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Effects of bedload transport in the vertical profile of the longitudinal mean velocity in hydraulically rough mobile beds

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The empirical characterisation of the longitudinal flow velocity and of flow resistance in rough channels has become a classical theme in open-channel hydrodynamics. An analysis of the current theoretical paradigm (schlichting-gersten-2000) shows that there are still open topics of research, despite decades of research. Of particular interest for the characterisation of flow resistance is the definition of the friction velocity, the parametrisation of the roughness height, z_0, for a given definition of u_* and the universality of the Von Kármán (κ). Considerable research efforts have also been placed to account for the influence of sediment transport. However, such research imported the ambiguities of the immobile bed conceptual framework. In this work, key concepts of this framework will be reviewed to accommodate the specificity of open-channel flows carrying bedlaod. The focus will be placed on the Von Kármán constant, κ, and the roughness height z_0.

The objectives are i) to derive a theoretical argument for the variation of κ as a function of flow anisotropy i) to quantify, by means of an adequate parametrisation, the changes induced by sediment transport on the roughness height considering $\kappa = 0.4$ and a variable κ.

As a first step, the similarity arguments leading to the log-law $u/u_* = (1/\kappa)\ln(z/z_0)$, where u is an ensemble-averaged longitudinal velocity (generally time-averaged) and z is the vertical coordinate, are re-assessed to account for bed mobility and for near-bed sediment movement. The analysis will explicitly distinguish water-worked beds under equilibrium sediment transport and immobile beds with upstream-imposed sediment feed. In the presence of sediment transport, the shear rate must be considered a variable of a two-phase (fluid and sediment) phenomenon. Applying Vaschy-Buckinghma's theorem and introducing appropriate hypothesis, the non-dimensional relation is

$$(z/u_*)\partial_z u = \Pi_m \left(h/z, k_s/z, \sigma_2/z^2, zu_*/\nu, zR/\left(\rho^{(w)}u_*^2\right)\right) \quad (1)$$

where z is the vertical co-ordinate, h is the water depth, k_s is the characteristic scale of the bed roughness, σ_2 is the 2^{nd} centred moments of the grain size distribution of the substrate material, μ is the fluid viscosity, $R = \rho^{(w)}g(s-1)$, $s = \rho^{(g)}/\rho^{(w)}$, $\rho^{(w)}$ is the fluid density, $\rho^{(g)}$ is the density of the particles that compose the granular material and g is the acceleration of gravity.

Given the appropriate similarity hypothesis in the overlapping layer two solutions are found. 1: If $\Pi_m \rightarrow A$ as $\frac{zR}{\rho^{(w)}u_*^2} \rightarrow \infty$, the log-law is retrieved with $A = 1/\kappa$ independent of the flow parameters and independent of the nature of the wall but, given the arbitrariness in position of the boundary zero Z_0, dependent on the particular choice Z_0. Experimental data fitted to logarithmic profiles with $\kappa < 0.4$ are due to the choice of Z_0 and not to sediment-induced changes in turbulent flow phenomena. 2: In case of incomplete similarity, the equation for the non-dimensional shear rate becomes

$$(zu_*\partial_z)\{u\} = \left(\rho^{(w)}u_*^2/(k_s R)\right)^{\alpha} A \quad (2)$$

The vertical profile of the longitudinal velocity would be logarithmic but the Von Kármán constant would depend on the Shields parameter.

A second step comprehends finding a theoretical model to accommodate bedload-induced changes in κ maintaining wall similarity, *i.e.* the idea that the direct effects of the roughness elements have disappeared in the overlapping layer. The main effect of the boundary would have been setting the inner kinematic scale u_*. Within this framework and with appropriate hypothesis, the Von Kármán constant can be written as

$$\kappa = 18((-b_{13}/p_w)C_{2w})^{3/2} \tag{3}$$

where $-b_{13}$ is the 13 component of the anisotropy tensor, p_w is the fraction of TKE associated to vertical motion and C_{2w} is the constant in the 2^{nd} order structure function. Subtle changes in flow anisotropy, as a result of extra momentum sink represented by near-bed sediment movement, are thus sufficient to justify changes in κ.

The results of laboratory work, performed in a 12 m long, 0.40 m wide tilting flume, are employed to characterise the vertical profile of the longitudinal velocity. Flow measurements were performed with a 2D LDA; bed texture measurements were performed with a laser displacement sensor. The results, the variation of z_0 with the Shields parameter, are grouped in two categories, depending on whether or not is considered that the Von Kármán constant is universal. It is shown that the qualitative behaviour is independent of κ but not the actual values.

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