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Some Thoughts on Measurements of Marginal Bedload Transport Rates Based on Experience from Laboratory Flume Experiments

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Abstract

Bedload measurements comprise an important component in the development of reliable formulae, in an effort to obtain the necessary constitutive relations between amount of transported material and flow parameters. The uncertainty of such measurements is rather well known, being much more pronounced at lower transport rates. This uncertainty stems from the multitude of factors affecting bedload transport and the lack of available trustworthy measuring technologies. Predictions of the limiting case of nearly zero bedload transport, typically reported in the literature as threshold of motion or critical condition, are even more challenging. The purpose of this contribution is twofold. First, to examine the sensitivity of bedload transport measurements at conditions moderately higher than critical, to the presence of a rather unobtrusive trap, designed through several iterations. Even under relatively simple laboratory flume channel and flow conditions, it proved difficult to measure the bedload transport rate in a completely unbiased way. Second, to develop a methodology, together with the appropriate instrumentation, for determining the condition of incipient motion. The non-intrusive approach described here proved to be reliable in detecting even the slightest movements of a particle. At the same time, it demonstrates the complexity of the problem due to the highly fluctuating nature of turbulent flow.

1. Introduction

Bed load transport rate fluctuates considerably even in laboratory flumes under uniform, steady flow conditions. These fluctuations are manifested in terms of changes in both amount and composition of the transported material. This is not surprising given that turbulent flow, which is responsible for the instantaneous values of the driving force, is highly variable in space and time. From results reported in the literature (e.g. Kuhnle and Southard 1988), it is evident that the amplitude and period of the fluctuations vary inversely with the magnitude of the average boundary shear stress or, equivalently, with the average bedload transport rate. Since the fluctuations are much more pronounced at low or marginal transport rates, it is expected that the lower bedload transport activity would be more difficult to capture because even the smallest interference with the flow may locally alter the nature of the flow in a crucial way. As a result, developing instrumentation to accurately measure bedload at low transport rates or even to identify threshold of motion conditions remain difficult tasks.

Information about low bedload transport rates and threshold of motion conditions is important for at least the following two reasons: 1) in gravel streams, most flows capable of transporting bedload experience boundary shear stresses that are typically slightly higher than those encountered under threshold conditions, and 2) characterizing a channel boundary as stable, as well as for calculating bedload transport rates using formulas based on the excess boundary shear stress notion, depend on accurately determining the threshold of motion shear stress value.

Since the authors' experience with bedload transport is predominantly from the laboratory, the focus of this contribution will be on laboratory flumes. More specifically, the effect of traditional/intrusive techniques employed for determining transport rates at shear stresses moderately higher than critical flow conditions will be considered first. A new non-intrusive technique for detecting threshold of motion conditions will be discussed next. Results from a controlled laboratory setting provide some indication about the sensitivity of the phenomenon on the selected measurement method and help identify the expectations we may have when using the same technique to collect field data in a natural environment that is typically more complex. It can also be used as a basis of comparison for alternative technologies employed for bedload transport measurements.

2. Bedload Transport Measurements

Laboratory experiments investigating various aspects of the mechanics of self-formed, stable, straight alluvial channels in the absence of bed forms were carried out in a tilting flume, 14.6 m long and 0.53 m wide, which recirculated both water and sediment (Diplas 1990). The median size of the bed material was 1.9 mm and its standard deviation 1.45. More specifically, the evolution of a half-trapezoidal channel, with one of the sidewalls representing the channel center, for a given water discharge was examined. The erodible bank was initially set at an angle of 45°, the bottom width of the channel section was 0.24 m and its height was 0.07 m. The duration of each experiment was about 17 hr. The "half-channel" arrangement, with one erodible bank and the vertical flume side-wall as the other bank, proved effective in preventing meandering tendencies. The sediment was sufficiently coarse to preclude its suspension and avoid the formation of ripples. For the flow conditions employed during the experiments, the boundary shear stresses were moderately higher than the critical Shields stress value. As a result, a plane channel bed configuration prevailed. Seven experiments were performed for various initial slopes and water discharges. The channel section for one of them after it reached equilibrium is shown in Figure 1. As it can be seen, a typical stable cross-section consists of a flat bed region joined smoothly by a continuously curving bank, which replaced the bank that was initially set as a plane surface inclined at 45°.

Figure 1. A section of the equilibrium channel at the completion of the experiment. The flow direction is towards the top of the page.

