Hydrodynamic characterization of mountain river flow: influence of bed hydraulic conductivity

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Abstract

The general objective of this dissertation is to study the effect of the hydraulic conductivity on near bed turbulent flows of viscous fluids over mobile and hydraulically rough beds of cohesionless sediment. In order to fulfill this objective, experimental tests performed in high conductivity beds (mono-sized glass sphere beads) are compared with the existing database of low conductivity beds of Ferreira et al. (2012), keeping constant the range of values of porosity, Shields parameters and roughness Reynolds numbers. The hydraulic conductivity is varied by changing the tortuosity (and the dimensions of the pore paths) and not the porosity, which results in an absolutely novel study. The database of Ferreira et al. (2012) is composed of mean-flow and turbulence quantities, obtained from an original Laser Doppler Anemometry (LDA) database. A new database of instantaneous velocities was acquired with Particle Image Velocimetry (PIV) and processed to gather time-averaged velocities and space-time averaged (double-averaged) quantities, namely velocities, Reynolds stresses and form-induced stresses. The hydraulic conductivity was measured for both types of bed. The experimental work was carried out in the Laboratory of Hydraulics and Environment of the Department of Civil Engineering and Architecture. This thesis specifically investigates the effects of hydraulic conductivity on the parameters of the log-law that is thought to constitute a valid model for the flow in the overlapping region of fully developed hydraulically rough boundary layers over mobile cohesionless beds. In the range of investigated Shields parameters, the bed mobility varies. The joint effect of hydraulic conductivity and bed mobility is explicitly addressed. The parameters of log-law obtained from high conductivity flows are compared with those of existing low conductivity flows, for mobile and immobile bed conditions. The main findings can be summarized as follows: i) hydraulic conductivity does not affect the location of the zero plane of the log-law, the thickness of the region above the crests where the flow is determined by roughness, ii) increase of hydraulic conductivity does not appear to decrease bed roughness parameters, iii) higher hydraulic conductivity is associated to a structural change: higher near-bed velocity and higher shear-rate in the inner region. In dimensional terms this means a same friction velocity, \( u_\tau \), is achieved with a flow with larger mass rate, thus a lower friction factor \( \left( \frac{u_\tau}{\nu} \right)^2 \) and iv) so flows over high conductivity beds appear drag-reducing even if roughness parameters do not change appreciably.

Keywords: mountain rivers, hydraulic conductivity, log-law, bed load transport, PIV, Double-Averaging Methodology.

1. INTRODUCTION

Gravel-bed rivers play an important ecological role as they provide habitat for fauna and flora. The detailed description of the structure of the near-bed turbulent flow is an essential aspect for the understanding the overall river dynamics. The effect of the macroscopic properties of bed morphology and the effect of the hyporheic region flow are of paramount importance to characterize the flow in the near bed and, in general, the inner flow layer. Not many studies addressed the issue of the influence of hyporheic/subsurface interactions. This thesis addresses this knowledge gap.

This paper will be mostly concerned with the effect of the hydraulic conductivity on near bed turbulent flows of viscous fluids over mobile and hydraulically rough beds of cohesionless sediment. In particular, this thesis seeks: i) to characterize the parameters of log-law for high hydraulic conductivity bed, ii) to discuss the differences observed in the log-law parameters between high and low conductivity beds and iii) to discuss the combined effects of bed mobility and hydraulic conductivity on the flow variables.
2. STATE OF THE ART

2.1. Physical system

The rough bed flow has similar flow properties to smooth boundary flow, at least at the distance from bed sufficiently greater than the roughness height but near-bed flow properties are different. In rough bed flow, Nikora et al. (2001) revised the Nezu and Nakagawa (1993) flow layers with specific reference to the double-averaging methodology (DAM) to overcome the uncertain intuitive approach of time-averaged momentum equations. The flow region in permeable rough bed is divided into five layers namely: outer layer, logarithmic layer, form-induced sublayer, interfacial sublayer and subsurface layer. These flow regions are subdivided to account the additional terms and variables in different flow regions. Ferreira et al. (2008) idealized the flow layer in mobile rough bed region based on the stresses and forces acting upon the flow that are dominant at each layer.

Ferreira et al. (2012) divide idealized open channel flow into four regions namely outer, inner, pythmenic and hyporeic region represented in Figure 1. There may be an overlap between every two adjacent regions as the phenomena that characterize each region do not cease to exist abruptly. In overlapping region between the outer and inner region, the longitudinal flow velocity will be logarithmic considering wall similarity in the sense of Townsend (1976).

![Figure 1- Idealized bed configuration (adapted from Ferreira et al., 2012)](image)

In idealized physical system shown in figure 1, \( Z_k \) is the elevation of the free-surface, \( Z_c \) and \( Z_q \) are the space-averaged elevations of the planes of the crests and of the lowest bed troughs respectively. \( Z_b \) is the plane below which there is no relevant vertical momentum transfer. \( Z_b \) is the boundary zero and if the bed amplitude is small, coincides with \( Z_c \). All elevations are relative to an arbitrary datum. The remaining variables are identified in the text.

