Cross-sectional shape of the channel was distorted gradually after the application of downward seepage (see Figures 11b and 11c).

Further, turbulent flow parameters are evaluated for no seepage and seepage experiments to understand the mechanism behind the development of bedforms. Results show that after the application of downward seepage to the channel, increase in the time-mean velocities and RSS are observed (see Figure 2). This suggests higher flow strength in flow, which can lead to sediment transport and consequent development of bedforms. Further, we observe that turbulent production and dissipation are increased and decreased, respectively, showing greater roughness on the channel in the presence of seepage. In this regard, previous study of Sumer et al. (2003) showed that the increased turbulence in the flow may cause increase in sediment movement by six times.

The characteristic of fluvial bedforms is needed in order to understand fluvial process in seepage environment. However, development of bedforms is an intricate in nature, which cannot be defined straightforwardly. The most important characteristics of migration bedforms is its intermittency, which create deterministic approach potentially difficult. One can show its characteristics from the measurement of several bed elevation profiles at different time intervals. Therefore, one has to describe the characteristics of bedforms through statistical analysis of various bed elevation profiles. Previous literatures have focused on the statistical characterization of the physical and dynamic characteristics of bed
topography under different variable controlling parameters such as flow discharge, grain size distribution, and flow velocity (Allen 1962; Van Rijn 1982; Julien and Klaassen 1995; Coleman et al. 2006). Some advanced statistical methods such as spectral analysis and structure function analysis have also been used to characterize the variability of bedform properties over multiple temporal and spatial scales (Nordin and Algert 1966; Hino 1968; Jain and Kennedy 1974; Nakagawa and Tsujimoto 1984; Nikora et al. 1997; Nikora and Goring 2001; Aberle et al. 2010; Singh et al. 2011).

Aforementioned studies observed that the variability and celerity of developing bedforms were increased and decreased, respectively, by increasing the flow discharge over plan bed channels. Also, they have not considered the influence of seepage on statistical behavior of bedforms. In the present study, scale dependent statistical analysis has been carried out on the wavelet coefficients to quantify the developing bedforms at different scales and percentages of seepage. In this regard, bed elevation profiles were discretized into multiple scales ranging from 2 mm to 500 mm by using Mexican hat wavelet to analyse the effect of seepage over different spatial scales on bedform characteristics. Results show that variability and fluctuation over the channel boundary increases when seepage percentage increases from 15% to 20%. These observations can be linked to the study of Patel et al., (2017), they observed that eddy length and time scales of flow increases by increasing seepage discharge, causing development of larger bedforms.

This study deals with the mechanism of bedform development and the effect of seepage on their physical characteristics. It concentrates on seepage as an important controlling factor for bedform size and the distribution of their different physical parameters. Moreover, the development of a new dataset consisting of spatial arrangement of bedforms and their detailed statistical analysis is an element of interest of this work. The reason behind collecting spatial dataset was to enhance the applicability of the analysis methods to
understand the seepage affected alluvial channels. Besides, these analysis techniques can be
easily applied to any real dataset of river bed profile as these are statistical analyses of
bedforms dynamics. The findings of this study can be used to better understand the evolution
pattern and variation in the geometry of alluvial migrating bedforms under the influence of
seepage in alluvial channels.

6. Conclusions

Experimental study has been performed to understand the flow hydrodynamics and earth-
surface morphology of a threshold alluvial channel under the influence of seepage
environments. Experiments were carried out under no seepage and with seepage scenarios on
a stable curvilinear cross-sectional shape channel. Through experiments, we observed that
bed particles were stable on a channel boundary and their movement was sporadic in nature
at no seepage condition. Investigation of Shields stress suggests that with the application of
downward seepage bed shear increases from its critical value, leading to sediment movement
and consequent development of bedforms. To get an insight behind the initiation of
bedforms, turbulent flow parameters are evaluated. We have found that streamwise time-
mean velocities and Reynolds shear stresses are increased with the application of seepage.
This suggests that the downward seepage causes more momentum and energy transfer
towards the channel bed, causing sediment transport and lead to development of bedforms.
Increase in turbulent production and reduction in turbulent kinetic energy dissipation have
been observed, justifying the presence of greater roughness on the channel boundary after the
application of downward of seepage.

Statistical analysis was performed on the wavelet coefficients, which represents the bed
elevation fluctuation at different scales. Further, higher order statistical analysis shows
greater fluctuations in the elevation of bedform, as well as the presence of multi-fractal
properties, which have been described in terms of local roughness and intermittency parameters. We observed that channel bed became more inhomogeneous and rough after increasing the seepage discharge, showing greater resistance on the channel bed. The dimensionalized probability distribution functions of the bed elevation fluctuations tend to become wider after increasing the amount of seepage, indicating higher probability of larger fluctuation if the amount of seepage is increased. Logarithmic exceedance probability plots of the normalized positive bed elevation fluctuations shift upwards after increasing the seepage amount, signifying a higher probability of occurrence of larger bed elevation fluctuations. PSD analysis shows an increased slope of the power spectra indicating more inhomogeneous and rapid arrangement of bedforms in the case of increased seepage discharge.

Acknowledgements

Basic experimental data used in the paper or displayed in Figures or Tables can be obtained from any of the authors. We are very thankful to Professor Astrid Blom, Delft University of Technology for providing us with the bedform tracking tool. We also thank to Prof. Nihar Biswas for devoting his precious time and providing us with useful suggestions.

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List of Tables

Table 1. Uncertainty associated with the ADV data.

Table 2. A summary of experimental parameters.
List of Figures

Figure 1. Schematic diagram of experimental setup.

