ABSTRACT
Some preliminary results of measurements of one-dimensional sediment transport on a flat bed are presented. Image processing was applied to measure the time evolution of the areal concentration and of the velocity of the transported grains in a series of bed load tests with values of the bed shear stress up to twice the threshold for incipient motion. The concentration and velocity data were used to compute the time evolution of the unit width solid discharge. It was found, as expected, that the sediment transport is an episodic phenomenon, particularly at low shear stress. The automatic measurement method enabled obtaining the instantaneous values of the solid discharge for a statistical analysis. The frequency distribution of the sediment rate values was analyzed; the shape of the distribution is not self-similar as the shear stress varies. Finally, it was found that up to 30% of the transport events have no significant contribution to the total transport; about 70% of the transported volume is related to only the 40% higher transport events.

Keywords: sediment transport, particle concentration and velocity, solid discharge

1 INTRODUCTION
The transport of sediments by a water stream in the proximity of a granular bed has been typically studied in order to develop reliable tools for the evaluation of the expected solid discharge for given flow conditions; pioneering work on this topic was made since the 30s of the last century, for example by Shields, Einstein or Meyer-Peter.

More recently, some researchers have paid attention to the behaviour of individual saltating particles (among the others, Lee & Hsu, 1994, Niño & García, 1998, Ancey et al., 2002, can be cited). Characteristics as the height or length of individual jumps, as well as the fractions of rolling or saltating sediments, have been analyzed in order to better describe the phenomenology of the particle motion at a scale comparable to the sediment size.

Some researchers proposed in the last years ideas according to which the sediment entrainment and motion is related to the events in the burst cycle within the turbulent boundary layer in the proximity of the bed (for a description of the features of the boundary layer on a rough bed see for example Grass, 1971). Nelson et al. (1995) made simultaneous LDA measurements of the flow velocity in one point and of the solid discharge; by means of correlation analysis, attributed the particle entrainment to the sweep events of the burst cycle. Sechet & Le Guennec (1999) made LDA single-point measurements of the flow velocity and particle tracking of the entrained sediment particles around threshold conditions; they compared the characteristic time scales of the ejection events and those of the sediment motion, finding a good correlation. Other works focused only on the sediment motion: Drake et al. (1988), when analyzing the bed load in a field case, attributed the most of the sediment motion to ‘sweep transport events’ of particular strength. Niño & García (1996) analyzed the almost suspended motion of sediments and attributed the sediment entrainment to ejection events. It can be seen that, although a large effort on this topic has been made, a prevalent trend is still lacking.
The precedent consideration suggest that observation of the phenomenology of the sediment transport on a plane bed may help understanding the process at a small scale. Although such characterization may be too refined with respect to engineering problems in a one-dimensional case, it may be needed for the understanding of more complex cases, that can be different from the one-dimensional case (Nelson et al., 1995). In this work, some preliminary observations on the phenomenology of the bed load will be made, with reference to weak sediment transport. Results of measurements of the concentration and velocity of the moving particles will be documented.

2 EXPERIMENTAL CAMPAIGN

2.1 EXPERIMENTAL SETUP

The experiments reported herein have been performed in a pressurized rectangular duct with transparent walls; the duct length is equal to 5.8 m and the cross section is 40 cm wide and 16 cm deep. The hydraulic head in the duct is imposed by a Bazin weir located in the downstream tank; the upstream tank is provided with a streamlined inlet to avoid wakes in the flow.

The test reach of the duct is 2 m long, starting at approximately 2.6 m from the inlet. Two different channel modules are available for it: for the experiments with a fixed bed a 16 cm deep module is used, while for the experiments with a movable bed a deeper module is used. The latter was filled with plastic sediments having a density equal to 1.43 times that of water. The sediments are almost uniform: the median diameter is \(d_{50} = 3.6\) mm, while the diameter corresponding to the 90th percentile has been estimated as \(d_{90} = 3.73\) mm. The latter was used as the representative bed roughness. In all the duct modules with small depth, the same roughness was obtained by gluing the same sediments onto metallic sheets located on the duct bottom wall.