2.2. Parameters of logarithmic law

The friction velocity \( u_* \) is the one of the variables of universal velocity logarithmic law (equation 1). It’s the most fundamental velocity scale which normalizes both mean velocity and turbulence stresses. According to Nezu and Nakagawa (1993), \( u_* \) determined from the measured Reynolds shear stress distribution \(-\overline{\tau_{xy}}(z)\) in conjunction with direct measurement of wall shear stress with instruments is most appropriate in turbulence research because direct measurement is obtain theoretically and Reynolds stress itself is turbulence quantity.

\[
\frac{\overline{u}}{u_*} = \frac{1}{\kappa} \ln \left( \frac{z - \Delta}{k_s} \right) + B
\]

where \( \overline{u} \) is double-averaged longitudinal velocity, \( u_* \) is the friction velocity which sometimes refers as shear velocity, \( z = Z - Z_0 \) is the coordinate normal to the bed above the elevation of the zero reference plane for the logarithmic law, \( Z_0 \) (herein zero for the log-law), \( Z \) is the coordinate normal to the bed above an arbitrary datum, \( \kappa \) is von Kármán constant, \( \Delta \) is displacement height, \( k_s \) is geometric roughness scale relative to bed troughs and \( B \) is the normalized flow velocity\((\overline{u})/u_*\).

The displacement height \( \Delta \) and geometric roughness scale \( k_s \) are the adjusting parameter to ensure best fit between log-law and lower boundary of inner region. \( \Delta \) can be above or below boundary zero (Ferreira et al., 2012). The universality of von Kármán constant \( \kappa \) has been topic of debates for last few decades. Authors like Dittrich and Koll (1997) argued that \( \kappa \) equal to 0.405 should be observational one and not theoretical result. Contradictory to Song et al. (1998) and Calomino et al. (2004a; 2004b) view of considering \( \kappa \) as constant equal to Nikurade clear-water roughness value 0.4, Gaudio et al. (2010) claimed \( \kappa \) should be derived from inner region velocity log-laws because it varies in the presence of bed load, suspended load and low submergence. In open-channel flows with bed load, \( \kappa \) mainly decreases with the sediment volumetric concentration (Gaudio et al., 2011). The Ferreira et al. (2012) revealed that the value of \( \kappa \) can be adjusted to both flow independent(\( \kappa = 0.4 \)), fitting log-law above the lowest bed troughs and flow dependent through choice of other parameters like \( \Delta \), \( k_s \) and boundary zero. Later, Ferreira (2015) studied the nature of \( \kappa \) theoretically, considering three scenario: no similarity, complete and incomplete similarity in dimensional parameters that describe bed composition and bed mobility. In no similarity, vertical distribution of longitudinal velocity would not be logarithmic. In complete similarity, \( \kappa \) doesn’t imply constant for rough mobile bed although it is constant in case of mobile bed. In incomplete similarity, \( \kappa \) should be determined as actual functional dependence of bed composition together with \( \Delta \). Several authors (Gust & Southard, 1983; Bennett & Bridge, 1995; Bennett et al., 1998; Nikora & Goring, 1999; Gallagher et al., 1999; Dey & Raikar, 2007) reported a decrease in \( \kappa \) from its universal value due to the bed mobility. Owen (1964) postulates the roughness height, \( Z_0 \) increases with saltation height as it include the momentum sink due to particle movement. Similarly, Dey et al. (2012) also found an increase in \( Z_0 \) and
k_s of log-law parameters in the presence of bed load transport.

2.3. Turbulence intensities

Turbulence is ubiquitous and represents a fundamental engine of transport, spreading, mixing and geomorphological evolution. It’s in particular the main sink for riverine flow total energy (Franca & Brocchini, 2015). Large turbulent eddies are responsible for the conversion of total flow energy into turbulent energy and it’s navigated by viscosity after it becomes small through break down. The fluctuation variables of hydrodynamic equation due to turbulence are based on division of mean and fluctuating component of Reynolds decomposition (Monin & Yaglom, 1971; Frisch, 1995; Pope, 2000). The structural characteristics associated with the time and space heterogeneity of flow are responsible for fluid fluctuation properties like secondary currents and large scale-vortices (Nikora & Roy, 2012; Abad et al. 2013; Proust et al. 2013, among others).

Authors like Cardoso et al. (1989), Nezu and Nakagawa (1993) and Graf (1994) among others produce enough literature on the Reynolds stress tensor components and turbulent kinetic energy of hydraulically smooth beds to provide good result for uniform flow. Nezu and Nakagawa (1993) clearly explained mean velocity distribution and turbulence structure above the bed roughness in open channel without bed load. For hydraulically rough bed, the vertical distribution on turbulence quantities is locally dependent on the bed forms below the height where the influence of bed is felt and inner region of flow correspond to roughness layer (Nikora & Smart, 1997; Smart, 1999; Nicholas, 2001; Franca, 2005b; Franca & Lemmin, 2006b, among others). The underlying mechanisms of flow in terms of interactions of transported particles with the fluid and those with the beds are different for mobile and immobile bed (Dey et al., 2012).