Figure 2. Investigation of Shields stress during no seepage run and seepage runs.

Figure 3. Distribution of time-mean velocities and Reynolds shear stresses against normalized depth for no seepage and with seepage runs. Where $u$ is time-mean velocity, $z$ is distance from bed, and $h$ is depth of flow.

Figure 4. Profiles of turbulent kinetic energy dissipation ($E_D$) and turbulent production ($T_P$) for no seepage and with seepage experiments.

Figure 5. Wavelet coefficients computed at 20 mm and 10 mm length scales from the bed elevation profile after 21 h run for 15% seepage.

Figure 6. Variation of statistical moments of the bed elevation increments as a function of length scale (a) after 9 h run for 15% seepage and (b) after 21 h run for 15% seepage. Changes in scaling exponent $\tau(q)$ obtained from the log-log linear regression within the scaling regime (c) after 9 h run for 15% seepage and (d) after 21 h run for 15% seepage.

Figure 7. Variation of statistical moments of the bed elevation increments as a function of length scale (a) after 9 h run for 20% seepage and (b) after 21 h run for 20% seepage. Changes in scaling exponent $\tau(q)$ obtained from the log-log linear regression within the scaling regime (c) after 9 h run for 20% seepage and (d) after 21 h run for 20% seepage.

Figure 8. Scale dependent pdf of dinemsionalized bed elevation increments (a) and (b) after 9 h and 21 h runs for 15% seepage (c) and (d) after 9 h and 21 h runs for 20% seepage.

Figure 9. Log-log exceedance probabilities of the normalized positive bed elevation increments (a) and (b) after 9 h and 21 h for 15% seepage (c) and (d) after 9 h and 21 h for 20% seepage.
Figure 10. Power spectral density versus wavenumber plots of bed elevations fluctuations (a) and (b) after 9 h and 21 h runs for 15% seepage (c) and (d) after 9 h and 21 h for 20% seepage experiment. x-axis denotes wave number (mm⁻¹) and y-axis denotes power spectral density.

Figure 11. Snapshots of the channel cross section after (a) no seepage run (b) 15% seepage run and (c) 20% seepage run (at the end of seepage experiment)
Table 1. Uncertainty associated with the ADV data

<table>
<thead>
<tr>
<th>Parameters</th>
<th>$u$ (m/s)</th>
<th>$v$ (m/s)</th>
<th>$w$ (m/s)</th>
<th>$(u'u')^{0.5}$ (m/s)</th>
<th>$(v'v')^{0.5}$ (m/s)</th>
<th>$(w'w')^{0.5}$ (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard deviation</td>
<td>$5.4 \times 10^{-3}$</td>
<td>$8.08 \times 10^{-4}$</td>
<td>$3.41 \times 10^{-4}$</td>
<td>$1.59 \times 10^{-3}$</td>
<td>$6.41 \times 10^{-4}$</td>
<td>$2.5 \times 10^{-4}$</td>
</tr>
<tr>
<td>Standard uncertainty</td>
<td>$1.7 \times 10^{-3}$</td>
<td>$2.56 \times 10^{-4}$</td>
<td>$1.08 \times 10^{-4}$</td>
<td>$0.5 \times 10^{-3}$</td>
<td>$2.03 \times 10^{-4}$</td>
<td>$0.8 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

Where $u$, $v$, and $w$ are the time-averaged velocities in the streamwise, lateral, and vertical directions, respectively. The quantities $u'$, $v'$, and $w'$ are the fluctuating components of the instantaneous velocities in the streamwise, transverse, and vertical directions respectively. The terms $(u'u')^{0.5}$, $(v'v')^{0.5}$ and $(w'w')^{0.5}$ are the root mean square values of $u'$, $v'$, and $w'$, respectively.

Table 2. A summary of hydraulic parameters

<table>
<thead>
<tr>
<th>Experimental run</th>
<th>Top width $B$, m</th>
<th>Maximum flow depth, $h$ m</th>
<th>Bed slope, $S$</th>
<th>Water surface slope, $S_w$</th>
<th>Inflow discharge, $Q_0$ m$^3$/s</th>
<th>Reynolds no.</th>
<th>Seepage discharge, $q_s$ (%$Q_0$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 1*</td>
<td>0.70</td>
<td>0.14</td>
<td>0.00116</td>
<td>0.000184</td>
<td>0.0175</td>
<td>21086.44-22920.04</td>
<td>15% and 20%</td>
</tr>
<tr>
<td>Run 2</td>
<td></td>
<td></td>
<td>0.00116</td>
<td>0.000151</td>
<td>0.0169</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Run 3</td>
<td></td>
<td></td>
<td>0.00249</td>
<td>0.000110</td>
<td>0.0161</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Sand size $D_{50} = 0.41$ mm, Froude no. for no seepage was 0.30 and for seepage case it was varied from 0.38 to 0.40.

Run used for analysing the flow and bedform characteristics.

Values of hydraulic parameters are given in the Table for no seepage runs where different percentages of seepage were applied without stopping the no seepage experiment.
Figure 1
\[ \theta = \frac{\tau}{\gamma} \] 

\[ R_* = \frac{u D}{\nu} \]
Figure 3

(a) Time-mean velocity, $u$ (m/s) vs. dimensionless depth, $z/h$

(b) Reynold shear stress, $-u'w'$ (m$^2$/s$^2$) vs. dimensionless depth, $z/h$
Figure 4.
Figure 5
Figure 6
Figure 7
Figure 8
Figure 9
Figure 10
Figure 11