In an effort to better understand the changes channels undergo as they approach an equilibrium configuration, it was deemed necessary to measure the bedload transport rate distribution in a given cross-section and monitor its changes with time. Two different methods were employed for this purpose. The first method was based on a video-recording system and the second on a small trap. The former did not interfere with the channel flow and resulted in accurate bedload transport measurements. In this case, the video-camera was mounted on a carriage with its lens placed as close as 1-2 cm above the water surface. The recorded area was a circle of about 8 cm in diameter. A frame of orthogonal shape was positioned between the water surface and the camera lens. This frame was used to attach wires parallel to the channel direction, every 2 cm across the channel. The recorded video could, thus, be analyzed to determine bedload transport across 2 cm wide strips. This method presented no problems for the type of experiments discussed here because the shallow water depths and the absence of suspended materials did not limit the visibility of the channel bed and, thus, the ability to clearly identify the moving grains. However, this technique is not appropriate for most field conditions, unless the camera is submerged, a procedure which interferes with the flow. Furthermore, this approach suffers two more limitations. It is not appropriate for high bedload transport rates and is rather difficult to provide accurate measures of the size and shape of the moving particles. The former limitation did not apply here because the rather low transport rate present in our experiments made it feasible to count the number of particles that were entrained by the flow by playing the video on slow motion. This is a tedious procedure that can be replaced by image analysis software.

Physical collection of the material that is in motion is preferable because it allows for further information about the phenomenon, such as grain size and shape, to be obtained. To accomplish this objective, the design of a small bedload trap was pursued during this study. This proved to be a very delicate task. Six different traps were constructed and tested through a laborious trial and error procedure to determine the most efficient design. Given the low transport rates, the placement of the trap and the resulting changes in the local flow patterns, however small, had a pronounced effect on the movement of sediment. The best design obtained through this process is shown in Figure 2. The sampling efficiency of the trap is very sensitive to the shape of the bed (the flatter the better) and to correct placement on the channel bottom. Its frame is made of thin wire. It has three lateral divisions, each 2 cm wide. A net was attached at the bottom of the frame and the rear side of the trap, generating three small buckets to collect the sediment (Fig. 2). To minimize the interference with the flow, its vertical components were located 8 cm downstream of the trap entry point. Once grains crossed the upstream end of the trap, they moved quickly over the smoother bottom net and were captured by the small buckets. A point gauge was used to introduce and withdraw the trap from the water. This trap collected on average 75% and sometimes almost 100%, of the moving grains. The variation of the boundary shear stress and bedload transport rate in a channel cross section measured from one of the experiments after the channel reached equilibrium is shown in Figure 3.

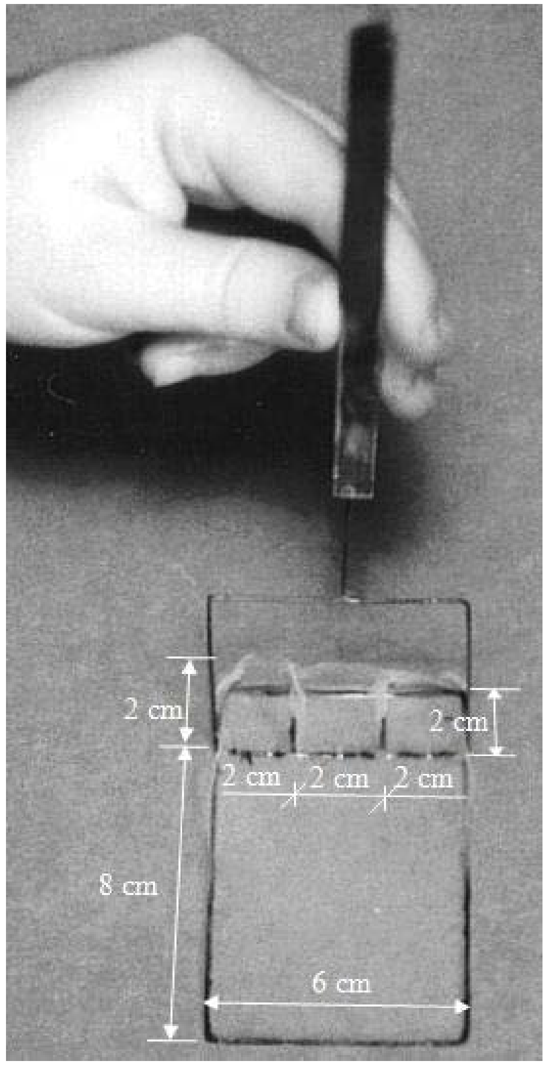

Figure 2. The final bedload trap design.

