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Advanced Particle Tracking for Sediment Movement on River Beds: A Laboratory Study

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Abstract

The behaviour of sediment transport has been investigated through photogrammetry assisted observation of individual particle movement. This movement is difficult to predict and is dependent on factors such as local turbulence bursts, particle physical properties and shielding or protrusion from the surrounding bed [1]. To improve the understanding of particle movement, an artificial river bed was closely observed using a particle tracking program developed by the author. All particles larger than 80% of the bed substrate were monitored. Particle movements were recorded and the position, dimensions and orientation of these are presented.

Introduction

Sediment transport is a complicated process, which is influenced by a number of factors. The initial entrainment of grains has attracted extensive investigation over the past few decades and is still being studied in depth [2-6]. Similarly, generalised bed load transport has been extensively researched, with questions still to be answered regarding the trends and processes behind particle movement [7, 8]. These two subjects are intrinsic to sediment motion, and it is their influence which contributes to the apparently random nature of particle movement. An understanding of particle movement can lead to insights into the formation of more coherent morphological structures on the bed surface, such as pebble clusters, ribs and riffle pools [1]. Sediment hiding and protrusion effects complicate the entrainment of particles, and as a result, entrainment of particles is not only related to their absolute size, but also their relative size [3, 4, 6, 9-11]. Digital Particle Tracking (DPT) can provide further insights into the behaviour of particles, as they are transported by allowing quantitative observation of individual particle movement.

While particle tracking is relatively easy to do by eye, it is a slow and laborious task. Technological advances have assisted in making image analysis a popular method for investigating sediment transport [12-16]. However, particle tracking of bed load movement is difficult as individual particles sporadically move in isolation to the rest of the bed. This requires a different tool to those developed for particle movement in the fluid column such as PIV and PTV [17]. Differentiation between a moving particle and the background can be obtained by image subtraction, which provides the viewer with only those parts of the image which have changed between two consecutive images [12]. Using this concept together with distinctive particles, a suitable frame rate, high quality images and information on the actual limits of particle movement, enables the development of a successful DPT tool [16]. In an attempt to determine the characteristics of gravel particle movement under constant flow, particles were observed continuously over an extended period of time. Photogrammetry and particle tracking were employed to provide a record of the particle movement and orientation for the gravel particles in a graded river channel.

Methodology

Experiments were conducted in the Hydraulics Laboratory at The University of Auckland. The flume used was 0.45 m wide, 0.45 m deep and 19 m long. The test section comprised of a fixed bed with a vertically adjustable recess filled with rounded river gravels. The sediment was well graded, with D_{98} = 25 mm and D_{50} = 4.5 mm. The gravel was initially manually mixed and placed into the sediment recess of the flume, so that it lay flush with the false floor. The bed was then water worked for 350 min with an average velocity of u_{av} = 0.912 m/s and bed shear velocity u^* = 0.0774 m/s. There was no sediment supply. Plan view images of the bed surface were continuously taken at 1fps, using a Nikon D90 camera. The gravel in the test section was separated into five size groups, with each group painted a different colour to enable identification of different sized particles. Thresholds for size groups were chosen to be D_{38}, D_{55}, D_{80} and D_{98}, of the grading curve. The test section was equipped with an adjustable table, allowing the bed material in the test section to remain flush with the fixed bed on either side of the section, throughout the experiment. To enable capture of a clear image of the surface sediment, a Perspex skimmer was fabricated to eliminate surface waves and ripples. The skimmer was vertically adjustable to enable it to sit lightly on the water surface. A velocity profile was taken of the flow upstream of the test section.

Matlab was used for all of the image processing and analysis of the photographs. Images were loaded into Matlab and calibrated for processing. The different colours were isolated enabling work with individual size fractions. A particle tracking algorithm was developed and the larger size fractions were successfully tracked. An example of this is shown in Figure 1. In a 100 frame accuracy test, 100% accuracy was achieved for the largest fraction, and 88% positive detection and 1.5% false detection was achieved for the second largest fraction. Tracking accuracy was far more diminished for smaller sizes due to their more dispersed nature and the 0.5fps frame rate which was not fast enough to capture a manageable amount of particles to track. Results from the tracking provided information on the x and y position of the particle, particle area in the plan view, long and short axis dimension, orientation and time of movement for any moved particle in the test section.

The particle tracking procedure analysed 11,413 images, with one image taken every 2 seconds. The surface area of the test section had a width of 45 mm and length of 950 mm, creating an area of 0.43 m^2. Results presented are the raw number of particles, which move within this area. Each movement represents one change in position that was made by an individual particle within a 2 s interval. A minimum threshold of 20 mm, equal to 80% or the maximum analysed grain size, was created to separate the rotation of particles from those which were displaced.

