# CHANGE OF PARTICLE SIZE DISTRIBUTION DURING CLUSTER EVOLUTION

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**Abstract**

The interaction between a gravel bed in a river and the localised flow is complicated, and knowledge of this is important for modelling the processes and characteristics of a stream channel. Stream bed armouring is a common phenomenon in gravel-bed rivers. Armouring occurs when selective entrainment of smaller, more unstable particles leaves a bed with a larger average surface gravel size than that of the underlying bed (Best 1993; Chin 1985; Nino and Musalem 2000). The armour layer of the gravel bed generally consists of cluster formations, where small and medium sized particles congregate around larger particles to form more stable structures (Brayshaw et al. 1983).

In order to further investigate the mechanics of cluster formation, an experiment using well graded sediment was conducted in the Hydraulics Laboratory at The University of Auckland. Formation of the armour layer over a test section in the flume was observed at three different flow rates. Flow data were collected with an Acoustic Doppler Velocimeter probe and gravel-bed properties were identified using photogrammetry. In order to enable identification of patterns which form due to variation in gravel size, different sized gravel particles in the test area were painted in different colours. At the beginning of each experiment, a 15 minute video was taken from aerial and side views, and then photographs and short videos were taken at regular intervals for the remainder of each experiment. To obtain quantitative results regarding the characteristics of the armour layer, image analysis was conducted using the programs Adobe Photoshop, ImageJ and Matlab. This paper details the methods developed to enable the retrieval of quantitative information from such experiments.

**Key Words :** Cluster formation, Armouring, Sediment transport, Photogrammetry, Image processing

## 1 INTRODUCTION

The movement of water over a bed of sediment results in the entrainment of particles. Investigation into sediment transport is important for revealing the behaviour of interactions between the fluid and the river bed. In water worked graded river beds, the finer sediment will be entrained earlier than the larger particles. The initial entrainment of a particle is usually a result of peak Reynolds stresses in the local flow field. When this occurs, some of the particles in the cohesionless bed will begin to move. This point of initial movement is called the ‘critical condition’ or ‘incipient condition’ ($T_{*cr}$) (Graf 1971). Not all particles in the surface layer of the bed will be entrained at the same time, due to the turbulent nature of the flow, sediment grading and the resulting fluctuations of hydrodynamic forces (Graf 1971). At the critical condition ($T_{*cr}$) the selective entrainment of sediment particles leaves the larger, more stable particles on the river bed. As flows increase, the frequency of entrainment increases and an armour layer begins to form. The armour layer is a layer of sediment with a larger average size than the underlying bed (Chin 1985).

## 2 BACKGROUND

The armour layer is comprised partially of cluster formations, which are more stable than individual particles. The cluster formations have a notable effect on bedload transport (Strom et al. 2004), they can provide bed stability either directly, through the retention of sediment within the cluster formation, or indirectly by reducing exposure of neighbouring particles (Brayshaw et al. 1983).

Cluster formations comprise of three distinct sections; the obstacle, stoss and wake. The obstacle is an unusually large bed particle (clast) that is deposited on the river bed. This provides an anchor for the cluster and initiates cluster formation (Brayshaw 1984). The obstacle clast, or anchor stone, is usually in the $D_{98}$ to $D_{99}$ fraction of the bed gravel (Brayshaw 1984). The area upstream of the anchor stone is referred to as the stoss, which is a relatively stable zone (Billi 1988) Sediment in the stoss area is usually in the size range of $D_{74}$ to $D_{94}$ (Brayshaw 1984). The area downstream of the anchor stone is termed the wake, with sediment sizes in the range of $D_8$ to $D_{46}$ (Brayshaw et al. 1983). The wake sediment is the least stable and is prone to re-entrainment and replacement deposition (Billi 1988). High local boundary shear stresses on either side of the anchor stone mean these areas are unlikely to have particles come to rest (Brayshaw et al. 1983).

Traditional analysis of cluster formations has relied on manual collection of data through observation, generally assisted by photography. The monitoring of cluster formation and disintegration in rivers is conducted by tagging and surveying cluster formations before and after flood flows (Biggs et al. 1997; Strom 2006; Strom et al. 2005). Laboratory experiments into the parameters which affect cluster formation have generally been conducted on idealised spherical particles using observation and manual counting of the particles to gather results (Papanicolaou and Schuyler 2003).