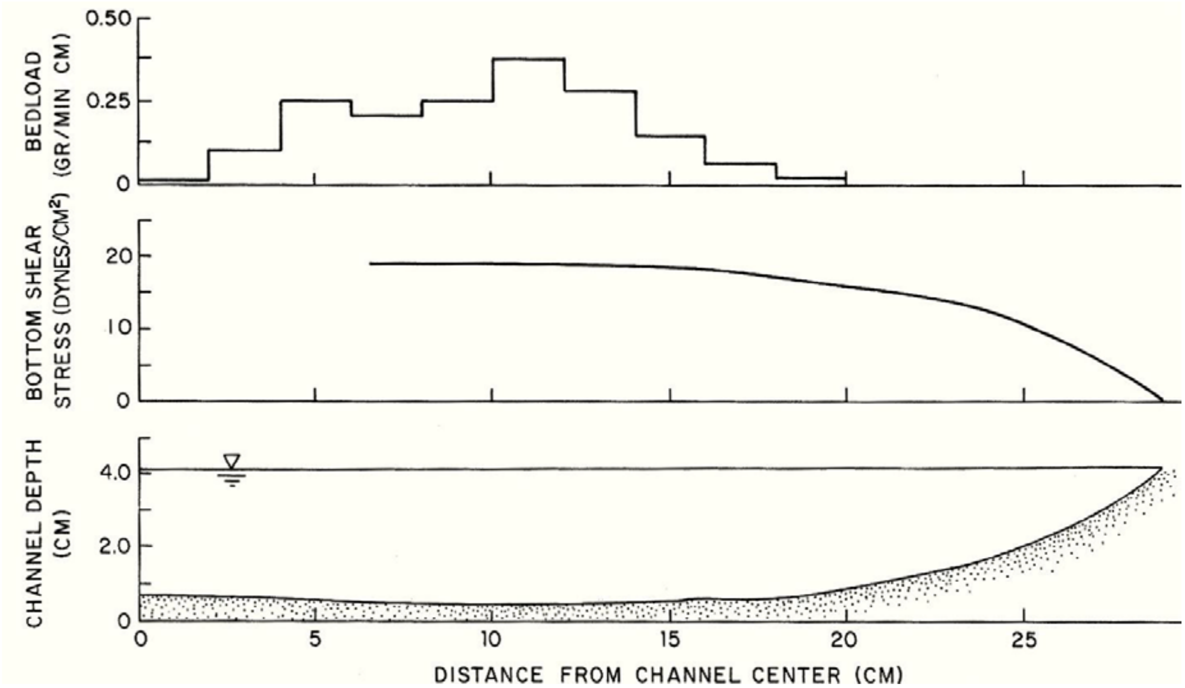

Figure 3. Shear stress and bedload transport rate distributions in a stable channel cross section obtained from the experiments.

As this rather minimally obstructive design could not provide perfect results, even under ideal flow/bed conditions, one should question the ability of various hand-held, temporary or permanently installed traps to measure bedload transport rates under field conditions in a completely unbiased way. It is also expected that the degree of bias will change with flow discharge, becoming less pronounced with increasing discharge. Moreover, even for a constant discharge the bias is likely to vary within a given transect because of the corresponding change of the boundary shear stress (see Fig. 3). This effect highlights the need for the development of reliable surrogate/non-intrusive technologies.

3. Threshold of Movement Determination

Over the years, several techniques, some of them quite ingenious, have been used for the precise determination of threshold of motion conditions (e.g. Shields 1936, Vanoni 1964, Fenton and Abbott 1977). An extensive overview of prior incipient motion studies has been provided by Buffington and Montgomery (1997). Given the violently fluctuating nature of velocity, pressure and other turbulent flow parameters, as well as the experimental difficulties in detecting the sediment entrainment and/or movement, such a determination remains elusive. Because of the fluctuating forces, some have argued whether such a criterion exists in turbulent flow (e.g. Einstein and El-Samni 1946). Nevertheless, most researchers and practitioners recognize the usefulness of a threshold criterion as a tool in engineering studies.

The sensitivity of the localized turbulent flow behavior to even a minute interference, observed during the low transport experiments discussed in the previous section, dictates that the precise determination of threshold of particle movement requires the use of non-intrusive techniques. Recent advances in digital photography and image analysis algorithms have made it possible to investigate the initiation of bed material motion, and bed-load transport in such a fashion (see for example: Sechet and Guennec 1999, Shvidchenko and Pender 2000, Dancey et al. 2002, Papanicolaou et al. 2002, Böhm et al. 2006, Roarty and Bruno 2006). The development of a non-intrusive method for particle tracking was part of a study at the Baker Environmental Hydraulics Laboratory, Virginia Tech, dealing with the relation between instantaneous turbulent flow velocities and inception of bed material movement. While it is not the objective of this study to expound on the appropriateness of a threshold criterion concept, it is advocated here that the flow phenomena occurring in the immediate vicinity and upstream of a mobile particle under consideration will dictate its behavior, movement or no movement. The study was carried out in a tilting flume, 0.60 cm wide and 20 m long. To reduce the number of parameters affecting the particle movement and facilitate the understanding of cause and effect mechanisms, the entrainment of a single, fully exposed Teflon® ball, having a diameter (d) of 8 mm, resting on four layers of well packed identical diameter glass spheres was examined in fully developed uniform turbulent open channel flow (see Fig. 4).