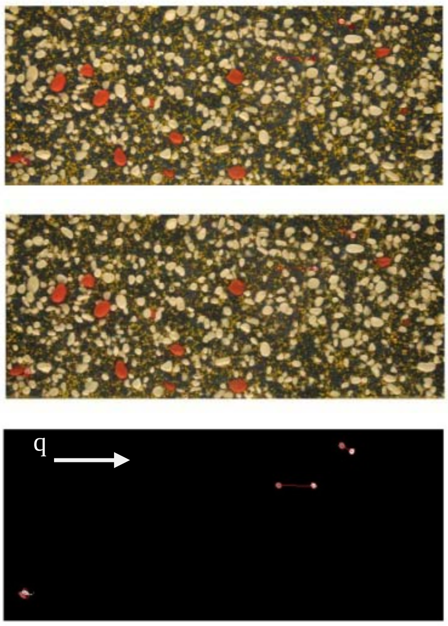

Figure 1. Image tracking example, top Figure shows image i, middle Figure shows image i+1, bottom Figure shows image subtraction (i-i+1) result.

Results and discussion

Surface grading curve

The different coloured particles allowed a quantification of the surface coverage of sediment over time (Figure 2). While this quantification of sediment is different to the traditional approach, which involves sampling the sediment in the top layer of the bed, it gives a good indication of the trend of the surface grain size over time. The initial grading curve was determined by sieve analysis (Figure 2, t=0). The subsequent grading curves show a trend towards coarsening of the bed, at a decreasing rate. The maximum surface coverage reached was 91%, due to shadows in the images, which reduce the detection of colours, particularly where the particles were coloured in darker shades.

A computation of theoretical $(d_{50}a)_{max}$ for a completely armoured bed was calculated using Chin's (1985) equation for static armour layers [18]:

$$(d_{50}a)_{\max} = \frac{d_{\max}}{1.8} = \frac{27}{1.8} = 15mm \tag{1}$$

where $(d_{50}a)_{max}$ is the maximum size that the average grainsize will reach in a fully armoured bed and d_{max} is the maximum grain size available in the bed. This value is plotted in Figure 2, and indicates there is a significant degree of armouring to undergo, before the maximum armoured state has been reached.

Particle movement over time

The number of particle movements in each minute was measured, in order to provide an observation of the rate of transport over time (Figure 3). A simple linear regression was added, to display the general decrease in sediment movement over time. There is still significant sediment flux occurring at the later stages of the 6 hour test. This indicates that there is a significant degree of armouring to undergo before the maximum armoured state has been reached, as is also indicated by Equation 1. It is expected that a fully armoured bed would show very little movement as there is no upstream sediment supply. The figure also shows patterns of high rates of flux and low rates of flux at different stages of the experiment. Peaks can be seen around 25, 150, and 310 minutes, and minimums around 75 and 240 minutes.

The particle movement time interval was deduced through subtraction of the time at which consecutive particles were found to move. This is displayed in a histogram (Figure 4), to highlight this aspect of particle movement patterns. The most common time interval between particles is between 0 and 2 seconds, but this can range up to 200 seconds. The average time between movements was 14 seconds. These results suggest that particle movement occurs in patterns, where particles are more likely to move when other particles are moving. This could be related to the larger sediment movement patterns observed in Figure 3. Additionally, this could be related to turbulence bursts, where the interaction of the burst with the bed causes a number of particles to move in response. Investigation into near bed, instantaneous shear stresses have found them to be significantly larger than average shear stresses by approximately 1.4 times [19]. The instantaneous stresses required to entrain a particle are therefore lower than the average shear stress [20]. This phenomenon is considered to be largely responsible for the stochastic nature of sediment entrainment, and may also be responsible for the entrainment of groups of particles. Further investigation into the flow field and the movement patterns is required, before this idea can be further developed.

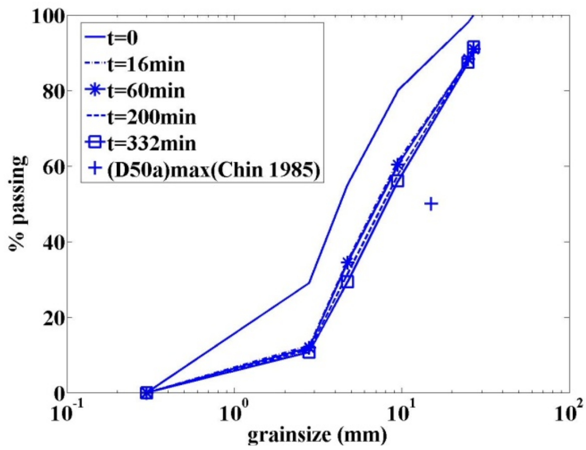

Figure 2. Change in grading curve over duration of experiment.

