Conference Paper, Published Version

Radice, Alessio; Ballio, Francesco; Nokes, R.

Preliminary results from an application of PTV to bed-load grains

River Flow 2010 - Dittrich, Koll, Aberle & Geisenhainer (eds) - © 2010 Bundesanstalt für Wasserbau ISBN 978-3-939230-00-7

Preliminary results from an application of PTV to bed-load grains

A. Radice & F. Ballio
Politecnico di Milano, Dept. I.I.A.R., Milan, Italy

R. Nokes
University of Canterbury, Dept. of Civ. and Nat. Res. Eng., Christchurch, New Zealand

ABSTRACT: Recent studies on the dynamics of sediment transport have progressively highlighted the need to explain the link between the turbulent near-bed boundary layer and the processes of particle entrainment and transport. As a result, a proper way to recognize and measure the entrainment and motion of individual particles is necessary for joint analysis with water flow field data. In this work we show the results obtained from the application of Particle Tracking Velocimetry (PTV) to bed-load plastic grains in a "natural" bed. Here "natural" means that the particles, though plastic, were not artificially coloured and moved over a background of similar loose ones, with no significant difference from the case of natural sand. Recognition of the moving grains was achieved by means of image subtraction and filtering, while particle tracking was made using the *Fluid Stream* software. The manuscript documents the results obtained from the application to a bed load experiment, as well as the measurement validation. The present limitations of the measurement are acknowledged and some strategies to improve its quality are proposed.

Keywords: Bed load movement; Particle Tracking Velocimetry

1 INTRODUCTION

Recent studies on the dynamics of sediment transport over a plane bed have demonstrated a growing interest for the link between the near-bed turbulent structure and the resulting particle motion. As known, the near-bed velocity fluctuations are organized as a succession of events with a certain degree of coherence (burst cycle, first documented for rough beds by Grass, 1971). At larger scale, the presence of macroturbulent structures has been recognized (e.g., Shvidchenko & Pender, 2001). Some evidence on the turbulence-sediment interaction has been produced (e.g., Drake et al., 1988; Nelson et al., 1995; Sechet & Le Guennec, 1999), yet the results are far from being synthesized in comprehensive conceptual frameworks.

Process visualization and following image processing have proved to be useful for the small-scale investigation of bed load transport (e.g., Fernandez Luque & Van Beek, 1976; Drake et al., 1988; Lee & Hsu, 1994; Nikora et al., 2002, among others). For example, in recent years the authors of the present manuscript have developed a methodology for the Eulerian measurement of sediment transport at intermediate scale (Radice et al., 2006) providing several results on sediment dynamics (e.g., Radice & Ballio, 2008; Radice, 2009; Radice et al., 2009). Yet it has been recognized that an Eulerian analysis does not yield information about entrainment, motion and distrainment of a single particle. To obtain these pieces of information, which are most needed for correlation with the turbulent dynamics of the near-bed boundary layer, a Lagrangian analysis of the single particle motion is needed.

Some examples of such analyses have recently appeared in the literature. Particle identification is the crucial aspect of similar works. In some cases, this has been achieved using very large target stones (as done, for example, by Booij & Hofland, 2004, or Hofland & Booij, 2004). In other cases, an artificial contrast was created releasing particles over a smooth surface (e.g., Sechet & Le Guennec, 1999; Frey et al., 2003) or using painted particles moving over still ones with different colour (e.g., Papanicolaou et al., 1999; Schuyler & Papanicolaou, 2000).

In this manuscript, an attempt is made to follow the motion of individual particles in a "natural-like" bed. With this definition we mean that a bed of loose particles is considered, with no artificial contrast but with a grain chromatic distribution similar to that of natural sand beds. Such configuration obviously complicates the particle identification, but is of larger generality compared to those previously described. In the following, the measuring method is described; some preliminary results are presented, together with the strategies used for measurement validation; potentialities and limitations of the approach are discussed; finally, possible future developments are outlined.

2 EXPERIMENTAL DATA USED

The findings presented here have been obtained using a sample visualization that refers to a bed-load experiment performed by Radice & Ballio (2008). The experiment was conducted in a pressurized duct with transparent walls and lid. The cross section of the duct was 0.40 m wide and 0.16 m deep. The sediments were uniform PVC grains with a specific density of 1.43 and a representative size d = 3.6 mm. Additional details are provided in the referenced paper.