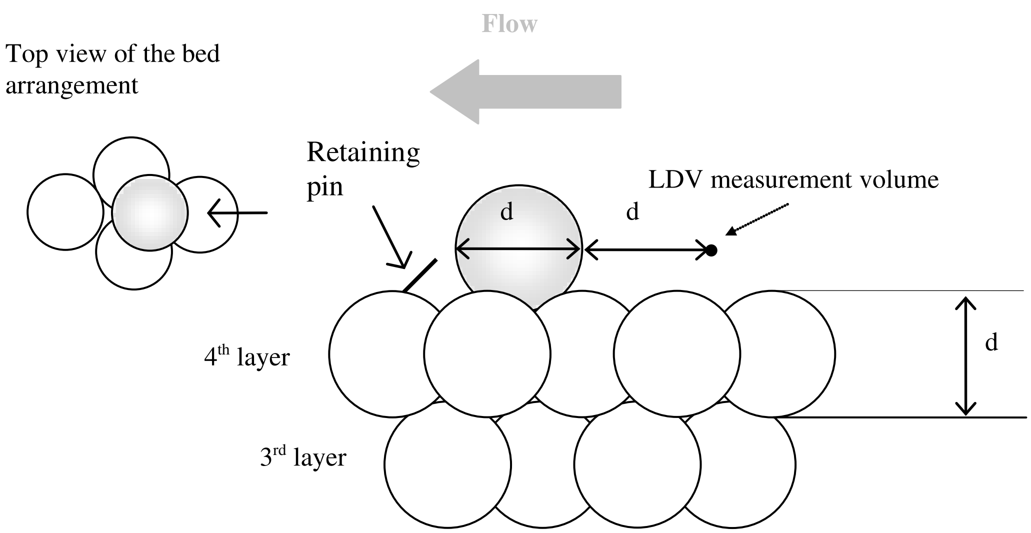

Figure 4. Sketches of the solitary test particle and pocket geometry. Sketch on the upper left side shows top view and sketch on the right shows side view.

In an effort to identify which turbulent events were potentially responsible for particle entrainment, a two-component laser Doppler velocimeter (2D-LDV) was used to record the streamwise and vertical components of the instantaneous velocity vector one diameter upstream of the center of the test particle, at an average sampling rate between 200 and 520 Hz. A laser based system was developed for detecting small particle displacements as well as entrainment. This system utilizes a He-Ne laser source (output power: 25-30 mW, wavelength: 632.8 nm) and a photo-detector in the manner of a simple “electric-eye” arrangement. The additional laser based system used a principle of operation similar to the forward scatter operation mode of an LDV. The He-Ne laser beam is aligned to be partially incident upon the particle under investigation (see Fig. 5 for the definition sketch). That is, some of the laser beam is allowed to pass entirely through the flume and some of the beam is scattered by the particle. The amount of light that is allowed to pass strikes an opaque boundary on the opposite side of the flume. The light incident on this boundary is viewed by the photo-detector with lens assembly (see Fig. 5). Very small changes in the position of the particle cause detectible changes in intensity of the transmitted light.