There is uncertainty regarding effect of bed load transport on mean flow and turbulence since relatively few studies are focused on it. Vanoni and Nomicos (1960) studied effect of bed load transport only taking sediment transport in suspension concluding damping of turbulence intensity leading to reduction of flow resistance due to suspended sediment. Contradictorily, Muller (1973) found the increment of turbulence intensity in the presence of mobile sediment, although there was suspended as well as bed load transport. This apparent contradiction is echoed in bed-load studies. Bed-load interact both with flow and bed, where flow accelerate but bed decelerate causing the bed-load to rest. Owen (1964) and Smith and McLean (1977) postulated near-bed momentum deficit and reduction of longitudinal velocity due to bed-load collisions exacting kinetic energy from mean flow. Coherently many researchers concluded in general, the flow resistance increases due to addition of bed-load (Gust & Southard, 1983; Wang & Larsen, 1994; Best et al., 1997; Song & Chiew, 1997). Carbonneau and Bergeron (2000) found that the bed load transport causes reduction of turbulence and an increase of mean flow velocity. Campbel et al. (2005) obtained relatively constant form induced stress for both fine and coarse bed in lesser bed-load. On increasing bed-load, it’s reduced by 50% and mean longitudinal flow velocities at any given depth were lower than their no bed-load counterparts. Similarly, Dey et al. (2012) concluded that the momentum provided by the flow to the bed load for overcoming the bed resistance leads to reduction of Reynolds shear stress magnitude over entire flow depth. The diminishing level of turbulence resulting from fall in magnitude of flow velocity relative to velocity of bed load transport lead to damping of Reynolds shear stress near bed. This leads to a reduction of mobile-bed flow resistance and friction factor.

3. THEORETICAL METHODOLOGY

3.1. Conceptual framework

The Double-Averaging Methodology (DAM) is the process by which the fundamental flow equations are averaged in both temporal and spatial domains. Nikora et al. (2007b) mentioned that to resolve the problem to study rough–bed flow, supplementing the time-averaging which is highly three-dimensional and heterogeneous with spatial-averaging of parameters is the solutions.

The spatial averaging on time derivative is different for the flow below (z < z_c) and above (z > z_c) the roughness crests. The Reynolds decompositions for instantaneous and time-average variables are shown in equation (2) and (3).

\[ \theta = \bar{\theta} + \theta' \]  
\[ \text{And } \bar{\theta} = (\bar{\theta}) + \tilde{\theta} \]

The wavy overbar denotes the spatial fluctuation in time-average variable and \( \theta \) is time-average flow variable (i.e. velocity and pressure). The flow above the roughness crests (z > z_c) in which \( \Theta_a = 1 \), Double-averaged Navier-Stokes (DANS) equations for momentum conservation is given by substituting equation (2 & 3) into Reynolds-averaged Navier-Stokes (RANS) equations as

\[ \frac{\partial \langle \bar{u}_i \rangle}{\partial t} + \langle \bar{u}_j \rangle \frac{\partial \langle \bar{u}_j \rangle}{\partial x_i} = \bar{g}_i - \frac{1}{\rho^{(w)}} \frac{\partial \langle \bar{p} \rangle}{\partial x_i} - \frac{\partial \langle \bar{u}_i' \bar{u}_j' \rangle}{\partial x_j} \]

\[ \frac{\partial \langle \bar{u}_i \rangle}{\partial x_i} + \nu^{(w)} \frac{\partial^2 \langle \bar{u}_i \rangle}{\partial x_i \partial x_j} \]  

Analogously like additional term in RANS from NS, there is additional term in DANS compared to conventional RANS equation. It is form-induced stress \( \langle \bar{u}_i \bar{u}_j \rangle \) which is due to spatial variations in time-averaged fields.

For the flow below the roughness crests (z < z_c), where\( \Theta_a < 1 \), DANS equation for momentum conservation is given by:

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\[
\frac{\partial (\bar{u}_t)}{\partial t} + (\bar{u}_t) \frac{\partial (\bar{u}_t)}{\partial x_i} = g_i - \frac{1}{\rho^{(w)}} \frac{\partial (\bar{p})}{\partial x_i} - \frac{\partial (u^{(w)}_t)}{\partial x_i} - \frac{1}{\sigma} \frac{\partial \bar{u}_t}{\partial x_i} + v^{(w)} \frac{\partial^2 (\bar{u}_t)}{\partial x_i \partial x_j}
\]

[5]

Similarly in this equation too, there is two additional term compared to equation (4). They are form drag \(\frac{1}{\rho^{(w)}} \frac{\partial (\bar{p})}{\partial x_i}\) and viscous drag \(v^{(w)} \frac{\partial^2 (\bar{u}_t)}{\partial x_i \partial x_j}\) which appeared due to pressure variations around individual roughness elements.