The experiment considered was made with a bulk water velocity of 0.35 m/s, corresponding to 1.14 times the threshold velocity of beginning of motion. The experiment was filmed using a black and white CCD with a resolution of 576×763 pixel at a rate of 50 fps. A picture from the movie of the experiment is presented in Figure 1.

3 MEASUREMENT

3.1 *Particle identification and tracking*

The bed-load particles move over a layer of similar loose ones. Therefore, a crucial step, preliminary to particle tracking, is a proper distinction between the moving grains and those remaining still at the instant of observation.

In this work, the identification of individual moving particles has been performed using the subtraction between consecutive frames. The subtraction produces a third image, which is black (zero difference) for the still particles and different from zero where motion has occurred in the time interval separating the two original frames of the film. More specifically, the image of a moving particle corresponds to a couple of regions, the first of which assumes negative values while the other assumes positive values. The negative-valued region corresponds to the start position of the particle if the latter is lighter than the local background and vice-versa. The opposite holds for the positive-valued region. Grain duplication is eliminated, for example, considering only the positive values in the difference image. After obtaining the difference image, the latter can be processed eliminating image noise, in order to obtain a clearer representation of the moving particles. In this work, two different types of refined images have been used. In the first case, greyscale images have been obtained where the pixels with an intensity lower than a certain threshold have been filtered to zero. In the second case, the filtering procedure by Radice et al. (2006) has been used, which is based on image binarization and on a subsequent selection of the particle blobs exceeding a certain threshold for blob size. Figure 2 presents sample difference and blob images for the movie analyzed in this work.

The second stage of the measurement is the Particle Tracking Velocimetry of the images of particles, either for the greyscale or for the white blobs. The particle tracking has been performed using the *Fluid Stream* software, developed by the second author (Nokes, 2005). The software has been successfully used for application of Particle Tracking Velocimetry to fluid flows (Nikora et al., 2007; Maxworthy & Nokes, 2007; Taylor et al., 2010). Application to bed-load sediments represents a novel frontier for the package. Fluid Stream identifies the centre of mass of each particle in the image and then enables a variety of PTV analyses to be made, with different algorithms for the process of particle matching. State-based tracking and velocity-based tracking are possible. For the images of the present bed-load experiment, which are characterized by low density of the moving particles, the strategy (*distance cost* in the suite) was chosen that evaluates the most probable particle match as that with minimum distance between the particle positions in two successive images (that is, in two successive instants). Figure 3 depicts some sample trajectories obtained with Fluid Stream for the greyscale images.

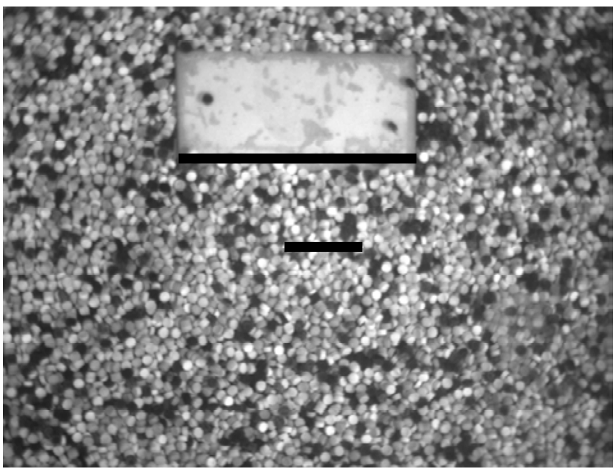

Figure 1. Picture of the sediment bed taken during the bed-load experiment. The metal plate and the black lines are discussed in sub-section 3.2.