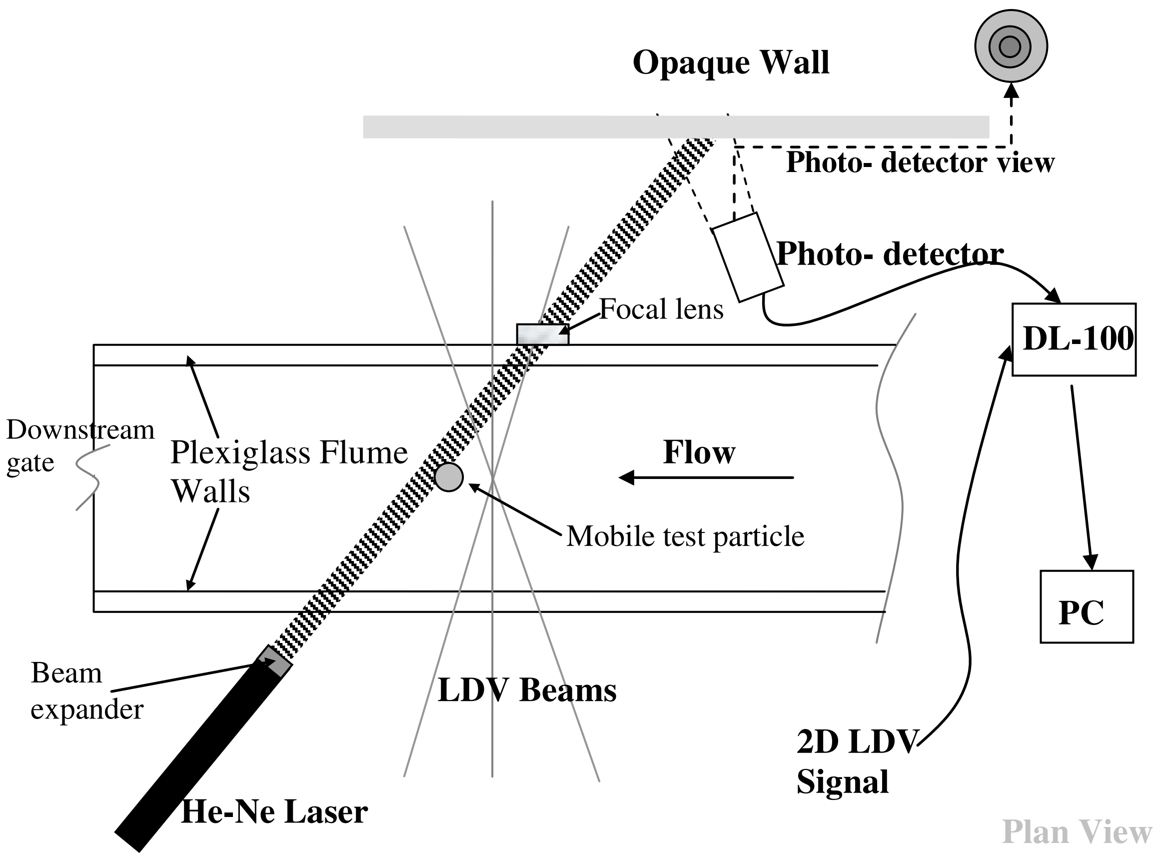

Figure 5. The sketch of the flume, showing the working section and associated instrumentation for the entrainment experiments.

The intensity of the photo-detector signal was recorded simultaneously with instantaneous velocity measurements obtained with the LDV system, using a multi-channel interface signal processor (TSI, Model DL-100). Therefore, the laser-based system requires no triggering in order to collect the photo-detector output. A retaining pin was used to prevent the mobile particle from being completely entrained by the flow (see Fig. 6). This small but important component allowed for continuous records of entrainment episodes without manual intervention. In this manner, statistically significant sets of particle displacement and local flow velocity pairs were obtained for various flow conditions.

The photo-detector output for the particular run presented here varied between -2.65 (V_{max}) and -1.6 (V_{min}) volts, due to the movement of the test particle. A relatively low background noise level (± 15 mV) was achieved by minimizing the ambient light during the calibration and test runs. The photo-detector output time series obtained for typical entrainment events (e.g. rocking and pivoting events) is shown in Figure 7. When the test particle is fully entrained by the turbulent flow forces (e.g. see pivoting signal in Fig.7), it rolls over the valley formed by the pocket arrangement until it reaches the retaining pin, which is located 1 mm away downstream of the rear face of the particle. The photo-detector signal corresponding to the pivoting of the particle is shown in the upper right corner of Figure 7.

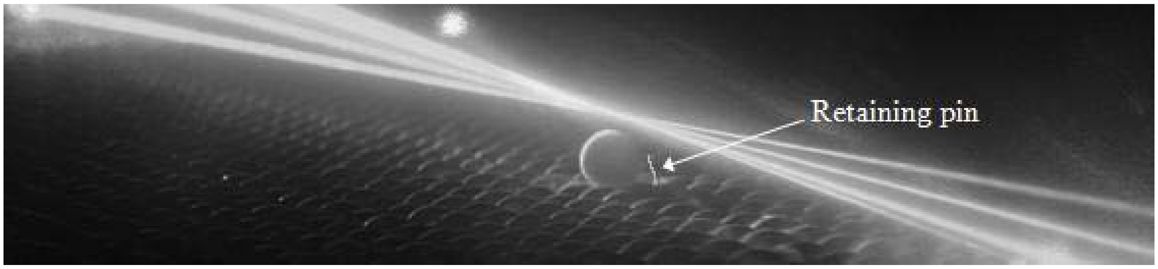

Figure 6. Teflon® test particle, retaining pin, 2D LDV beams, and identically size well packed glass spheres forming the flume bed.

