EFFECTS OF THE GRANULAR MOBILITY ON A TURBULENT FLOW

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Abstract. *The transport of granular matter by a fluid flow is frequently found in nature and in industry.The presence of bed-load, a mobile granular layer which is in contact with the fixed part of the bed, may affect the turbulent liquid flow. This phenomenon is known as feed-back effect. The experiments were performed on a closed-conduit channel of rectangular cross section where the grains were transported as bed-load. The employed fluid was water and a PIV (Particle Image Velocimetry) device was employed to measure the turbulent liquid flow. The turbulent fully-developed velocity profiles over fixed and mobile granular beds were measured for two differents diameters of grains, 160 μm and 360 μm, for roughly the same water flow rates, in conditions near the threshold of the bed-load. The fluctuation profiles were obtained in order to obtain the effects of bed-load on the turbulent flow.*

Keywords*: feed-back effect, sediment transport, bed-load*

1. INTRODUCTION

The transport of granular matter entrained by a fluid is frequently found in nature and in industry. It is present, for example, in the erosion of river banks, in the displacement of desert dunes and on the transport of sand in hydrocarbon pipelines. A better knowledge of this kind of transport is of great importance to understand nature and to improve human activities.

Among the possible two phase liquid/solid flows, one common case is the horizontal liquid flow in a closed-conduit channel of rectangular cross section in the presence of a granular bed. Usually, the bed is constituted of sand. When the shear stress of the fluid exceeds a threshold value for the mobilization of grains, a mobile layer of grains known as bed-load takes place in which the grains stay in contact with the fixed part of the granular bed. When the shear stress exerted by the fluid flow is capable to move some grains, but are relatively small compared to the grains weight, the flow is not able to transport grain as a suspension. Thus, below the threshold for the mobilization the grains, the granular bed remains fixed.

Therefore, the bed-load existence depends on the balance of two forces:

a) An entraining force, of hydrodynamic nature, proportional to τd^2, where τ is the shear on the bed and d is the mean grain diameter;
b) A resisting force, in this case related to the grains weight, proportional to $(\rho_f - \rho_p) g d^3$, where ρ_f is the specific mass of the fluid, ρ_p is the specific mass of the grains and g is the gravitational acceleration.

One relevant dimensionless parameter is the Shields number θ, which is the hydrodynamic force to weight ratio

$$\theta = \frac{\tau}{(\rho_f - \rho_p) g d} \tag{1}$$

and bed-load takes place for $O(0.01) < \theta < O(1)$.

In the case of a fully-developed, two-dimensional turbulent boundary-layer over a granular bed, the shear stress is $\tau = \rho u_*{}^2$, where u_* is the shear velocity. Near the bed, near-wall velocity holds

$$u^+ = {}^1/_\kappa \ln(y^+) + B \tag{2}$$

where κ is the Kármán constant (we consider here $\kappa = 0.41$), $u^+ = {}^u/_{u_*}$(u is the velocity profile), $y^+ = {}^{y u_*}/_\nu$ is the transversal distance normalized by the viscous length (ν is the kinematic viscosity) and B is a constant. In the case of hydraulic rough regimes, Eq (2) is usually written as

$$u^+ = {}^1/_\kappa \ln({}^y/_{y_0}) \tag{3}$$

where y_0 is the roughness length. The other relevant parameter is the Particular Reynolds number Re_*, which is the Reynolds number of the fluid at the grain scale. It relates the fluid inertia to the fluid viscosity terms at the grain scale

$$Re_* = \frac{\rho u_* d}{\mu} \quad (4)$$

where u_* also represents the characteristic velocity of the fluid at the grain scale (shear velocity), d is the characteristic length at the grain scale (grain diameter) and μ is the liquid dynamic viscosity.

The Shields number and the Reynolds number characterize bed-load. On the other hand, the presence of the mobile granular layer affects the fluid flow, an effect known as feed-back.

2. EXPERIMENTAL SET-UP

2.1 Experimental Device

To study the effects caused on a turbulent water stream by the bed-load an experimental loop was built. To characterize this perturbation, the water flow over fixed and mobile granular beds was measured, in conditions near the bed-load threshold (Bagnold,1941; Raudkivi ,1976; Buffington and Montgomery ,1997).

The experimental device consisted of a transparent horizontal closed-conduit channel of rectangular cross section, *160 mm* wide, *50 mm* high and *5 m* long of which the last *2 m* corresponded to the test section. Access windows ensure the introduction of grains and the formation of the mobile and fixed granular beds. Two types of test were run to characterize the feed-back effect: the first type employed a fixed granular bed throughout the channel length by introducing plates in the channel (side by side) and covering the entire channel bottom; In the second type, the plates were removed (only) in the test section, being replaced by grains of same granulometry, forming a loose granular bed of same thickness. Water was used as the liquid phase and glass beads as the granular media composing the bed.