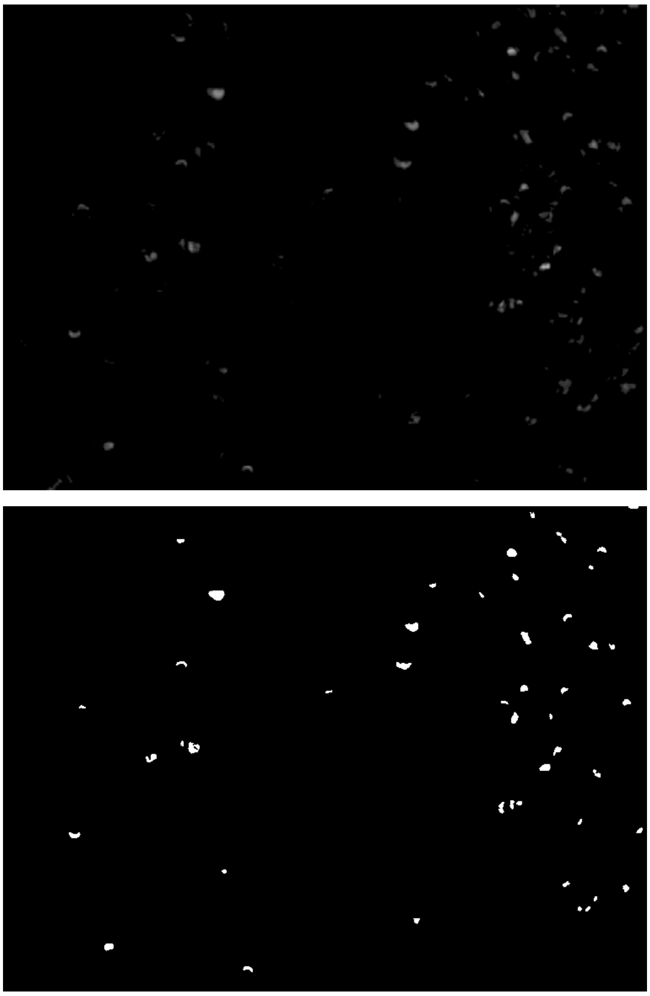

Figure 2. Difference image (top) and blob image (bottom) obtained from two frames of the experiment film.

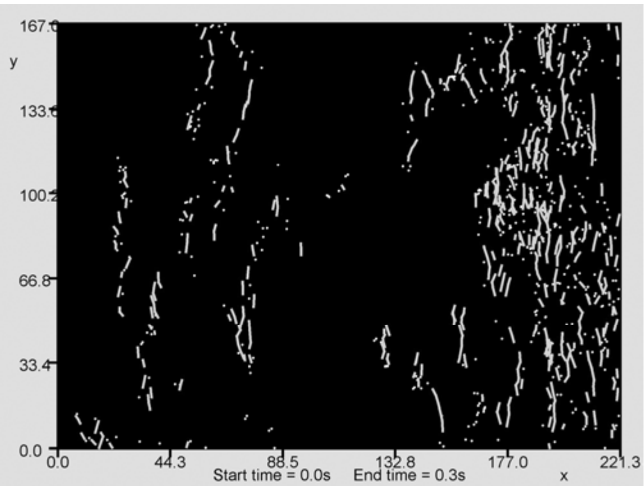

Figure 3. Example of particle trajectories obtained with Fluid Stream (grayscale images). The isolated points correspond to unmatched particles.

3.2 *Methods for validation*

A proper methodology for measurement validation has been sought, to check the reliability of the obtained results. In the following, two strategies will be shown, namely (i) an integral validation and (ii) a trajectory-based validation.

For the integral validation, the particles that, during the experiment, progressively cross the two black lines in Figure 1 have been manually counted. The resulting number has been compared with the number of crossings obtained through the PTV analysis. The first line used is at the upstream edge of a metal plate placed at the sediment level, while the second one is an imaginary sediment-embedded line.

For the trajectory-based validation, a set of particle trajectories has been randomly selected and the corresponding successive particle positions have been manually extracted from the movie. The ability of the PTV analysis to detect these trajectories has been used as a qualitative indicator of measurement reliability.

4 RESULTS OF PTV VALIDATION

The outcome of the integral validation of the measurements is depicted in Figure 4. In general, the PTV measurement underestimates the number of particle crossings. A better behaviour of the greyscale images is evident compared to that of the blob ones. Furthermore, the number of particles crossing the sediment-embedded line is better reproduced than that of the particles crossing the line at the edge of the plate. It is believed that this difference is caused by the colour of the plate, which corresponds to a grey intensity similar to that of many of the moving particles. The number of particles crossing the sediment-embedded line is correctly reproduced if the grey difference images are used for the PTV analysis.