Water discharge has been measured by a magnetic flowmeter posed on the delivery pipe. All the remaining measurements have been made by image processing: to capture the movies, a black and white CCD camera has been used, with a sampling frequency of 50 Hz.

2.2 INCIPIENT MOTION AND BED SHEAR STRESS

The experimental tests of one-dimensional bed load will be characterized in the following by the excess of the dimensionless shear stress with respect to its critical value. The dimensionless shear stress will be identified with the Shields number \(\phi = \tau / (\gamma \Delta d_{50})\); in the last equation, \(\tau\) is the bed shear stress, \(\gamma\) is the specific weight of water and \(\Delta = (\rho_s - \rho) / \rho\) is the specific gravity of the sediments, where \(\rho_s\) and \(\rho\) are the densities of the sediments and of water, respectively. The critical value of the Shields number will be indicated with \(\phi_c\).

In previous years, some researchers stated that the incipient motion of bed particles is not a well defined phenomenological condition, and therefore it is not possible to define a sharp threshold for sediment motion (see, for example, Grass, 1970, Buffington, 1999, Shvidchenko & Pender, 2000). We defined the incipient motion as the condition corresponding to a weak sediment transport: in particular, we identified the threshold conditions with a dimensionless solid discharge per unit width \(\Phi = q_s / (g \Delta d_{50}^3)^{0.5} = 5.7 \cdot 10^{-5}\), where \(q_s\) is the solid discharge per unit width and \(g\) is gravity. We made some experimental tests where we measured the solid discharge by counting the grains passing over a plate used as a sight (Figure 1); the unit width solid discharge over the plate for each test was calculated as \(q_{sp} = N W_g / (d \cdot w)\), where \(N\) is the number of grains passed over the plate, \(W_g\) is the volume of a single grain, \(d\) is the test duration and \(w = 8.7\) cm is the plate width. We eventually determined the critical water discharge, intended as that inducing the sediment rate corresponding to the incipient sediment motion. The critical discharge was \(Q_c = 18.95\ l/s\).
The shear velocity at the granular bed (hereafter indicated with $u^*$) was evaluated through the vertical distribution of the flow velocity in an experiment with a fixed bed and a discharge $Q = 17.9 \text{ l/s}$. The velocity profile was measured in the channel axis. A Particle Tracking Velocimetry algorithm (see Malavasi et al., 2004) was applied to movies captured after seeding the current with neutrally buoyant polystyrene particles of a size of $400 \, \mu m$. The time average velocity profile is shown in Figure 2(a); the profile is obviously non-symmetric owing to the different roughness of the granular bed and of the top cover. A logarithmic law of the wall (Figure 2, b) was fit to the experimental data, in the form:

$$
\frac{u(z)}{u^*} = \frac{1}{\kappa} \ln \frac{z}{d_{50}} + B,
$$

where $u$ is water velocity at a certain $z$ level and $\kappa$ is the von Karman constant, that we assumed equal to 0.41. We found a shear velocity value of $2.46 \, \text{cm/s}$ and a $7.2$ value for the constant $B$ from the velocity profile. The ratio $Q/Q_c$ was assumed to be equal to the ratio $u^*/u^*_c$, since no significant bed forms occurred in our experiments. The critical value of the shear velocity $u^*_c$ was therefore equal to $2.60 \, \text{cm/s}$, and the corresponding value of the Shields number was $\phi_c = (u^*_c)^2/(g \cdot \Delta \cdot d_{50}) = 0.045$.

In the bed load tests here documented, the water discharge $Q$ was measured and therefore the ratio $Q/Q_c$ was computed. The shear velocity was calculated as $u^* = u^*_c \cdot Q/Q_c$ and the ratio $\phi/\phi_c$ was calculated as $(Q/Q_c)^2$.