A recent technique for the acquisition of information from a gravel-bed test area is the use of photogrammetry. This uses photography to capture images of the bed during cluster development, and then analysis to retrieve quantitative data from the image (Moore 1976). This application of photogrammetry has not been explored in-depth, and currently only a couple of studies have used this technique (Lane et al. 2001; Schuyler and Papanicolaou 2000). The ability of digital analysis to deal with vast quantities of data in relatively short amounts of time indicates the potential to conduct detailed investigation into areas which previously would have been too time consuming (Heays et al. 2010).

An artificial bed was created to investigate the development of cluster formations. The bed was a well graded gravel test section and was observed using photogrammetry. Cluster formations were identified during experiments. Analysis of these is discussed in the following sections.

## 3 EXPERIMENTAL SETUP

The cluster experiments were conducted in the Hydraulics Laboratory at The University of Auckland. The flume used was 0.45 m wide, 0.5 m deep and 19 m long. The test section comprised of a fixed bed with a vertically adjustable recess filled with graded rounded gravel. A constant flow rate of $0.07 m^3/s$ was run through the flume and aerial photographs were taken of the test section for the duration of the experiment.

The gravel in the test section was separated into five size groups and each group was painted a different colour to enable identification of different sized particles. Thresholds for size groups were chosen to be the $D_{38}$, $D_{55}$, $D_{80}$ and $D_{98}$, thus fitting roughly into the predictable size groups for the anchor stone, stoss and wake formations. The colours used for painting the rocks were chosen to be as visually different as possible, and were decided to be grey, yellow, green, white and red were used in ascending size order. Four flood lights were used to illuminate the test area surface, with two lights on either side of the flume. 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 each experiment. To eliminate distortion of the image from fluctuations on the water surface reflecting and refracting light, a 1 m long Perspex skimmer was fabricated. The skimmer was adjustable to enable it to sit lightly on the surface of the water. Velocity information was obtained using the Acoustic Doppler Velocimeter (ADV). Velocity profiles were recorded downstream of the test section with the ADV for all tests.

The images taken of the experiment were loaded onto the computer's hard drive either continuously during the experiment for the NikonD90, or periodically during the experiment for the Canon Powershot TX1. The video footage was loaded into Image Grabber, a software which extracts still frames from video. Matlab was the main tool used for image analysis, and code was written to first of all calibrate the images, and then to perform surface grading analysis and/or particle tracking.

Before analysing the images for cluster evolution, they required calibration to remove distortion created by the camera lens. The images were also observed for basic trends in surface grading and tracking of the largest size fraction of particles. For more in-depth details about this work, and for a comprehensive description of the camera specifications and set up, refer to Heays et al. (2010).

# 4 CLUSTER ANALYSIS METHODOLOGY

Observation of the cluster formation process showed that initially a buried anchor stone would be initially uncovered as surface sediment was entrained, then medium sized particles were deposited upstream of the anchor stone, as well as the build up of very small sediment particles in the wake of the anchor stone. The typical cluster would remain in this state for a period of time, and then disintegrate. At this point, the anchor stone would be swept downstream and then re-deposited, where a new cluster would form, repeating the process.

## 4.1 Cluster boundary determination

To begin modelling this process, the distribution of particles in one cluster during one moment in time was observed. This presented the problem of defining the spatial boundaries of the cluster. Solving this problem was identified as the first goal for achieving the quantitative analysis of cluster formations. Subsequent goals for cluster analysis were identified as analysing the spatial distribution of the particle size within the cluster over time, and conducting particle tracking of particles comprising the cluster, eventually combining this with information about the local pressure distribution over time.

The method to achieve the first goal, determination of the cluster boundaries, is discussed in this paper. The method developed comprised of the following steps:

1. Identify the cluster of interest
2. Determine side boundaries
3. Crop a strip the length of the test section
4. Determine the surface colour coverage along the length of the strip
5. Use the colour distributions along the strip to determine the boundary coordinates

Step 1: For the development of the procedure, a naturally formed cluster with a clearly identifiable stoss and wake region was chosen from one image.