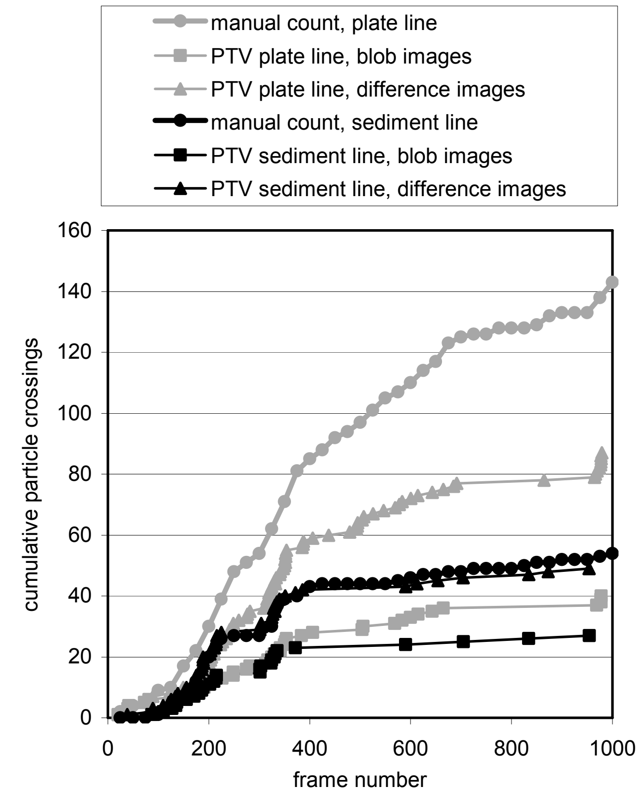

Figure 4. Integral validation of PTV measurements.

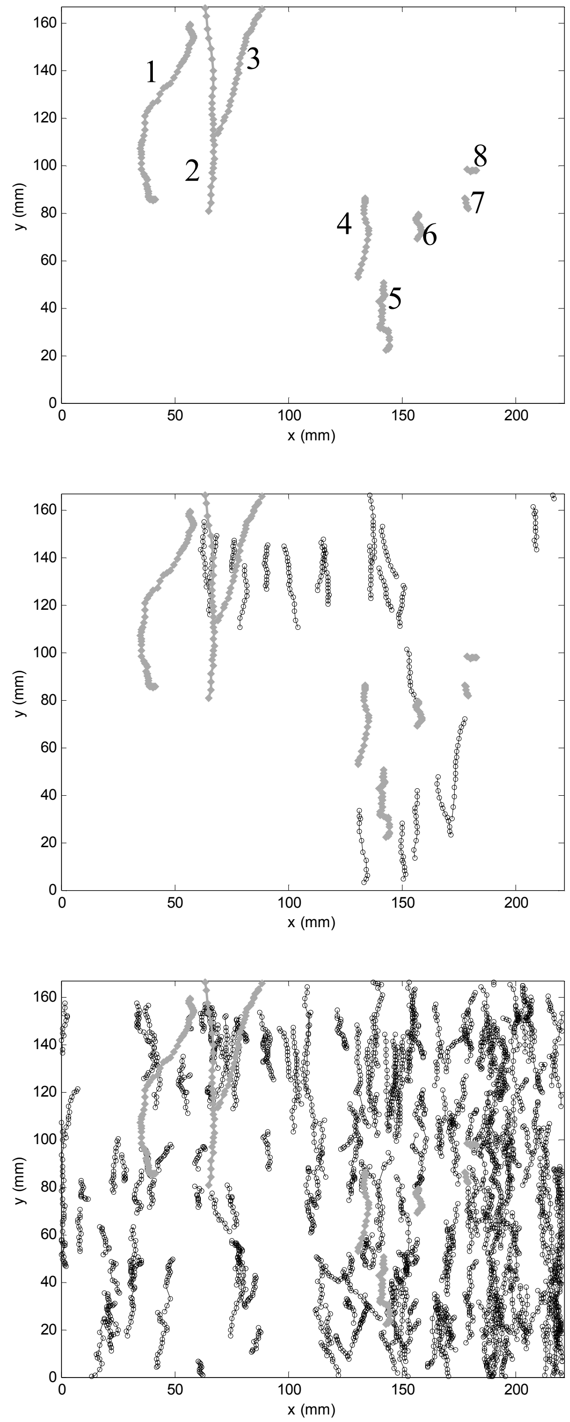

Figure 5. Sample trajectories used for the trajectory-based validation of the PTV measurements (top). Sub-sample of the obtained trajectories (only those with duration larger than 0.2 s) with the blob (middle) and grey images (bottom).