3.2. Methods of calculation of the parameters of log-law

The method of log-law parameters calculation is based on Ferreira et al. (2012) method on mono-sized glass beads bed configurations. Ferreira et al. (2012) computed the log-law parameters for water-worked beds of poorly sorted mixtures of sand and gravel.

The flow independent von Kármán constant, \(\kappa\) is giving irrelevant results so we compute parameters of log-law based on following two scenarios:

Scenario (sA): The boundary zero is set at the elevation of crests \((z_0 = Z - Z_c)\). The friction velocity is called from measured bed shear stress. The \(\kappa\) is considered non universal but the fitting parameter and the roughness scale \(k_s\) and the normalized flow velocity, \(B\) are subjected to fitting procedures.

Scenario (sB): This scenario is similar to scenario sA except \(\kappa\) is considered constant \(\kappa = 8.5\). The \(k_s\) scale is computed through roughness law

\[
d (\bar{u}_t) = \frac{1}{u_*} \ln \left( \frac{z - \Delta}{k_s} \right) + B
\]

[7]

Where, \(z_* = \frac{z - \Delta}{k_s}\). The value \(B\) is adjusted by lower bound \(k_s\) through \(z_*\) in equation (7). The \(k_s\) computed above is scale of roughness scale relatively to boundary zero and not zero of log-law so it’s actually \(k_s\). Subtraction of displacement height from above \(k_s\) value will give real \(k_s\). Once \(k_s\) and \(B\) is confirmed, the roughness height \(z_0\) is computed from equation (8).

\[
z_0 = k_s e^{-\kappa x_B}
\]

[8]

In scenario sB, the displacement height \(\Delta\) and von Kármán constant \(\kappa\) are retrieved with same procedure illustrated in scenario sA. The \(B\) is considered constant i.e. \(B = 8.5\). The roughness scale is computed through roughness law

\[
k_s = z_0 e^{\kappa x_B}
\]

[9]

The log-law is now written in the form shown in equation (10) to apply the roughness law.

\[
\frac{d (\bar{u}_t)}{dz} = \frac{1}{\kappa} \ln \left( \frac{z - \Delta}{k_s} \right) + B
\]

[10]

The \(z_0\) positions the velocity profile vertically. Plotting both \(\frac{d (\bar{u}_t)}{dz}\) and \(\frac{1}{\kappa} \ln \left( \frac{z - \Delta}{z_0} \right)\) with respect to \(z\) adjusting \(z_0\) to fit \(\frac{d (\bar{u}_t)}{dz}\) and \(\frac{1}{\kappa} \ln \left( \frac{z - \Delta}{z_0} \right)\) together. Once the best \(z_0\) is found, equation (9) compute back the \(k_s\).

4. LABORATORY FACILITIES, INSTRUMENTATION AND EXPERIMENTAL PROCEDURES

4.1. overview

Five new experimental tests were performed in the recirculating tilting flume (CRIV) in the Laboratory of Hydraulics and Environment of Instituto superior Técnico (IST). The purpose of these tests was to build an experimental database of instantaneous velocities from which mean flow and turbulence quantities could be derived and compared with the existing database of Ferreira et al. (2012). The two databases were obtained in similar flumes.

The different features should highlight the role of hydraulic conductivity. In particular, it was intended that the new databases would be obtained for a granular bed with higher hydraulic conductivity or, in what concerns the classification of the granular bed, higher permeability.
### 4.2. Instrumentation

Particle Image Velocimetry (PIV) is the newest entrant to the field of fluid flow measurement and provides instantaneous velocity fields over global domains. The PIV system used in this experimental work is composed of: i) laser head and lens, ii) power supply or laser beam generator, iii) CCD camera (charge-couple device), iv) timing unit and v) acquisition and control software. The PIV system used in this project was operated with a sampling rate of 15 Hz and its power source is able to generate a pulse of energy of 30 mJ. The whole systematic component of PIV is shown in Figure 2.

![Figure 2 - Depicts a schematic representation of a PIV system with all its components.](image)

In the present experiment, it was started with wide IA size (128 x 128 px²) to get approximated flow and its direction. It was ended with smaller IA (16 x 16 px²) to get better estimation of the velocity flow field and its correct displacement after 3 iterations on correlation process. This choice intended to maximize the spatial resolution of the velocity field. An overlap of the 50% was considered for validations. The time between the pulses, Δt was imposed in the range of 350 – 500 μs, satisfying the general displacements around 25% of the dimension of the final IA. The quantity of seeding was chosen based on final IA size after imposing the time between pulses to have enough seeding particles.

In present experiment, the artificial seeding called Decosoft 60 which is polymerized material with density 1.31 g/cm³ is used. This artificial seeding has an average size of 60 μm in a range from 50 to 70 μm. It is a white material with round shaped particles and its chemical composition consists of 73% polyurethane and 27% of titanium dioxide.