Step 2: To determine the spatial boundaries of the cluster, first of all the side boundaries were assumed to be set at the edge of the anchor stone, as the high shear stresses on either side of the anchor stone discourage deposition in these areas (Brayshaw et al. 1983).

Step 3: The upstream and downstream limits are visually identifiable, and are therefore quantifiable. Analysis of the size composition of the stoss and wake should show that the two sections have respectively a higher percentage of larger and, and a higher percentage of smaller particles than the average grading curve for the bed. A strip was cut from the image which has the width of the cluster from which the upstream and downstream cluster limits could be calculated (Figure 1).

Step 4: Vertical sections of the strip that were 5 pixels wide were analysed individually to determine the composition of colours in that section. For a description of the algorithm development for this application refer to (Heays et al. 2010). This produced the red, white, green, yellow and grey percentage coverage for each 5 pixel wide section of the strip. These percentages were then plotted, producing a graph showing how the amount of area covered by each of the colours varied along the length of the strip (Figure 2).

Step 5: The distribution of colour along the test section was observed to detect any trends in the data. Where the cluster is present there should be a different grading to that of the rest of the bed. The coordinates of the upstream and downstream boundary of the cluster can then be used to isolate the cluster for further analysis.

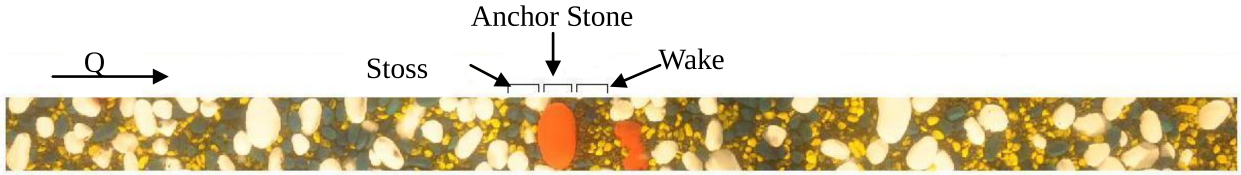



**Figure 1. Strip cropped to the width of the cluster**

## 4.2 Particle size distribution within cluster

The particle size distribution within the cluster was observed both at one instant, when the cluster was fully developed and over time as the cluster formed and disintegrated. The instantaneous particle size distribution in the cluster was determined by dividing the cluster into three regions; the stoss, wake and anchor stone. The size distribution in the stoss and wake were calculated using the surface grading algorithm described in (Heays et al. 2010).

Observation of the size composition of the cluster was observed over a 3.5 hour period. The images analysed were those from the beginning of the experiment until recording stopped. One frame per minute from this duration was analysed.

First, the presence of the anchor stone within the entire cluster area was quantified. Secondly, the presence of the two largest size groups, the green and white stones, was quantified within the stoss region for each frame over the two hours. Thirdly, the amount of fines present in the wake region was calculated over the duration of the experiment. The presence of the other size groups was not analysed, because they play an insignificant role in the composition of the cluster.

# 5 RESULTS AND DISCUSSION

## 5.1 Boundary determination

The surface grain size distribution along the length of the strip is presented in Figure 2. The cluster of interest is identifiable by the presence of the anchor stone, which is the large peak of the red stone around the 800 pixel mark. Inspection of Figure 2 shows that there is a significant increase in the concentration of fines ($>D_{35}$) immediately downstream of the anchor stone. This is observed to remain fairly high and then sharply decrease. The position of this decrease in fines concentration was judged to be the downstream boundary of the cluster, as indicated by $X_2$ in Figure 2.

The upstream boundary of the stoss is harder to define. The region should theoretically comprise primarily of green and white stones, and while this is the case, it can be observed that much of the upstream section of the strip comprises primarily of green and white stones. This makes differentiation between the stoss and general surface area difficult. The boundary of the cluster was chosen to coincide with the decrease in green stones directly upstream of the anchor stone, indicated by the marker $X_1$.

These values were compared with the boundary values determined by eye. The graphically determined $X_1$ and $X_2$ values were at x = 727 and 887 pixels respectively. The manually determined boundaries were $X_1$ = 736 and $X_2$ = 883 pixels. These values compare favourably.