The particle trajectories from Fluid Stream have been compared to the sample trajectories obtained from the manual analysis. The sample trajectories are shown in Figure 5, highlighting the peculiar features of sediment transport: the particles frequently move and stop (as a result, no trajectory spans the entire focus area); the trajectories present highly variable length; even though most paths are directed downstream, several transverse movements are present (see, for example, trajectory number 8). The validation is set out in Figure 5. Parts of the sample trajectories are caught by the automatic measurement, but paths are often split and merged incorrectly, due to interception between the motion of couples of particles. Figure 5 presents only the particle trajectories with a duration larger than 0.2 s. Particle density is larger for the greyscale images than for the blob ones. Indeed, in the former case, a larger number of particles has been detected, with typically larger durations.

5 POTENTIALITIES AND LIMITATIONS

The application of PTV to bed-load particles yields a variety of results. For example, Figure 6 depicts the cumulative frequency distribution of the duration of particle trajectories. According to the plot, the most frequent durations are the shortest, and the distribution presents a long tail on the right-hand side. Similarly, Figure 7 shows the frequency distribution of the average particle velocity during a motion event. The distribution is not symmetrical, with the modal velocity being around 50 mm/s while the mean velocity equals 90 mm/s. The last value is consistent with the Eulerian measurement of velocity made by Radice & Ballio (2008) for the same experiment. The right tails of both distributions reflect the nature of path duration and particle velocity as intrinsically positive quantities being bounded below by the zero value and virtually unbounded above. Finally, Figure 8 presents the temporal evolution of the particle velocity within some of the measured trajectories. Such pieces of information may be useful in development and verification of probabilistic (e.g., Einstein-like) theories of sediment transport.

On the other hand, at the present stage of development the measurement is still affected by too much uncertainty. In this respect, it may be pointed out that bed-load particles represent a tougher challenge for PTV compared to particle tracers in a fluid flow. For example, as seen, the motion is not continuous, with frequent starts and stops. Furthermore, the particle trajectories are often not smooth, due to collisions between the moving and the still grains. Finally, a technique like that presented here suffers from another problem, which is related to the temporal resolution of the measurement: since the identification of the moving particles is made by means of a subtraction between consecutive frames, a single matching process requires two difference images and thus three frames of the original movie. Wang et al. (2009) proposed to apply the PTV to two difference images, with the first difference image being the first frame minus the second (1-2) while the second difference image is the second frame minus the first (2-1). In this case, this procedure could not be applied since the particles used were variable in colour. In some cases the moving particles were lighter than the local background and in other cases they were darker. As a result, there was no systematic correspondence between the (1-2) difference and the particle start positions and between the (2-1) difference and the particle stop positions.

6 STRATEGIES FOR DEVELOPMENT

The Lagrangian measurement of particle motion described here is a combination of two steps, namely the particle identification and the matching process. Both these phases can be improved to obtain a more reliable measurement. In this section some strategies are outlined.

Particle identification is a crucial step in the measurement. The choice to work releasing particles over a smooth bed or releasing coloured particles over a fixed bed of non-coloured ones may surely help this step. Yet, at the same time, it seems undesirable, since in this way the motion of the released particles would be measured, instead of that of the grains that are entrained by the flow field (with all particles eligible for motion). It should be possible to avoid the image subtraction working with colour images. In this way, the particles (still or moving) may be identified based on their colour and afterwards the moving particles may be tracked. In such a way, the use of the original movie frames would also avoid the need for three frames for a single measurement of particle velocities.

The particle matching algorithm may be also improved. In this respect, for example, the second author is presently developing a method to consider the shape of the particles as a further criterion to choose the best matches.

Of course, proper validation strategies will be devised. In this respect, the integral validation used here had a satisfactory outcome even if the trajectory-based validation had evident faults. This likely indicates that the integral validation may be quite insensitive to the correctness of the matching process in PTV.

7 CONCLUSIONS

The present manuscript has presented a tentative application of Particle Tracking Velocimetry to bed-load particles, as a step towards obtaining Lagrangian measurements of particle motion to support the development of probabilistic models for bed load.