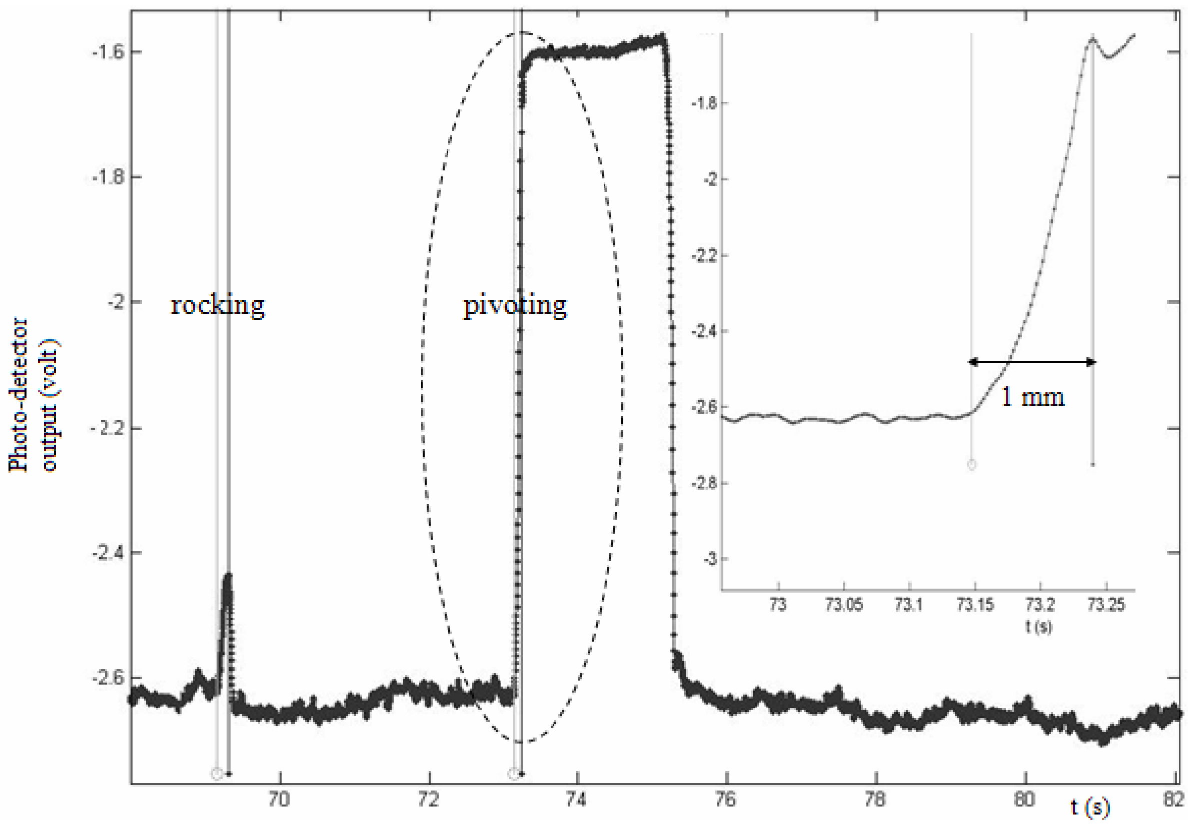

Figure 7. A typical photo-detector output displaying rocking and pivoting sample events of the mobile test particle. Upper right side: Enlarged voltage signal corresponding to 1 mm displacement of the ball in the streamwise direction (dashed ellipse in the main figure).

While the flow-induced forces are strong enough, the particle is temporarily pushed against the rigid pin. When these forces subside, the particle falls back to its original pocket. The photo-detector (Volts) output was used to identify within the LDV velocity/time record the instants when a specific level of particle movement had occurred (e.g. see pivoting signal in Fig.7). Once the instants of entrainments were determined, a binary 0/1 signal, with "1" indicating any detectable particle movement was constructed. A representative streamwise velocity time series coupled with the binary entrainment signal is shown in Figure 8. This figure presents a small portion of the local velocity time series, including a turbulent event corresponding to particle dislodgement (instant of particle entrainment obtained from the binary signal is shown with a vertical dashed line). The calibration of the He-Ne based system and results are discussed below.