To obtain more accurate boundaries analysis of smaller sections, for example squares of 5x5 pixels, could be done. This would give the colour distribution at points along the test section instead of strips, allowing the definition of angular or curved cluster boundaries.

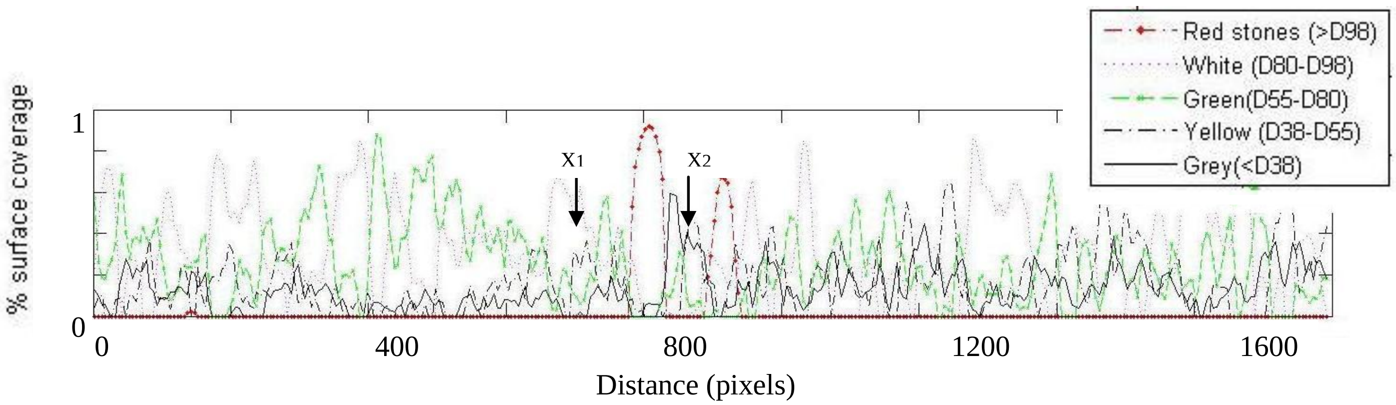
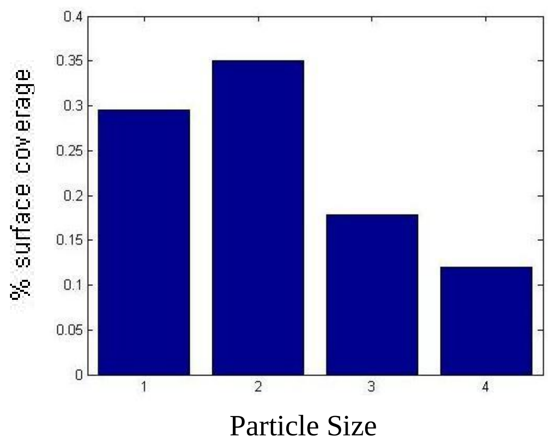



**Figure 2. Grain size variation along length of strip**

## 5.2 Particle size distribution of a cluster

The particle size distributions in the stoss and wake of a typical cluster formation at an instantaneous point in time are shown in Figure 3 and Figure 4 respectively. The two regions show distinctly different particle size distribution. The results conform to the predicted result, where the majority of particles in the stoss are from the two larger size groups, and the vice versa in the wake region.



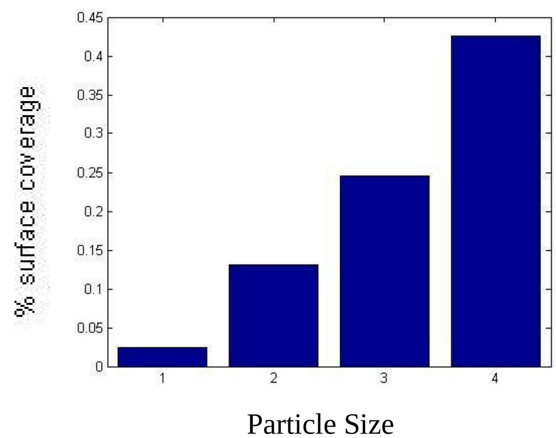




**Figure 3. Grain size distribution in the stoss** **Figure 4. Grain size distribution in wake (where for both figures, 1 = $D_{80}$-$D_{98}$, 2 = $D_{55}$-$D_{80}$, 3 = $D_{38}$-$D_{55}$, 4 = >$D_{38}$)**

A selection of images taken at stages throughout the experiment is presented in Figure 5. These show the development of the cluster (image a, b and c) and its disintegration (image d and e). The grain size distribution of the cluster was observed, and is presented quantitatively. Results from the inspection of the size distribution of a cluster over an extended period of time are presented in Figure 6.