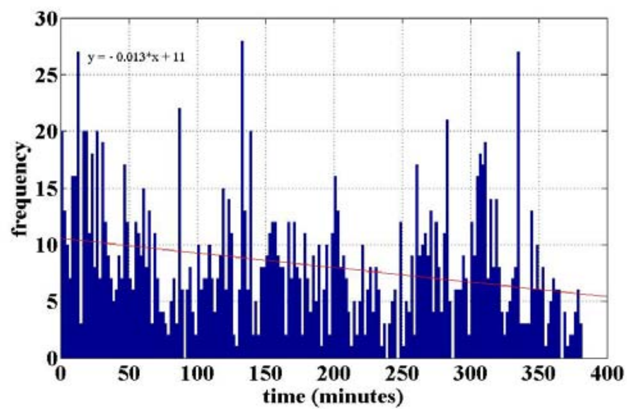

Figure 3. Frequency of particle movements (greater than the maximum particle diameter) over the duration of the experiment.

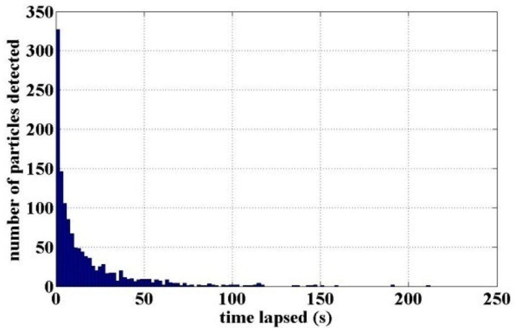

Figure 4. Histogram of the time elapsed between individual particle movements.

Figure 5 shows the overall spatial distribution of particle movement. This observation was achieved by dividing the test section into a grid with 34x34 mm spacing and counting the frequency of particles entrained from each section. This shows that the majority of the particles were removed from the upstream end of the test section, which is to be expected due to the rotation of the bed [18]. A compounding factor in this result is that the particle tracking program only detected particles that were both entrained and deposited within the test section, therefore eliminating any chance of detection of particles that moved from the test section to further downstream. Entrainment of the particles occurred primarily toward the centre of the channel, but was skewed to the side of the channel centreline.

The distance travelled by a particle has been compared to the particle size (Figure 6). This is an interesting relationship in that the distance travelled is not always a function of particle size, as one might expect. An envelope can be fitted around the data, which shows that the maximum particle size, which moved at each distance, does decrease with the travelled distance. A simulation of particle movements was conducted by Malmaeus and Marwan [1], where particle movements were generated using a number of rules, based on the expected behaviour of particles. Their results show a similar, but more exaggerated trend, where larger particles travel smaller distances and smaller particles travel longer distances. Their results show a relatively bimodal trend, where none of the larger particles travel distances remotely close to those travelled by smaller particles [1]. It can be seen that shorter distances are travelled more frequently and smaller particles are more likely to do so than larger ones. However, this also correlates to the size grading, where there is a larger proportion of smaller particles available.

Particle orientation

Data obtained from the DPT process also included the orientation of the particle, where the particle shape was simplified into an ellipse, with the long axis corresponding to the major axis length, with the same normalised second central moments of the region. The orientation of the particle is the angle between the y-axis (transverse to flow) of the image and the major axis of the particle. Due to the assumed symmetry of ellipse, this angle ranges only between 0 and 180 degrees. This is done through the Matlab command ‘regionprops’, with the input command ‘orientation’ used from the image processing toolbox.

The detected particles were separated by distance travelled into two groups; those which travelled less than 20 mm and those which travelled more than 20 mm. This is to differentiate between particles which remain in place but are shifting or rotating slightly, and those which actually travel a distance. The orientation of these groups both before and after movement is presented in Figures 7 and 8.

Figure 7 displays the orientation of particles as they move but remain in position. Both plots show that the primary orientation is transverse to the direction of flow. This aligns well with current knowledge which states that the most stable orientation of a particle is that where its major axis is transverse to the flow [19]. It can be observed that this trend is more pronounced in Figure 7b, which implies the particles move towards an increasingly transverse position.

Figure 8 shows an opposite trend, in which particle orientation is similar to the direction of flow. This means that when a particle is moving, it rotates to become more streamlined. Similarly to the trend in Figure 7b, Figure 8b shows a more pronounced trend than Figure 8a. In order to add detail to this process, a higher frame rate must be used. The current rate of 2 fps gives only an image of the particle either mid-flight or stationary before and after movement. A higher frame rate would allow insight into the rotation process before and after landing.