### 2.3 EXPERIMENTAL TESTS

We performed six bed load experiments with different solid discharges. The test conditions are summarized in Table 1. Each experiment was filmed for a duration of 20 s; sampling duration was limited by the memory available for image storage. After the tests, the number $N$ of the grains passed over the plate was manually determined, and the corresponding unit width solid discharge $q_{sp}$ was calculated.
### Table 1. Characteristics of the experimental tests (U indicates average water velocity over the cross section). During the incipient motion test (test 0) acquisition of films was not performed.

<table>
<thead>
<tr>
<th>Test</th>
<th>Q (l/s)</th>
<th>U (cm/s)</th>
<th>u (cm/s)</th>
<th>φ/φc</th>
<th>φ</th>
<th>φ-φc</th>
<th>N</th>
<th>qsp (cm²/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>18.95</td>
<td>30.6</td>
<td>2.60</td>
<td>1</td>
<td>0.045</td>
<td>0</td>
<td>-</td>
<td>2.53·10^-4</td>
</tr>
<tr>
<td>1</td>
<td>19.8</td>
<td>32.0</td>
<td>2.73</td>
<td>1.09</td>
<td>0.049</td>
<td>0.004</td>
<td>8</td>
<td>1.12·10^-3</td>
</tr>
<tr>
<td>4</td>
<td>21.0</td>
<td>33.9</td>
<td>2.90</td>
<td>1.23</td>
<td>0.055</td>
<td>0.010</td>
<td>70</td>
<td>9.83·10^-3</td>
</tr>
<tr>
<td>2</td>
<td>21.6</td>
<td>34.8</td>
<td>2.97</td>
<td>1.29</td>
<td>0.058</td>
<td>0.013</td>
<td>125</td>
<td>1.75·10^-2</td>
</tr>
<tr>
<td>3</td>
<td>24.8</td>
<td>40.0</td>
<td>3.42</td>
<td>1.72</td>
<td>0.077</td>
<td>0.032</td>
<td>284</td>
<td>3.99·10^-2</td>
</tr>
<tr>
<td>5</td>
<td>26.7</td>
<td>43.0</td>
<td>3.68</td>
<td>1.98</td>
<td>0.089</td>
<td>0.044</td>
<td>624</td>
<td>8.76·10^-2</td>
</tr>
<tr>
<td>6</td>
<td>27.5</td>
<td>44.4</td>
<td>3.79</td>
<td>2.11</td>
<td>0.095</td>
<td>0.050</td>
<td>2461</td>
<td>3.46·10^-1</td>
</tr>
</tbody>
</table>

2.4 IMAGE PROCESSING

The concentration and the velocity of the moving grains have been measured by image processing in the region upstream of the plate. Radice et al. (2006) measured instantaneous values of such quantities through an image processing technique that is based on the subtraction of consecutive frames. Under weak sediment transport the depth of the active sediment layer equals the particle dimension, and the instantaneous values of the unit width solid discharge can be calculated as:

\[ q_s = C \cdot v \cdot d_{50}, \]  

(2)

where C is the areal concentration of the moving sediments and v is the sediment velocity.

![Figure 3. Comparison between the dimensionless solid discharges evaluated through the manual count of the grain passing over the plate and the image processing.](image)

Radice et al. (2006) showed that image processing is very powerful in measuring instantaneous values of the quantities of interest, but the parameters of the image processing algorithms have to be determined via a calibration of the measuring method against given solid discharge values. In this work, the processing parameter have been estimated via the observation of some sample frames, and it was then verified that the solid discharge values of Table 1 were correctly measured. The temporal series of the solid discharge have been averaged in order to obtain values to be compared to the real ones, coming from the direct count of the grains. The comparison between the real values and those obtained by image processing is presented in Figure 3. It is possible to see that solid discharge values from image processing are in good agreement with the real ones. Solid discharges varying of two orders of magnitude are correctly measured, except for a visible underestimation of the sediment flux for very low solid discharges. Such behaviour is analogous to that found by Radice et al. (2006) when measuring the solid discharge of natural sand.
3 RESULTS ON INSTANTANEOUS SEDIMENT MOTION

The temporal evolution of the sediment concentration, of the sediment velocity and of the solid discharge is presented in Figures from 4 to 6 for three different shear stresses. The progressive means are also presented in the plot. It appears that it has been difficult to achieve steady transport conditions in our duct for the highest solid discharge test, since we did not feed sediments from upstream; it is particularly evident for test 6 that after some seconds with stable values, all the quantities tended do decrease, probably owing to some erosion occurring in the working section of the duct.