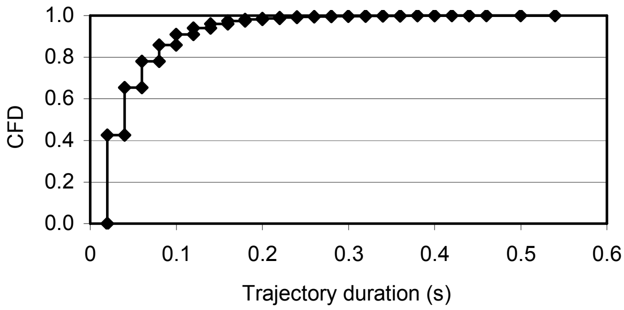

Figure 6. Cumulative frequency distribution of travel times (in seconds) for the grey images.

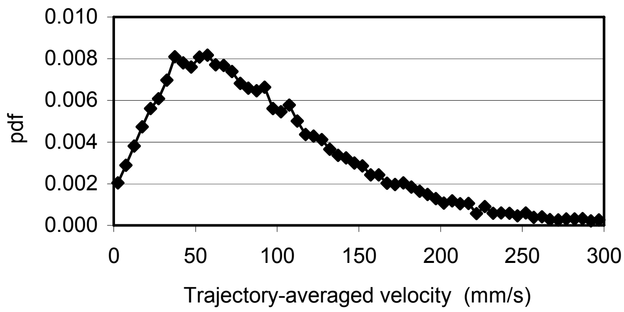

Figure 7. Frequency distribution of average velocity in a trajectory (in mm/s) for the grey images.

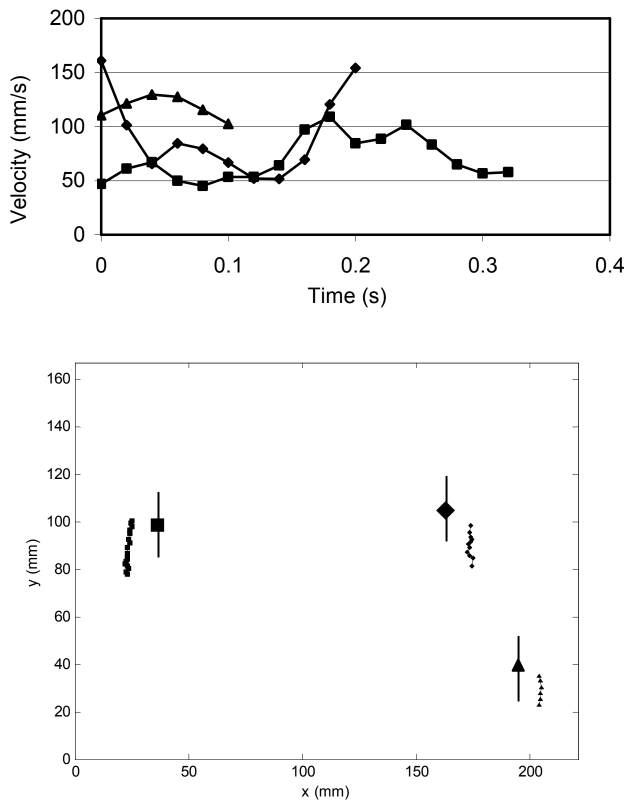

Figure 8. Evolution of longitudinal velocity in some sample jumps for the grey images. Symbols in the temporal plot and in the plan view correspond.

The PTV analysis has been applied to a bed-load experiment conducted during earlier work. The moving particles have been identified by image subtraction and the match between the particles in subsequent difference images has been made using the Fluid Stream software.

The sample results have shown the unquestionable potentialities of a Lagrangian analysis of particle motion. On the other hand, some flaws of the measurement as it presently is have been highlighted. Even if the results are encouraging, reliability of the measurement is still not enough for robust conclusions to be drawn. Proper strategies for improvement of the measurement have been sketched.

ACKNOWLEDGMENTS

This work has been supported by the Italian Ministry of University and Research under the 'MOMICS' Project. The Authors wish to thank Paolo Cravedi and Serena Scotton, who have contributed to the work during their B.Sc. Thesis.