### 4.3. Characterization of experiments

All experiments were done in the same flume bed reaches made up of fixed-bed and mobile-bed. A fixed-bed comprises of 1.5 m of large boulders (50 mm average diameter), followed by 3.0 m of smooth bottom (PVC) and 2.5 m of one layer of glue mono-sized spherical glass beads (5.0 mm diameter) to ensure the development of a rough-wall boundary layer. A spherical beads of 4.0 m long and 2.5 cm deep made mobile reach.

Five tests were carried out in nearly-uniform subcritical flow or quasi-uniform steady flows. The channel is sufficiently wide enough to avoid the side-wall friction. The turbulent boundary layer is fully developed over an irregular, porous, mobile bed composed of cohesionless particles and suspended load is absent. After certain elapse of time, the bed texture becomes time-invariant and uniform in longitudinal direction. Tests were performed increasing the bed-load rate. Test 1 is performed under sub-threshold conditions (no beads moving), while Test 2, 3, 4 and 5 has bed-load rate of 0.33, 6.23, 21.12 and 28.72 beads/sec respectively. All the flow variables are shown in Table 1.

<table>
<thead>
<tr>
<th>Test</th>
<th>(Q) (m³/s)</th>
<th>(I)</th>
<th>(h_i) (m)</th>
<th>(\bar{u}) (m/s)</th>
<th>(R_h) (m)</th>
<th>(\tau_0^{(1)}) (N/m²)</th>
<th>(\nu_0^{(2)}) (N/m)</th>
<th>(n) (beads/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.01498</td>
<td>0.0037</td>
<td>0.0714</td>
<td>0.0181</td>
<td>0.0528</td>
<td>1.6393</td>
<td>0.00405</td>
<td>0.00</td>
</tr>
<tr>
<td>2</td>
<td>0.01590</td>
<td>0.0040</td>
<td>0.0703</td>
<td>0.0588</td>
<td>0.0528</td>
<td>2.0666</td>
<td>0.0455</td>
<td>0.33</td>
</tr>
<tr>
<td>3</td>
<td>0.01667</td>
<td>0.0045</td>
<td>0.0686</td>
<td>0.0616</td>
<td>0.0511</td>
<td>2.2872</td>
<td>0.0478</td>
<td>6.23</td>
</tr>
<tr>
<td>4</td>
<td>0.02083</td>
<td>0.0062</td>
<td>0.0744</td>
<td>0.6914</td>
<td>0.0944</td>
<td>3.2923</td>
<td>0.0577</td>
<td>21.12</td>
</tr>
<tr>
<td>5</td>
<td>0.002135</td>
<td>0.0071</td>
<td>0.0696</td>
<td>0.7574</td>
<td>0.0516</td>
<td>3.6290</td>
<td>0.0602</td>
<td>28.72</td>
</tr>
</tbody>
</table>

The flow variables in Table 1 are the flow rate Q, the slope i, the uniform flow height \(h_i\), the longitudinal velocity \(\bar{u}\) and the hydraulic radius \(R_h\). The bed shear stress is computed from equation of conservation of momentum in longitudinal direction as \(\tau_0^{(1)} = \gamma R_h i\). The hydraulic radius \(R_h\) is used instead of \(h_i\) to include the effect of side-wall friction expressed in kinematic terms. \(\gamma\) and \(i\) are specific weight and slope of channel respectively. And subsequently friction velocity is computed from bed shear stress as follow:

\[
\bar{u}_*^{(1)} = \sqrt{\frac{\tau_0^{(1)}}{\rho}}.
\]

Where, \(\rho = 1000\ \text{kg/m}^3\) is the density of fluid, water. Although these method is simple and generally used, but it’s not adequate for characterizing turbulent flow since it gives overall value rather than local one with channel bed and water surface dependent accuracy. Therefore Nezu and Nakagawa (1993) recommend to evaluating \(\bar{u}_*^{(2)}\) from measured Reynolds shear stress distribution since Reynolds stress itself is a turbulence quantity. \(\tau_0^{(2)}\) is measured bed shear stress which is sum of Reynolds shear stress and form induced stress. The values obtain through this method for the experimental tests are represented in Table 2.

<table>
<thead>
<tr>
<th>Test</th>
<th>(\tau_0^{(2)}) (N/m²)</th>
<th>(\bar{u}_*^{(2)}) (N/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.6033</td>
<td>0.0400</td>
</tr>
<tr>
<td>2</td>
<td>2.1800</td>
<td>0.0467</td>
</tr>
<tr>
<td>3</td>
<td>2.1867</td>
<td>0.0468</td>
</tr>
<tr>
<td>4</td>
<td>3.0800</td>
<td>0.0555</td>
</tr>
<tr>
<td>5</td>
<td>3.2233</td>
<td>0.0568</td>
</tr>
</tbody>
</table>
The non-dimensional variables which characterize the flow shown in Table 3 are Froude number \( F_r = U/\sqrt{gh_u} \), Reynolds number \( R_e = Ud/\nu(w) \), bed Reynolds number \( R_{e_\text{b}} = u^2/\nu(w) \), shield parameter \( \theta = \frac{(2)}{(s-1)pgd} \), and the non dimensional bed load discharge \( \Phi = \frac{q_u}{\sqrt{(s-1)gd^3}} \). Where, \( g \) is acceleration due to gravity, \( \nu(w) \) is kinematic viscosity of water, \( d \) is diameter of bed material, \( s = \rho^{(s)}/\rho \) is the specific gravity of the sediment particles and \( \rho^{(s)} = 2607 \text{ kg/m}^3 \) is the density of bed material. The bed load discharge rate is evaluated as \( q_u = Vb/B \), where volume of glass beads \( V \) is \( 6.545 \times 10^{-8} \text{ m}^3 \), \( b \) is number of beads counts per second and \( B \) is width of flume.