It can be noted that the sediment transport is largely episodic for values of the shear stress just exceeding those corresponding to the incipient motion (Figure 4, b). The sediment velocity assumes considerable values also for very weak sediment transport when it is non-zero, indicating a sort of delta-behaviour of this quantity. Mean values of the sediment velocity are of the same order of magnitude as the shear velocity, while peak values are almost equal to the average velocity of the flow.

As the shear stress is increased, time persistence of the sediment transport increases, and all the quantities are more regular (Figures 5 and 6). Still, the curves for the sediment velocity present some peaks with values similar to those of the bulk flow velocity.

Irregularity of the sediment transport was represented through the progressive coefficient of variation (i.e. the ratio between the standard deviation and the mean). It was found that for low sediment rates the coefficient of variation is higher than for growing shear stress, owing presumably to the episodic nature of the sediment transport process.

Figure 4. Temporal series of the concentration (a), longitudinal velocity (b), longitudinal unit width solid discharge (c). Solid discharge, enhanced scale (d). Test 4, $\phi/\phi_c = 1.23$. In each plot: --- quantity; --- progressive mean; --- progressive coefficient of variation (values on the right).
Figure 5. Temporal series of the concentration (a), longitudinal velocity (b), longitudinal unit width solid discharge (c). Test 3, $\phi/\phi_c = 1.72$. In each plot: quantity; progressive mean; progressive coefficient of variation (values on the right).

Figure 6. Temporal series of the concentration (a), longitudinal velocity (b), longitudinal unit width solid discharge (c). Test 6, $\phi/\phi_c = 2.11$. In each plot: quantity; progressive mean; progressive coefficient of variation (values on the right).
The instantaneous values of the longitudinal solid discharge per unit width were analyzed in the amplitude domain. Figure 7(a) presents the frequency distribution of the solid discharge for the three tests whose time series were shown in Figures from 4 to 6. All the distributions are obviously non-symmetric as the solid discharge is intrinsically positive. There is a prevalent presence of zero values at low shear stress, while it decreases for larger sediment rates. The distribution is peaked for small transport, while it tends to become flat for increasing $\phi/\phi_c$ values. We cannot say how it would evolve for shear stresses larger than $\phi/\phi_c = 2$. Figure 7(b) shows the cumulated frequency distribution (CFD) for all the experimental tests: the presence of the zero values is evident for tests 1, 4 and 2; the curve is almost linear for test 6, as a result of the flat (almost uniform) frequency distribution.

![Figure 7. Sample frequency distribution of the solid discharge (a); class amplitude is 0.05 cm$^2$/s, and labels indicate the top value in the classes. Cumulated frequency distribution (b).](image)

We calculated also the contribution to transport of the solid discharge values, by evaluating the fraction of the total sediment volume transported due to events smaller than any given value. After sorting ascending the solid discharge values, the contribution to transport of the $n$-th one was evaluated as:

$$c_t n = \frac{\sum_{i=1}^{n} q_{sx,i} \Delta t}{\sum_{s} q_{sx,s} \Delta t},$$

where $S$ is the sampling size. It can be noted that the denominator is the total volume transported per unit width. The contribution to transport was correlated to the cumulated frequency distribution of the solid discharge values in Figure 8(a). Again, the significant presence of the zero values shows that at low shear stress the effective events correspond to a very small part of the total time. The same correlation was made after computing the CFD considering only the non-zero values (Figure 8, b). In this case there is not systematic trend of the curves for variable shear stress; furthermore, the curves are very close one to another, indicating that the relation between the temporal occurrence of values and the contribution to transport is, as a first approximation, self-similar with respect to the transport rate. In particular, it was found that the 30% lower events contribute to the bed load for just the 10%. Furthermore, the 40% higher events contribute to the 70% to the sediment transport. Our results confirm the conclusion of Drake et al. (1988) about the non linear increase of sediment transport with the instantaneous stress. Similar statistics are not frequent in the literature: in some cases, the contribution to transport has been compared to the temporal frequency of the events in the turbulent boundary layer. Drake et al. (1988) attributed the 70% of sediment transport to sweep transport events occurring for the 9% of time; Nelson et al. (1995) attributed the 70% of the sediment transport to sweep and ejection events (43% and 27%, respectively), whose time occurrence was 31% for sweeps and 35% for ejections, summing 66%. Even if a rigorous comparison cannot be made since the correlated quantities are
different, our results are probably more in agreement with those of Nelson et al. (1995) than with those of Drake et al. (1988), that were obtained for non-uniform sediments in a real creek.

4 RESULTS ON AVERAGE SEDIMENT MOTION

The time series of each measured quantity were averaged in order to compare the measured mean values with previous literature results. The variation of the areal concentration of moving sediments with the shear stress was compared to the equations proposed by Fernandez Luque & van Beek (1976) and by van Rijn (1984). The structure of the van Rijn equation refers to a depth averaged approach: the solid discharge is calculated as \( q_s = C_s \delta_s v_s \), where \( C_s \) is the depth averaged concentration in a bed load layer where saltation height is \( \delta_s \) and \( v_s \) is particle velocity; for analogy with equation (2), our areal concentration was compared to the quantity \( C_s \delta_s/d_{50} \). The variation of the dimensionless unit width solid discharge with the shear stress was compared to the equations of Meyer-Peter (1951, quotation in Chanson, 1999, p. 192) and of van Rijn (1984). The comparison is presented in Figure 9. For the concentration values, the literature equations differ of one order of magnitude; our data lay within the corresponding range. For the solid discharge values, our test are in closer agreement with the equation of van Rijn (1984). The agreement between the measured data and the Meyer-Peter equation increases with the shear stress.

Figure 10 presents the correlation between the average solid discharge and the statistics of sediment concentration and velocity. The sediment velocity was made dimensionless with
the shear velocity, while the unit width solid discharge was made dimensionless with the shear velocity and the particle size. Averaged values of the quantities are obviously correlated; it is however interesting that, for the same variation of the shear stress, concentration and solid discharge values vary of more than three orders of magnitude, whereas velocity values vary of only two orders of magnitude, indicating that, whatever the reason of the sediment motion, it influences the concentration more than the sediment velocity. Typical velocity values equal some times the shear velocity, in agreement with previous works (see the synthesis made by Niño & García, 1998). The coefficient of variation of the quantities is presented in Figure 10(b); it is rather high (up to 10) for transport conditions little above the incipient ones, while it decreases for larger shear stresses. It is interesting to note that the values of the CV are similar for both quantities.

5 CONCLUSIONS

Our preliminary observations on sediment motion on a plane bed lead to the following major conclusions:

(1) the sediment transport is an episodic phenomenon, particularly at shear stresses just above those corresponding to the threshold for the sediment motion. Time-persistence of the particle motion increases with the shear stress.

(2) The time variation of the primitive quantities that concur in the determination of the solid discharge is different. The sediment velocity exhibits a delta-behaviour at low shear stresses and then becomes more regular as the sediment rate increases.

(3) The automatic measurement provided a large amount of instantaneous solid discharge values, for a statistical analysis. The frequency distribution of the solid discharge values is dominated by the zero values at very low shear stress. For growing stress, the zero values tend to vanish and the distribution tends to become progressively flatter. Correspondent variations in the cumulated frequency distributions can be seen.

(4) There is a non-linear relation between the temporal frequency of the solid discharge values and their contribution to the total sediment transport. The 30% lower values of the solid discharge contribute for only the 10% of the transported volume. The 70% of the volume is due to only the 40% higher solid discharge events.

(5) The average values of sediment concentration are much more variable than those of sediment velocity with the sediment rate (that is, with the shear stress). The coefficient of variation of the quantities are similar and relatively little variable.
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REFERENCES