REFERENCES

Booij, R., Hofland, B. 2004. Measurement of the mechanisms of stone entrainment. Proc. ICSE 2004, II Int. Conf. on Scour and Erosion, Singapore, 2, 260-267.

Drake, T.G., Shreve, R.L., Dietrich, W.E., Whiting, P.J., Leopold, L.B. 1988. Bedload transport of fine gravel observed by motion-picture photography. Journal of Fluid Mechanics, 192, 193-217.

Fernandez Luque, R., Van Beek, R. 1976. Erosion and transport of bed-load sediment. Journal of Hydraulic Research, 14, 127-144.

Frey, P., Ducottet, C., Jay, J. 2003. Fluctuations of bed load solid discharge and grain size distribution on steep slopes with image analysis. Experiments in Fluids, 35, 589-597.

Grass, A.J. 1971. Structural features of turbulent flow over smooth and rough boundaries. Journal of Fluid Mechanics, 50, 233-255.

Hofland, B., Booij, R. 2004. Measuring the flow structures that initiate stone movement. Proc. River Flow 2004, II Int. Conf. on Fluvial Hydraulics, Naples, Italy, 1, 821-830.

Lee, H.L., Hsu, I.S. 1994. Investigation of saltating particle motions. Journal of Hydraulic Engineering, 120, 831-845.

Maxworthy, T., Nokes, R. 2007. Experiments on gravity currents propagating down slopes. Part 1: The effect of initial conditions on the release of a fixed volume of heavy fluid from an enclosed lock into an open channel. Journal of Fluid Mechanics, 584, 433-453.

Nelson, J.M., Shreve, R.L., McLean, S.R., Drake, T.G. 1995. Role of near-bed turbulence in bed load transport and bed form mechanics. Water Resources Research, 31(8), 2071-2086.

Nikora, V., Habersack, H., Huber, T., McEwan, I. 2002. On bed particle diffusion in gravel bed flows under weak bed load transport. Water Resources Research, 38; DOI: 10.1029/2001WR000513.

Nikora, V., Nokes, R., Veale, W., Davidson, M., Jirka, G. 2007. Large scale structure of uniform shallow free-surface flows. Environmental Fluid Mechanics, 7(2), 159-172.

Nokes, R. 2005. FluidStream, version 6.01: system theory and design. Dept. of Civil Engineering, University of Canterbury, New Zealand.

Papanicolaou, A.N., Diplas, P., Balakrishnan, M., Dancey, C.L. 1999. Computer vision technique for tracking bed load movement. Journal of Computing in Civil Engineering, 13(2), 962-970.

Radice, A. 2009. Use of the Lorenz curve to quantify statistical nonuniformity of sediment transport rate. Journal of Hydraulic Engineering, 135(4), 320-326.

Radice, A., Ballio, F. 2008. Double-average characteristics of sediment motion in one-dimensional bed load. Acta Geophysica, 56(3), 654-668; DOI: 10.2478/s11600-008-0015-0.

Radice, A., Ballio, F., Nikora, V. 2009. On statistical properties of bed load sediment concentration. Water Resources Research, 45, W06501; DOI: 10.1029/2008 WR007192.

Radice, A., Malavasi, S., Ballio, F. 2006. Solid transport measurements through image processing. Experiments in Fluids, 41, 721-734.

Schuyler, A., Papanicolaou, A.N. 2000. Image analysis technique to track the evolution of sediment clusters. Experimental Techniques, 24(5), 31-34.

Sechet, P., Le Guennec, B. 1999. Bursting phenomenon and incipient motion of solid particles in bed-load transport. Journal of Hydraulic Research, 37(5), 683-696.

Shvidchenko, A.B., Pender, G. 2001. "Macroturbulent structure of open-channel flow over gravel beds." Water Resources Research, 37, 709-719.

Taylor, D.I., Delaux, S., Stevens, C., Nokes, R., Shiel, D. 2010. Settlement rates of macroalgal algal zygotes: Cross-species comparisons of settlement in a turbulent stirred tank. Limnology and Oceanography, 55(1), 66-76.

Wang, Y., Wang, D., Wang, L., Zhang, Y. 2009. Measurement of sand creep on a flat sand bed using a high-speed digital camera. Sedimentology, 56, 1705-1712, DOI: 10.1111/j.1365-3091.2009.01053.x.