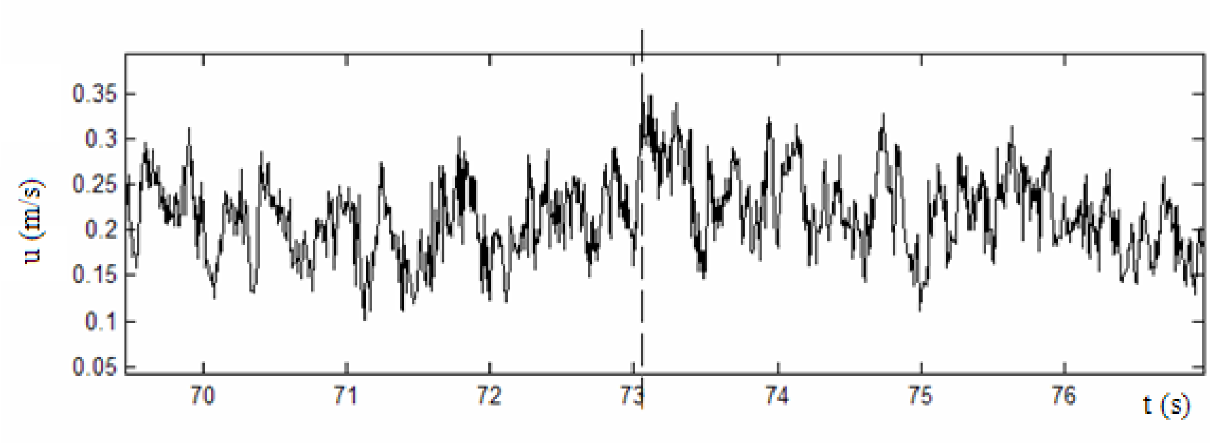

Figure 8. Representative time series of stream-wise velocity (measured at one diameter upstream of the particle, at a sampling rate ~300 Hz). The time instant of the initiation of the test particle motion (matching the pivoting event shown in Fig. 7) is displayed with a dashed vertical line.

This calibration of the He-Ne system was performed *in situ* and resulted in a resolution of 10 µm over the full 1 mm range of motion of the particle. The relationship between the photo-detector output and the position of the mobile particle was determined throughout the entire range of mobile particle displacement. The calibration procedure and the calibration curve are given in Figure 9. He-Ne signal for all calibration runs was observed to be free of oscillations in large time scales. The voltage values for each "test particle displacement step" are time averaged values of 3,000 data points. All of the three calibration experiments were performed under well-controlled ambient light conditions. c1 and c2 were carried out in the flume filled with clean stagnant water, while c3 was done under the actual experimental conditions (LDV was on, flow was on, flow was seeded for LDV measurements). Based on the aforementioned calibration calculations, the three raw calibration data were normalized by their usable range. (Usable voltage range = R_v: the acquired signal between the conditions of initial test particle position (resting), V_{max}, and the step right before the full dislodgement, V_{min}). Resulting data indicate the normalized voltage intensity vs. particle displacement steps (Fig. 9b). All data points follow the same trend, indicating a linear variation of voltage output with particle displacement (Fig. 9b).

Owing to the precisely defined 3D pocket geometry and well-defined motion of the mobile particle within the (streamwise-vertical) x-z plane, both the streamwise, x(t), and vertical, z(t), displacements can be obtained from the calibration results and the He-Ne signal, while the instantaneous local velocity record is provided simultaneously by the LDV system. Figure 10 shows the displacement of the centre of the particle in streamwise direction as a function of time obtained during one of the experiments.