Table 3-Non-dimensional parameters characterizing experimental tests

<table>
<thead>
<tr>
<th>Test</th>
<th>( F_r )</th>
<th>( R_e )</th>
<th>( R_{e_\text{b}} )</th>
<th>( \theta )</th>
<th>( \Phi )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.6191</td>
<td>41405.58</td>
<td>224.07</td>
<td>0.0203</td>
<td>0.0E+00</td>
</tr>
<tr>
<td>2</td>
<td>0.6725</td>
<td>43938.73</td>
<td>261.28</td>
<td>0.0277</td>
<td>3.8E-05</td>
</tr>
<tr>
<td>3</td>
<td>0.7345</td>
<td>46057.37</td>
<td>261.68</td>
<td>0.0277</td>
<td>7.2E-04</td>
</tr>
<tr>
<td>4</td>
<td>0.8093</td>
<td>57571.72</td>
<td>310.56</td>
<td>0.0391</td>
<td>2.4E-03</td>
</tr>
<tr>
<td>5</td>
<td>0.9166</td>
<td>58999.50</td>
<td>317.71</td>
<td>0.0409</td>
<td>3.3E-03</td>
</tr>
</tbody>
</table>

The data collected from experimental tests are compared with existing database of Ferreira et al. (2012), where 17 subcritical and nearly uniform flow experiment test were conducted. All the variables are computed using same formula as above experiment. \( d_{84} \) of bed substrate (below the lowest bed troughs) is used as variable diameter in all formulas. The existing database tests differ from experimental tests in terms of macroscopic properties such as hydraulic conductivity, permeability and tortuosity. The initial bed composition varies among database tests itself. The tests type E are gravel-sand mixture, type T are gravel mixture and type D are type E bed subjecting to water-work till armouring level. The bed composition of both experimental tests and existing database are shown in Figure 3.

The hydraulic conductivity for both new and existing database are obtained experimentally in hydraulic lab at IST. Once hydraulic conductivity is obtained, the parameters \( k \) and \( \tau \) are calculated using equation 11-12. All the parameters are shown in Table 4.

\[
k = \frac{K \mu}{\rho g}
\]

\[
\tau = \frac{n^3}{36cK(1-n)^2d^2p}
\]

Table 4-Macroscopic properties of new and existing database

<table>
<thead>
<tr>
<th>Tests</th>
<th>high conductivity bed</th>
<th>low conductivity bed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>New database</td>
<td>Existing database</td>
</tr>
<tr>
<td>( d_{84} ) (mm)</td>
<td>4.97</td>
<td>5.40</td>
</tr>
<tr>
<td>( \rho ) (kg/m(^3))</td>
<td>2607</td>
<td>2590</td>
</tr>
<tr>
<td>( n ) (-)</td>
<td>0.325</td>
<td>0.301</td>
</tr>
<tr>
<td>( T ) (-)</td>
<td>0.88</td>
<td>9.96</td>
</tr>
<tr>
<td>( k ) (m(^2))</td>
<td>3.E-08</td>
<td>3.E-10</td>
</tr>
<tr>
<td>( K ) (m/s)</td>
<td>3.E-01</td>
<td>4.E-03</td>
</tr>
</tbody>
</table>

5. RESULTS AND DISCUSSION

5.1. The double-average (DA) quantities

a. Mean velocities

It’s evident from Figure 4, the logarithmic layer starts from crest of spherical beads, \( z/h \approx 0 \). There is increment of longitudinal velocity with increasing the bed load which is due to increasing flow and not of bed load increment. There is no particular trend in the case of vertical velocity with respect to bed load.

![Figure 4- Double-average instantaneous longitudinal velocity profiles](image)

b. 2\(^{nd}\) order moments

The second order moments of the high conductivity bed flows are analyzed. The form-induced stresses decrease with...
sediment transport since the drag on moving particles acts as a sink of momentum. The double-averaged Reynolds shear stresses are seen increasing with increase in bed load transport. The bed shear stresses are also increasing with increase of bed load transport due to increment of Reynolds shear stresses (Figure 5). The raise in value of Reynolds shear stresses is essentially due to increase of velocity. The increase velocity promotes higher drag on the roughness element and consequently rising shear velocity, u, and bed micro-topography. The thickening of bed micro-topography due to additional beads increases the drag force raising the bed shear stresses.

