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Velocity fields of a bed-load layer under a turbulent liquid flow

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ABSTRACT

The transport of sediments by a fluid flow is commonly found in nature and in industry. In nature, it is found in rivers, oceans, deserts, and other environments. In industry, it is found in petroleum pipelines conveying grains, in sewer systems, and in dredging lines, for example. This study investigates experimentally the transport of the grains of a granular bed sheared by a turbulent liquid flow. In our experiments, fully developed turbulent water flows were imposed over a flat granular bed of known granulometry. Under the tested conditions, the grains were transported as bed load, i.e., they became entrained by rolling and sliding over each other, forming a moving granular layer. The present experiments were performed close to incipient bed load, a case for which experimental data on grains velocities are scarce. Distinct from previous experiments, an entrance length assured that the water stream over the loose bed was fully developed. At different water flow rates, the moving layer was filmed using a high-speed camera, and the grains' displacements and velocities were determined by post-processing the images with a numerical code developed in the course of this study. The bed-load transport rate was estimated and correlated to the water flow conditions.

1. Introduction

The transport of sediments by a fluid flow is directly related to the shear forces exerted by the fluid on the granular bed. When the shear forces are very strong in relation to the grains' weight, the granular bed is fluidized and grains are entrained as a suspension. Conversely, when the ratio between the shear forces and the grains' weight is moderate, the grains are entrained by the fluid flow as a mobile granular layer, known as bed load, which remains in contact with the fixed part of the granular bed. Within the bed-load layer, grains become entrained by rolling and sliding over each other, or by effectuating small jumps.

The transport of sediments as bed load by a turbulent liquid flow is commonly found in nature and in industry. For example, it can be found in rivers, oceans, petroleum pipelines conveying grains, sewer systems, and dredging lines. In practical situations, the bed load accounts for a considerable proportion of the transport rate, and therefore, it is of interest for many environmental and industrial applications. Although of importance, the problem is not fully understood and remains open. Some of the major difficulties related to the problem are the feedback mechanisms. For example, the water stream is responsible for the solid discharge, which, in its turn, modifies the morphology of the bed through erosion and sedimentation processes [1,2]. Another example is the modification of the fluid flow by momentum transfers from the fluid to the moving grains, and from the latter to the fixed part of the bed, known as the feedback effect [3].

To determine the bed-load transport rate, two dimensionless groups are necessary, usually taken as the Shields number, θ, and the particle Reynolds number, Re_*. The Shields number is the ratio between the shear force caused by the fluid and the grains' weight, and the particle Reynolds number is the Reynolds number at the grain scale [4]. They are given by Eqs. (1) and (2), respectively:

$$\theta = \frac{\tau}{(\rho_s - \rho)gd} \tag{1}$$

$$Re_* = \frac{u_* d}{\nu} \tag{2}$$

Here τ is the shear stress caused by the fluid on the granular bed, d is the grain diameter, g is the gravitational acceleration, ν is the kinematic viscosity, ρ is the specific mass of the fluid, and ρ_s is the specific mass of the grain. In the case of two-dimensional turbulent boundary layers, the shear stress is $\tau = \rho u_*^2$, where u_* is the shear velocity. The mean velocity u in the overlap region is given by

$$u^+ = \frac{1}{\kappa} ln\left(\frac{z}{z_0}\right) = \frac{1}{\kappa} ln(z^+) + B, \tag{3}$$

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where $\kappa = 0.41$ is the von Kármán constant, z_0 is the roughness length, $u^+ = u/u_*$ is a dimensionless velocity, $z^+ = zu_*/\nu$ is the vertical distance normalized by the viscous length, and B is a constant. In Eq. (3), the second ($\sim ln(z/z_0)$) and third ($\sim ln(z^+)$) terms are equivalent, the second being generally employed for hydraulic rough regimes and the third for hydraulic smooth regimes, for which $B = 5.5$.

Some previous studies were devoted to the kinematic properties of moving grains within a bed-load layer under liquid flows. Fernandez Luque and van Beek [5] presented an experimental study on the average motion of individual grains and bed-load transport rates. The experiments were performed in a 8 m long, 0.20 m high and 0.10 m wide inclinable closed-conduit channel, where they imposed different water flow rates over different granular beds. The authors measured the bed-load transport rate, deposition rate, mean grain velocity, and displacement length of grains. They proposed that the mean longitudinal velocity of grains v_x is given by $v_x = 11.5(u_* - 0.7u_{*,th})$, where $u_{*,th}$ is the shear velocity corresponding to the threshold shear stress.

Charru et al. [6] presented an experimental study on the dynamics of a granular bed sheared by a viscous Couette flow in the laminar regime. The experimental results concerned the displacement of individual grains (velocities, durations, and lengths) and the surface density of the moving grains. For a given shear stress caused by the fluid, at a given flow rate, and an initially loose bed, Charru et al. [6] showed that the surface density of moving grains decays while their velocity remains unchanged. They proposed that this decay is due to an increase in bed compactness, caused by the rearrangement of grains, known as armoring, which leads to an increase in the threshold shear rate for the bed load. They found that the velocity of individual grains is approximately given by the shear rate times the grain diameter times a constant factor equal to 0.1, and that the duration of displacements is approximately given by 15 times the settling time, considered to be the grain diameter divided by the settling velocity of a single grain. Charru et al. [7] presented experiments on laminar flow in which PIV (Particle Image Velocimetry) was used to measure the velocity profiles of the fluid inside the mobile granular layer, as well as the grains' displacements, by using a background subtraction technique. They proposed correlations between the displacements of grains and the fluid flow, applicable in the laminar regime.