The size of the anchor stone indicates the degree of submersion of the stone. This is observable in Figure 6 a), where the stone is at least partially submerged for the first 20 minutes of the experiment. Cluster formation will only occur subsequent to full particle exposure. Without protrusion from the bed, the anchor stone will not influence the surrounding flow field, therefore not initiating the cluster formation process.

Coinciding with full anchor stone exposure, an increase in the percentage of large particles can be seen in the stoss region (Figure 6b). Shortly after the establishment of the stoss, around the 60$^{th}$ minute, fines also begin to accumulate in the wake region (Figure 6c). At this point the cluster is fully developed. The percentage coverage of large particles peaks around the 130$^{th}$ minute, at which point the anchor stone changes position (Figure 6d). A change in position of the anchor stone implies a complete break-up of the cluster formation, as the stability of the stoss and wake regions are entirely dependent on the presence of the anchor stone. This appears to be the case, as the change in position of the anchor stone also coincides with a drastic decline in the percentage surface coverage of the fines in the wake region.

These results show three stages of cluster formation; the formation, cluster, and disintegration. The cluster appeared to be stable from the 60$^{th}$ minute to the 150$^{th}$ minute. The wake region shows a decline in fines before the final cluster break-up, suggesting the wake is the least stable section of the cluster and that entrainment of the wake particles will lead to total cluster disintegration.

Photos from the significant times during the experiment were chosen to visually display the cluster formation process (Figure 5). Image 1 shows the sedimentary structure prior to the 20$^{th}$ minute and shows the anchor stone when it is still partially submerged in the bed. Image 2 (t = 20 min) and 3 (t = 60 min) respectively show the accumulation of large particles in the stoss, and small particles in the wake. Image 4 (t = 110 shows a significant reduction in wake particles, and image 5 (t = 140) shows the new position of the anchor stone, where it has come to rest closer to the large red particle downstream.