5.2. Discussion of log-law parameters

a. Log-law parameters of new database
The overview plots of scenario sA is shown in figure 7 and 8 while for scenario sB is shown in figure 9.

![Figure 5-Bed shear stresses](image)

Figure 5-Bed shear stresses

![Figure 7- Double-Average longitudinal velocity profiles and regression lines for scenario sA](image)

Figure 7- Double-Average longitudinal velocity profiles and regression lines for scenario sA. The lower bound of regression lines is marked with Red-dash line for all tests. The upper bound are marked with black-solid line (Test 1), black-dashed line (Test 2), black-dotted line (Test 3), black-dash-dot line (Test 4) and blue-solid line (Test 5)

![Figure 8- Double-Average longitudinal velocity profiles and theoretical velocity for scenario sB](image)

Figure 8- Double-Average longitudinal velocity profiles and theoretical velocity for scenario sB

The parameters of log-law computed through each scenario are presented in Table 5 and 6. The parameter k_{sA} is introduced to make it uniform with existing database of Ferreira et al (2012). It is roughness scale relatively to bed troughs.

<table>
<thead>
<tr>
<th>Test</th>
<th>( \Delta ) (m)</th>
<th>k_{sA} (m)</th>
<th>( \kappa ) (-)</th>
<th>( Z_0 ) (m)</th>
<th>B (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.00014</td>
<td>0.00620</td>
<td>0.349</td>
<td>0.00019</td>
<td>8.65</td>
</tr>
<tr>
<td>2</td>
<td>-0.00156</td>
<td>0.00590</td>
<td>0.324</td>
<td>0.00036</td>
<td>8.08</td>
</tr>
<tr>
<td>3</td>
<td>0.00139</td>
<td>0.00650</td>
<td>0.361</td>
<td>0.00011</td>
<td>8.81</td>
</tr>
<tr>
<td>4</td>
<td>0.00083</td>
<td>0.00770</td>
<td>0.366</td>
<td>0.00016</td>
<td>8.96</td>
</tr>
<tr>
<td>5</td>
<td>0.00255</td>
<td>0.00870</td>
<td>0.371</td>
<td>0.00014</td>
<td>8.81</td>
</tr>
</tbody>
</table>

Table 5- Parameters describing log-law for scenario sA
b. Comparison between database and discussion

Ferreira et al. (2012) proposed three scenarios to interpret the log-law parameters assuming the wall similarity in the sense of Townsend (1976) is valid. In scenario s1, the boundary zero is set at the elevation of lowest troughs, \( u_c \) expresses the momentum transmitted to the bed troughs, von Kármán constant is assume flow independent i.e. \( \kappa = 0.4 \), roughness scale \( k_z \) and normalized flow velocity \( B \) is subjected best fit procedure. In scenario s2, the boundary zero is set at the elevation of crest, \( u_c \) expresses the momentum flux at the elevation of crests, both \( \kappa \) and \( B \) is assume constant as value 0.4 and 8.5 respectively and \( k_z \) is computed from roughness function. In scenario s3 is similar to s1 except the universality of \( \kappa \) value which is not fitting parameter. The roughness scale \( k_z \) is defined as the lowest height above the zero of the log-law for which the velocity profile is logarithmic.

None of the scenarios are exactly same with the scenario defined in section 3.2. Nevertheless, the bed is not very thick, so the differences in the definition \( u_c \), can be ignored. Since in scenario s2 and sB, the roughness scale \( k_z \) is computed from roughness function, therefore, scenario s2 is compared with scenario sB. Likewise scenario s3 is compared with scenario sA since both these scenario obtain the roughness scale \( k_z \) from actual region on plot of log-law.

In the following sections, the individual parameters of log-law will be discussed based on the difference between the high and low hydraulic conductivity beds of tests. The high conductivity bed are represented with purple star while low conductivity bed type E, D and T are represented by black filled diamond, black open diamond and open circles respectively. All the parameters are represented as function of relative Shields number. Since Shield number means different in water-worked gravel bed and granular bed in the sense it’s easier to dislodge granular bed than the mixture of gravel bed of same size diameter. With the same force, it’s even more difficult to dislodge the gravel bed particles in centre than in side wall. The relative Shield parameters are Shield parameters of tests after subtraction of reference Shield parameters. The reference Shield parameter is the Shield parameters in which bed-load discharge is very low. Here on, the experimental tests database will be called high conductivity bed while existing database of Ferreira et al. (2012) will be called low conductivity bed.

Displacement height \( \Delta \)

The figure 10 discusses how much above or below the plane of the troughs, the plane of log-law is. Only scenario sA-s3 is shown since scenario sB-s2 is similar to this scenario.