The employed grains consisted of glass spheres exhibiting specific mass of ρ_p=2500 kg/m³ and classified in two populations. One population had its size spanning from d = 300 μm to d = 425 μm, and it is assumed that the mean diameter is d_{50} = 360 μm; the other population had its size spanning from d = 106 μm to d = 212 μm, and it is assumed that d_{50} = 160 μm. For the construction of a static granular bed, PVC plates (*250 mm* long by *155 mm* wide) were sandblasted, and the glass spheres were glued on their surface. The averaged thickness of theses granular plates was, approximately, *7 mm*.

The tests were performed at ambient condition, i. e., atmospheric pressure of 1 atm and temperature of 25ºC. It was necessary to apply an increasing water flow rate in order to determine the bed-load threshold . The minimum water flow rate took place when the beginning of the movement of grains was observed (Bagnold, 1941; Buffington and Montgomery, 1997; Raudkivi, 1976; Yalin, 1997). The upper limit for the flow rate was imposed by the formation of ripples on the bed surface. The tests' nominal flow rates were of *5*, *5.5*, *6*, *6.5* and *7 m³/h*, corresponding to mean velocity $\overline{U}$ of, respectively, *0.17*, *0.19*, *0.21*, *0.23* and *0,24 m/s* and to Reynolds number ($Re = \rho_f \overline{U} 2H_{gap}/\mu$) in the range 16000 < Re < 28000, where H_{gap} is the distance from the granular bed to the top wall.

2.2 Measurement Device

A PIV (Particle Image Velocimetry) device was used to obtain the instantaneous field velocities of the water stream. The instantaneous velocity field and the time averaged velocity field were obtained, respectively, by image cross-correlation and average operators built in the software Davis. Fluctuations fields were also obtained by the software Davis. Matlab scripts were written to further process the averaged velocity and the field of fluctuations.

The PIV device employed light source of dual cavity Nd:YAG Q-Switched laser, capable to emit at *2 x 130 mJ* at *15 Hz* pulse rate. The thin laser beams were controlled by the Davis software and by a synchronizer with *10 ns* time resolution. The laser power was fixed between *65%* and *75%* in order to assure good balance between images' contrast and light reflection from the granular bed. The employed PIV tracers (seeding particles) were the suspension of particulate already present in city water, together with hollow glass spheres of *10* μm and *S.G. = 1.05*. A CCD (charge coupled device) camera with spatial resolution of *2048px x 2048px* was employed to acquire *500* pairs of images for each test.

The total field employed was *80mm x 80mm* for the tests with fixed beds and *70mm x 70mm* for the tests with mobile beds (note that in the transversal direction only *50 mm* correspond to the channel height). The employed interrogation area was *8px x 8px*, corresponding then to *256* interrogation areas of *0.28mm x 0.28mm*. The computations were made with *50%* overlap, which increases the number of interrogation areas to *512*, and corresponds to a resolution of *0.14mm x 0.14mm*. The time interval between a pair of frames was set to correspond to a computed displacement of *5 px*.

2.3 Evaluation of the apparent roughness, of the constant *B* and the shear velocity

The experimental data was fitted according to Eq. (3) and the values of u_* and *B* were obtained iteratively:

$$u = \frac{u_*}{\kappa}\ln(y) - \frac{u_*}{\kappa}\ln(y_0) \qquad (5)$$

where y_0 is the roughness length and for a given fluid flow.

We can identify the constants $A = \frac{u_*}{\kappa}$ and $C = ({u_*}/{\kappa})\ln(y_0)$. When plotted in the log-normal scales, the inclination of Eq. (5) is proportional to u_* and the intersection between Eq. (5) and the line *u = 0* gives y_0. For each water flow condition, the experimental data was fitted to Eq. (5) in the region *70<* y^+ *<200*, and the shear velocity and the roughness length were found. The constant *B* is obtained directly from Eq. (2).

3. RESULTS

PIV measurements of the velocity fluctuations were obtained and the Reynolds stresses for the cases over fixed and mobile beds were compared, where *u'* is the velocity fluctuation in the longitudinal direction, *v'* is the velocity fluctuation in the vertical direction and the over-bar corresponds to an average in time.

Figure 1.a presents the profile of Reynolds stresses $-\rho\overline{u'v'}$ for the water stream over the fixed bed composed of $d_{50} = 360\ \mu m$ grains and the Reynolds stresses are normalized by the shear velocity and the vertical coordinate is in dimensional form. Figure 1.b presents the profiles of the mean velocities over fixed and mobile granular beds, normalized by the internal scales (shear velocity and viscous length), for glass beads of mean diameter of 360 µm. Table 1 presents the values of u_* and of *B* computed from data of Fig 1.b.