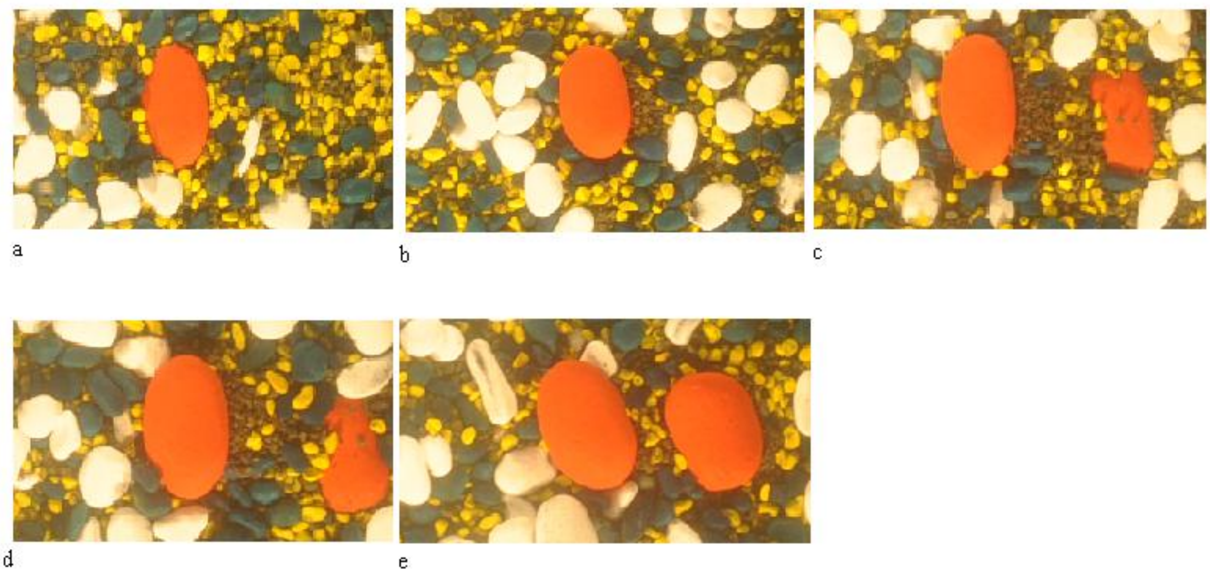



**Figure 5. Image sequence of phases of cluster formation and disintegration**

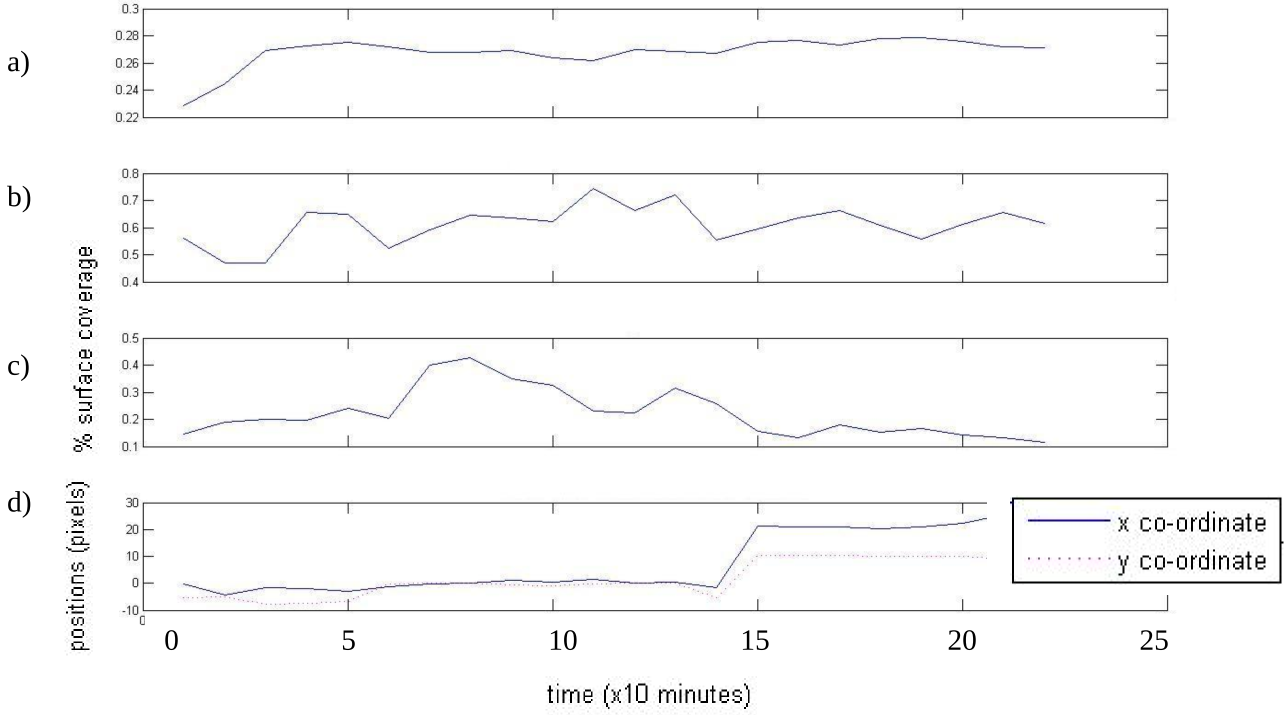



**Figure 6. Plot a) Anchor stone size, Plot b) Dominant particle size in the stoss, Plot c) Dominant particle size in the wake, Plot d) Anchor stone position over time**

## 6 SUMMARY AND CONCLUSIONS

Research into cluster formations was conducted using coloured particles to assist photogrammetry. The analysis of these tests has focused on observing the development of an armour layer, the tracking of particle movement and the distribution of particle size in a cluster.