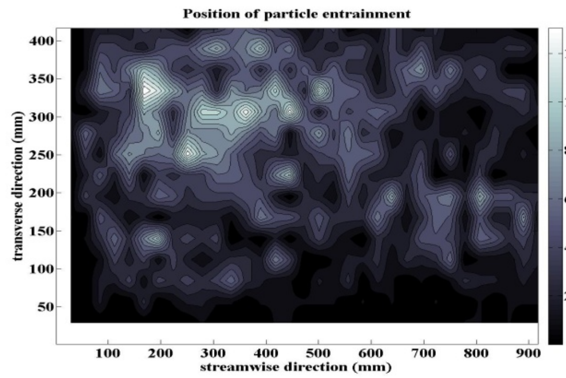

Figure 5. Frequency of position of particle entrainment (number of particles entrained from the bed for the duration of the test. Tallied by dividing the bed into a grid)

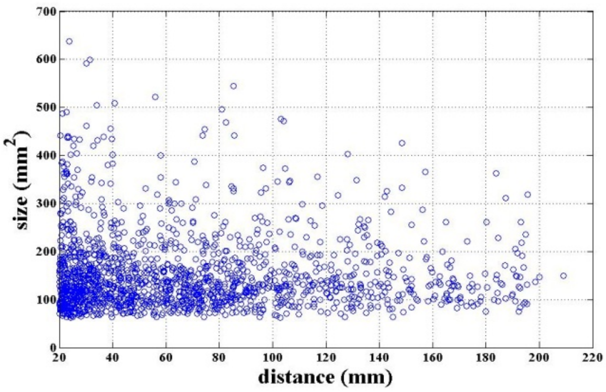

Figure 6. Relationship between distance moved by individual particles and particle size

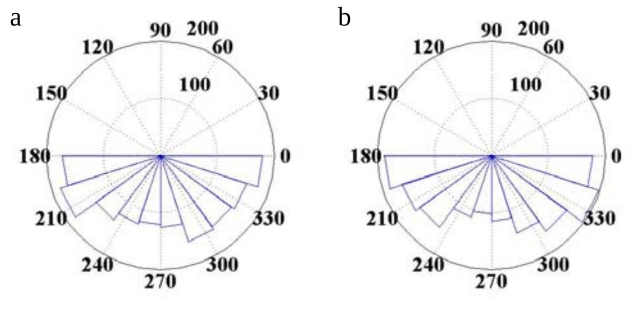

Figure 7. Orientation of particle a) prior to and b) subsequent to small movement (distance moved less than the maxi mum particle diameter)

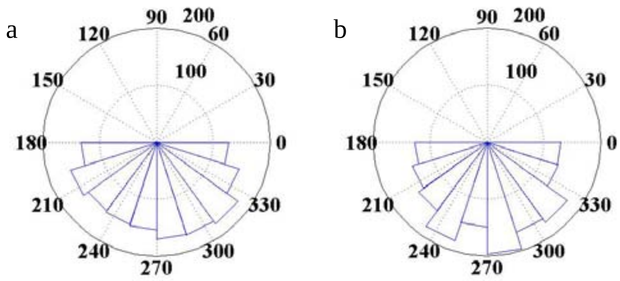

Figure 8. Orientation of particle a) prior to and b) subsequent to entrainment (ie. movement greater than the maximum particle diameter)

Conclusions

This paper displays the results obtained from a particle tracking algorithm, which was used to analyse 6 hours of images of the evolution of an artificially created river bed, while being water worked. Only the larger size particles were analysed. The results are useful as a step towards fully understanding the behaviour of sediment, as it is transported downstream.

Data collected from the particle tracking included the x and y position of a particle before and after displacement, particle size, major and minor axis details, orientation and the time at which movement took place. This has allowed presentation of the surface grain size distribution at various times over the duration of the experiment, the frequency of particle movement per minute, the time lapsed between particle movements, position of entrainment for all moved particles, a comparison between distance travelled and the plan area of the entrained particle and the orientation of particles before and after movement or entrainment.

Observation of these results indicates that further investigation into the relationship between particle movement and turbulence in the flow promises to be useful in showing the effect of turbulence bursts on the river bed. The relationship between particle size and the distance travelled shows that generally larger particles tend to move less far than smaller particles, however this is loosely constrained. Finally, particle orientation when only shifting slightly conforms to the known rule that the particle is most stable with its long axis transverse to the flow. Moving particles showed the opposite of this, that is, when moving the long axis of the particle tended to be in a similar direction to the flow.

Further investigation at a higher frame rate with additional flow information could provide some valuable insights into the behaviour of individual particles on a river bed.

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