![Figure 9-Variation of the displacement height normalized with median diameter of substrate as a function of relative Shields number](image)

From Figure 9, for both scenarios, it is evidently shown that in tests on high conductivity bed with low relative Shields number, the displacement heights are below zero of log-law \( z_0 \) and in low conductivity beds, the displacement height is rarely negative. When there is no much bed load transport, it appears that the \( \Delta/d_{50}^{(ab)} \) nearly uniform at the plane of crest (figure 9, left of vertical line) but highly scattered when bed load transport increases. Nevertheless the tests with higher bed morphology diversity or higher bed load transport will have log-law higher above the plane of the crests. In both case of conductivity, apparently there is no definite trend in \( \Delta/d_{50}^{(ab)} \) with respect to relative Shields number. The zero plane of the log-law is not dependent of hydraulic conductivity.

von Kármán constant \( \kappa \)

Contrarily to Ferreira et al. (2012) there was no possibility to adjust a theoretical curve with von Kármán constant \( \kappa \) approximately 0.4. Figure 10 clearly shows that the high conductivity bed has \( \kappa \) values consistently below the low conductivity beds. This indicates that higher conductivity leads to lowering of von Kármán constant \( \kappa \). This indicates that higher conductivity may lead to a change in turbulence structure in the inner region (Ferreira 2015). The velocity profile of new database is indeed different. It has larger shear-rate in the inner region, for the same friction velocity. This database also indicates that \( \kappa \) may be higher at higher transport rate.
Variation of the von Kármán constant as a function of relative Shields number

**Geometric roughness scale** $k_{sA}$

The parameter $k_{sA}$ is the geometric roughness scale relatives to bed troughs in both cases (term different notation to highlight that it refers same in both older database of lower hydraulic conductivity and present data of higher conductivity). This figure discusses the thickness of the layer where roughness effects are predominant.

In high conductivity bed, the total thickness of roughness is lower than in low conductivity bed as clearly seen in both scenarios in Figure 12. The $k_{sA}/d_{84}$ ratio is seen increasing with increase in relative shield parameter so it appears the sediment transport rate increases the total thickness of roughness.

The comparison between figure 11 (top) and figure 12, it appear that the differences between high conductivity and low conductivity are smaller if $k_{sA}$ normalized with $d_{84}$. This shows the influence of conductivity but also of bed micro-topography.

In high conductivity bed, the total thickness of roughness is lower than in low conductivity bed. However, note that the thickness of the bed is lower for the higher conductivity beds. So, the effects of the roughness above the plane of the crests extend for the same distance approximately. In other words, even if the bed is thinner, the scale of the roughness above the crests is of the same magnitude.

**Roughness height $z_0$ and Normalized flow velocity $B$**

The Figure 13 discusses the concept of roughness height. It is related to the shearing of the log-law near the crests.

There is no clear trend of increment of $z_0$ with respect to Shield parameter in both high conductivity and low conductivity bed from Figure 13 as well as figure 14. It is seen that roughness of sand-gravel bed (represented with black filled diamond) lower than gravel bed (represented with open circle). This undoubtedly convinced that addition of sand smoothen the bed in line with Ferreira et al. (2012).
Figure 13 and 14 indicate conductivity does not appear to change the roughness height and as the results, the high conductivity bed has roughness height similar to the gravel bed of low conductivity in both figures.

Figure 13-Variation of the roughness height normalized with median diameter of substrate as a function of relative Shields number

Figure 14-Variation of the roughness height normalized with diameter of spherical beads (for all tests) as a function of relative Shields number

In Scenario s2 in Figure 15 (top), the \( z_0/k_s \) ratio represents the classical value 0.033 of (Nikuradse, 1933) since it is retrieved with \( \kappa = 0.4 \) and \( B = 8.5 \). Scenario sB is seen decreasing with increase of relative Shields number due to increasing value of \( \kappa \) from the equation (13).

\[
\frac{z_0}{k_s} = e^{-\kappa B} \tag{13}
\]

In scenario SA-S3, the high conductivity bed has the same ratio as the gravel low conductivity bed. This shows that \( B \) is larger in the high conductivity bed, compensating a smaller \( \kappa \). Together they express a larger mass flux for the same friction velocity and explain the lower critical movement conditions in high conductivity beds. The presence of moving sand appears to render the bed smoother even if conductivity is low.

6. CONCLUSIONS AND FUTURE WORK

The parameters of log-law obtained from high conductivity flows are compared with those of existing low conductivity flows, for mobile and immobile bed conditions. The main findings can be summarized as follows: i) hydraulic conductivity does not affect the location of the zero plane of the log-law, the thickness of the region above the crests where the flow is determined by roughness, ii) increase of hydraulic conductivity does not appear to decrease bed roughness parameters, iii) higher hydraulic conductivity is associated to a structural change; higher near-bed velocity and higher shear-rate in the inner region. In dimensional terms this means a same friction velocity, \( u \), is achieved with a flow with larger mass rate, thus a lower friction factor \( = \left( \frac{u}{u_c} \right)^2 \) and iv) so flows over high conductivity beds appear drag-reducing even if roughness parameters do not change appreciably.

To further advance the research, it is recommended to perform same tests with artificial barriers in the bed so that porosity remains unchanged but tortuosity is greatly increased. The effect on the location of the log-law should be monitored.
REFERENCES