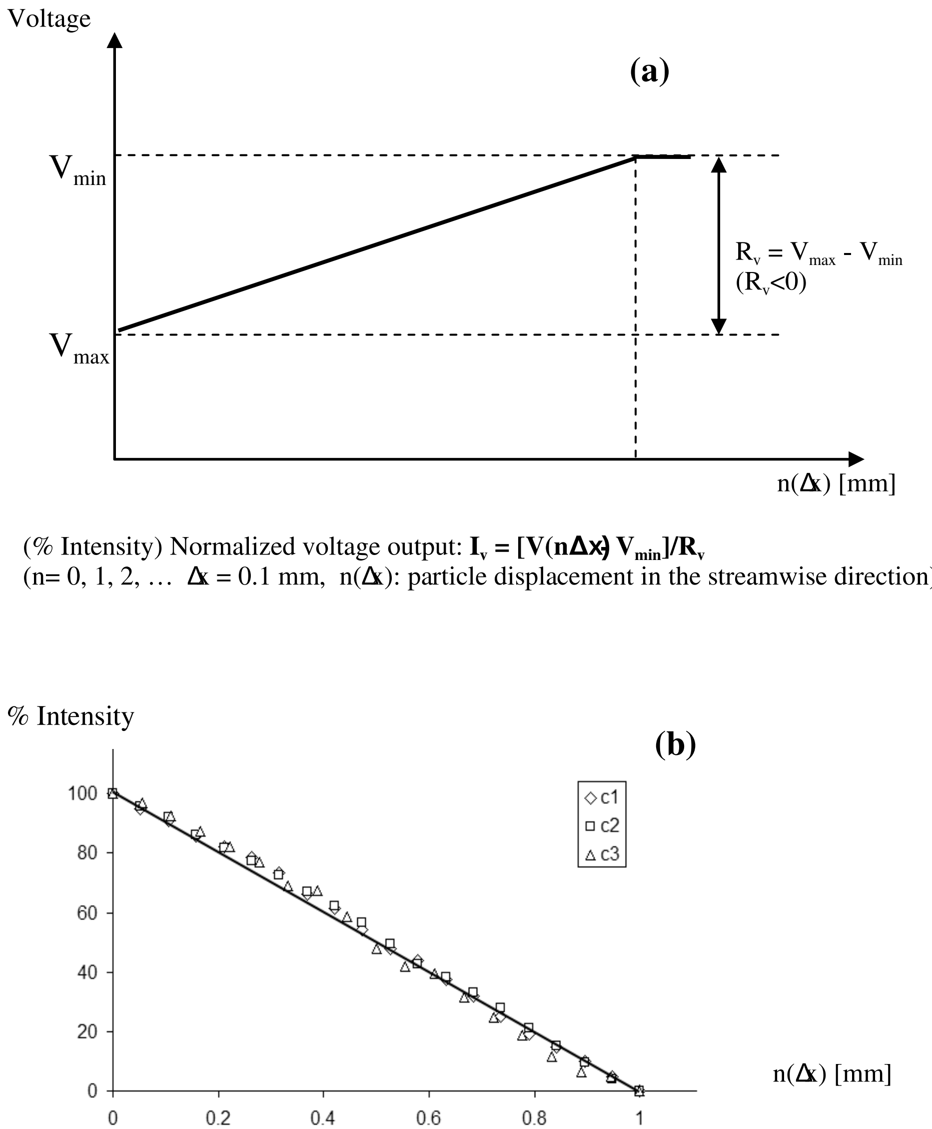

Figure 9. a) Treatment of raw calibration data (voltage vs. displacement); b) Entrainment signal calibration procedure (normalized voltage intensity vs. particle displacement); c1 and c2 data points from still water and c3 from running water tests.

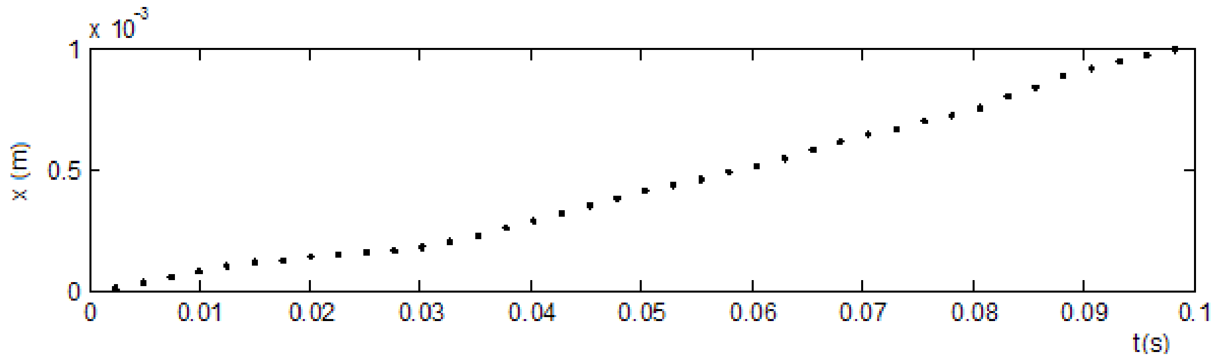

Figure 10. Results from the calibration of the entrainment signal: Displacement of the center of the particle in the streamwise direction.

4. Discussion and Conclusions

The present work demonstrated the high sensitivity of low to moderate bedload transport rates on the presence of small and rather unobtrusive traps used for collecting sediment, even under relatively idealized laboratory flume conditions. For the detection of threshold of motion conditions, it is necessary to employ non-intrusive techniques and objective methodologies for identifying accurately the instant of particle dislodgement. The He-Ne system discussed here appears to satisfy these requirements in well-controlled laboratory conditions. However, this technique is not suitable for use in the field and for higher bedload transport rates. Furthermore, specifying uniquely the threshold condition remains a difficult task as it depends on the frequency of particle dislodgement in both space and time.

Field conditions are much more complex. Typically, the range of particle sizes present in a gravel stream spans several orders of magnitude, bedload transport rates and modes of transportation vary widely among streams, up to 10 orders of magnitude (Diplas and Shaheen 2008), and tend to be highly unsteady, suspended and dissolved load concentrations change substantially, and flow depths exhibit a wide range. All of these factors, together with intricate channel topography and life threatening conditions prevailing during floods, make bedload measurements in a natural setting challenging. It is, therefore, important for new and old technologies to be tested and calibrated over a wide range of flow and bed material conditions. Range of conditions suitable for the use of each method, as well as the error involved in the measurements, need to be determined to the extend possible. The potential of many of these technologies can be evaluated in large laboratory flumes and channels with relatively simple geometry.

Acknowledgements

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