The distribution of particle sizes within cluster was under investigation. Before this could be successfully achieved, the cluster boundaries needed to be identified by analysing a strip of the test section containing the cluster. The colour distribution of the particles in the strip was calculated to determine where the grain size distribution of the strip changes from normal to containing a particularly large percentage of fines for the wake, or medium and large sized particles in the stoss.

Investigation into the particle size distribution of a cluster was undertaken using two methods. First, an in depth investigation was conducted into the three separate regions of an individual cluster. The regions used for analysis were determined by the cluster boundary determination method. The size distribution of the stoss showed a high proportion of large stones. The size distribution of the wake showed the highest proportion of particles were the fines, with the proportion of area covered for the remaining size groups decreasing as the particle size increased.

Analysis of the size distribution of the cluster over time was also investigated. This indicated that cluster formation would begin to occur only when the anchor stone was exposed. Once exposed, large particles came to rest directly upstream of the anchor stone, and subsequently fines settled in the wake of the anchor stone. The wake particles were entrained shortly before the anchor stone moved, and cluster disintegration was complete. This process verifies the literature to date on the formation and disintegration process of clusters, indicating that photogrammetry combined with coloured particles has great potential for insights into cluster formation.

## 7 ACKNOWLEDGEMENTS

The authors would like to acknowledge the excellent assistance and expertise of the lab technicians Geoff Kirby and Jim Luo.

## REFERENCES:

Best, J. L. (1993). "On the Interactions Between Turbulent Flow Structure, Sediment Transport and Bedform Development: Some Considerations from Recent Experimental Research." In: *Turbulence: Perspectives on Flow and Sediment Transport*, N. J. Clifford, J. R. French, and J. Hardisty, eds., John Wiley and Sons, West Sussex.

Biggs, B. J. F., Duncan, M. J., Francoeur, S. N., and Meyer, W. D. (1997). "Physical characterisation of microform bed cluster refugia in 12 headwater streams, New Zealand." *New Zealand Journal of Marine and Freshwater Research*, 31(4), 413-422.

Billi, P. (1988). "A note on cluster bedform behaviour in a gravel-bed river." *Catena*, 15(5), 473-481.

Brayshaw, A. C., ed. (1984). *Characteristics and origin of cluster bedforms in coarse grained alluvial channels*, Canadian Society of Petroleum Geologists, Calgary, Alberta, Canada.

Brayshaw, A. C., Frostick, L. E., and Reid, I. (1983). "The hydrodynamics of particle clusters and sediment entrainment in coarse alluvial channels." *Sedimentology*, 30(1), 137-143.

Chin, C. O. (1985). "Stream Bed Armouring PhD Thesis," University of Auckland, Auckland.

Graf, W. H. (1971). *Hydraulics of Sediment Transport*, McGraw Hill.

Heays, K., Friedrich, H., and Melville, B. W. (2010). "Re-evaluation of image analysis for sedimentary process research." In: *IAHR APD*, Auckland.

Lane, S. N., Chandler, J. H., and Porfiri, K. (2001). "Monitoring river channel and flume surfaces with digital photogrammetry." *Journal of Hydraulic Engineering*, 127(10), 871-877.

Moore, E. J. (1976). "Underwater Photogrammetry." *The Photogrammetric Record*, 8(48), 748-763.

Nino, Y., and Musalem, R. (2000). "Turbulent entrainment events of sediment grains over bedforms." University of Chile.

Papanicolaou, A. N., and Schuyler, A. (2003). "Cluster evolution and flow-frictional characteristics under different sediment availabilities and specific gravity." *Journal of Engineering Mechanics*, 129(10), 1206-1219.

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

Strom, K., Papanicolaou, A. N., Evangelopoulos, N., and Odeh, M. (2004). "Microforms in gravel bed rivers: Formation, disintegration, and effects on bedload transport." *Journal of Hydraulic Engineering*, 130(6), 554-567.

Strom, K. B. (2006). "Cluster bedforms in mountain rivers," Ph.D., The University of Iowa, United States -- Iowa.

Strom, K. B., Papanicolaou, A. N., Billing, B., Ely, L. L., and Hendricks, R. R. (Year). "Characterization of particle cluster bedforms in a mountain stream." American Society of Civil Engineers, Reston, VA 20191-4400, United States, Anchorage, AK, United States, 399.