Lajeunesse et al. [8] presented an experimental study on the motion of individual grains of a bed-load layer over a flat granular bed. Free-surface turbulent water flows in steady state regime, with Reynolds numbers based on the water depth between 1500 and 6000, were imposed over different granular beds. The granular beds consisted of three populations of grains, employed separately: quartz grains with median diameters of 1.15 mm, 2.24 mm, and 5.5 mm, corresponding to $12 \leqslant Re_* \leqslant 500$. The displacements of individual grains were filmed using a high-speed camera, and the grains velocities, displacement lengths, and durations of flights were determined from the acquired images. The authors found that the distributions of longitudinal and transverse grain velocities follow, respectively, a decreasing exponential law and a Gaussian law, that the surface density of moving grains varies with $\theta - \theta_{th}$, and that the grains velocity and flight length vary with $\theta^{1/2} - \theta_{th}^{1/2}$, where θ_{th} is the Shields number corresponding to the threshold shear stress. They also found that the flight duration scales with the settling velocity of a single grain.

In the last few decades, many works were devoted to correlating the bed-load transport rate as a function of the fluid flow. Meyer-Peter and Müller [9], applying their data from exhaustive experimental work, proposed that $\phi_B = a(\theta - \theta_{th})^{3/2}$, where $a = 8$ if both form drag (due to ripples) and skin friction are considered, and $a = 4$ if only skin friction is considered [10]. $\phi_B = q_B((S-1)gd^3)^{-1/2}$ is the normalized volumetric bed-load transport rate, where $S = \rho_s/\rho$ is the ratio between the specific masses and q_B is the volumetric bed-load transport rate by unit of width. Bagnold [11] proposed that $\phi_B = \eta\theta^{1/2}(\theta - \theta_{th})$, where η is given by $\eta \approx A\sqrt{2\mu_s/(3C_D)}$, A is a constant that depends on the Reynolds number [11], μ_s is the friction between grains, and C_D is the drag factor for the grains. Based on energetic considerations, Bagnold [12] proposed that $i_b \tan\alpha = e_b\omega$, where i_b is the immersed bed-load transport rate, ω is the flow power per unit area, $\tan\alpha$ is the dynamic friction coefficient, and e_b is the efficiency of bed-load transport (proportion of the flow power dissipated within the bed-load transport). Lettau and Lettau [13] proposed that $\phi_B = \xi\theta(\sqrt{\theta} - \sqrt{\theta_{th}})$, where $\xi = C_L((S-1)gd)^{-3/2}\rho/g$ and C_L is a constant to be adjusted.

Abrahams and Gao [14] developed a bed-load transport equation valid for open-channel turbulent flows in rough regime. The obtained equation, derived from Bagnold's energy approach [11] and based on exhaustive experimental data, is $i_b = \omega G^{3.4}$, where $G = 1 - (\theta/\theta_{th})$. This equation was proposed for both bed-load and sheet-flow regimes by replacing the dynamic friction coefficient of Bagnold [12] by a stress coefficient that takes into account both the grains contact and the fluid drag.

According to his measurements of aquatic dunes under turbulent liquid flows, Franklin [15] proposed that $\phi_B = 12Re_*(\theta - \theta_{th})^3$. As opposed to previous expressions, the proposed relation has an explicit dependence on Re_*. The author argued that the bed-load transport rate must vary with the type of turbulent boundary layer, i.e., hydraulically smooth or hydraulically rough. Using the same argument, Franklin and Charru [16] proposed that $\phi_B = 34Re_s(\theta - \theta_{th})^{2.5}$, where $Re_s = U_s d/\nu$ is the Reynolds number based on the settling velocity of a single grain, U_s.

Gao [17] compared the equation proposed by Abrahams and Gao [14] with exhaustive experimental data and other bed-load equations. For this compilation, Gao [17] used a data set from 264 flume or closed-conduit experiments not used in obtaining the Abrahams and Gao [14] equation. The author found that the Abrahams and Gao [14] equation has the best predictive capacity among the tested bed-load equations.

Recently, Franklin et al. [3] measured the velocity profiles of turbulent water flows over fixed and loose granular beds of the same granulometry using PIV. They quantified the perturbation caused solely by the effect of the bed load on the turbulent stream, known as the feedback effect. Their experimental device had an entrance length of 40 hydraulic diameters upstream of the loose bed. In the entrance length, a static bed of same thickness and granulometry of the loose bed was fixed on the bottom of the channel, assuring that the water stream was fully developed over the loose granular bed. The time scale of the experiments were such that no ripples were observed in the course of tests.

The objective of the study is to, first, determine experimentally the displacement and velocity fields of the moving grains within the bed-load layer in a liquid, and, second, as a consequence, to be able to estimate the bed-load transport rate from these. In order to achieve this, a granular bed was filmed using a high-speed camera and the images were post-processed using scripts developed by the authors. The present experiments were performed close to incipient bed load, a case for which experimental data on grains velocities are scarce, and the granular bed remained flat in the course of all tests. Distinct from previous experiments, an entrance length of 40 hydraulic diameters assured that the water stream over the loose bed was fully developed.