The profiles over the mobile beds and over a fixed bed (Fig. 1.b) have a logarithmic region above the bed. However, the profiles over mobile beds are displaced to higher locations (the same velocities are reached at higher transversal coordinates), and this displacement tends to increase as the granular mobility is increased. This can be interpreted as follows: the ratio of mobile grains to static ones increases with the water flow rate, which increases the momentum transfers from the water to the granular bed. The vertical displacement of the mean flow profiles is then due to the feed-back effect.

The profiles showed in Fig. 1.a have a high noise and this noise stems from the higher errors related to second order momentum measurements. Even with this noise, the dimensionless profiles showed in Fig. 2 are almost superposed and have the expected form (Schlichiting, 2000): they tend to zero at the walls, reach their maxima in a region close to the walls, and tend to zero in the center of the channel.

It is expected$-\overline{u'v'}/u_*^2 \approx 1$, instead of the obtained value of *0.5*. However, the deviation from the unity can be explained by some uncertainties, like the small order of magnitude of fluctuations, and deviations in the adjustment of u_*. For instance, if it is supposed that a *15%* bias has occurred in the determination of u_*, and if this deviation in u_* (Tabs 1) is discounted, $-\overline{u'v'}/u_*^2 \approx 1$ is obtained. In this work, the authors preferred to avoid further fittings and to present the obtained data without more adjustments.

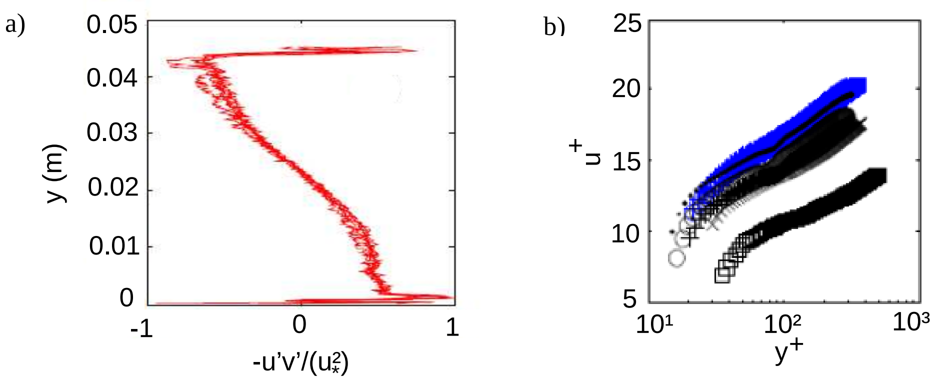

Figure 1 – (a) Normalized Reynolds stress profiles obtained for flows over the fixed bed composed of $d_{50} = 360\ \mu m$ grains. The Reynolds stresses are normalized by the shear velocity and the vertical coordinate is in dimensional form. (b) Profiles of the mean velocities over fixed and mobile granular beds, normalized by the internal scales (shear velocity and viscous length), for glass beads of mean diameter of *360 µm*.

Table 1 - Computed shear velocity u_*, roughness length y_0 and constant *B*, for the mean diameter of $360\ \mu m$, according to the water flow rates, Q."Fix" stands for fixed bed and "mob A", "mob B" and "mob C" stand for, respectively, the three series of tests with mobile beds, called A, B and C.

	Q(m³/h)	B	y_0	u_*(m/s)	Re*
fix	5.0	5.30	d/37	0.0117	0.03
	5.6	5.70	d/47	0.0126	0.03
	6.1	6.00	d/57	0.0134	0.03
	6.8	5.20	d/47	0.0150	0.04
	7.3	5.20	d/50	0.0161	0.05
mob A	5.3	4.40	d/28	0.0130	0.03
	5.8	5.00	d/38	0.0136	0.03
	6.1	4.10	d/29	0.0145	0.04
	6.8	2.90	d/21	0.0171	0.05
mob B	5.3	3.90	d/24	0.0133	0.03
	5.9	3.40	d/22	0.0149	0.04
	6.3	5.30	d/46	0.0145	0.04
	6.7	3.00	d/21	0.0168	0.05
	7.3	-0.50	d/7	0.0228	0.10
mob C	5.4	5.10	d/37	0.0126	0.03
	5.9	5.00	d/38	0.0136	0.03
	6.4	4.30	d/32	0.0153	0.04
	6.8	3.80	d/27	0.0162	0.05

4. CONCLUSION

This article presented an experimental study on the perturbation of a turbulent boundary-layer of a liquid by a mobile granular bed, in conditions close to incipient motion, in a closed-conduit flow. A PIV (Particle Tracking Velocimetry) device was used to measure the perturbation caused on the turbulent stream by bed-load.

5. ACKNOWLEDGEMENTS

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