Laboratory study of gravel-bed cluster formation and disintegration

K. G. Heays¹, H. Friedrich¹, and B. W. Melville¹

¹Department of Civil and Environmental Engineering, University of Auckland, Auckland, New Zealand

Abstract Increased knowledge of clusters is essential for the understanding of sediment transport behavior and the monitoring and protection of aquatic life. A physical study using graded river gravels is conducted in a laboratory environment. Using photogrammetry and painted gravels, a cluster identification tool (CIT) is developed based on image subtraction between subsequent frames, allowing identification of any stable areas and groups of particles on the bed. This is combined with digital particle tracking (DPT) to present a novel approach for monitoring the formation and disintegration of clusters. Clusters from graded gravels are formed successfully during the experimental stage, allowing investigation into the complex dynamic behavior of cluster formation and disintegration in a simulated natural environment. Various anchor stone arrangements are used in the experiments. However, only about one fifth of the potential anchor stones on the bed surface enable cluster formation. In general, clusters classified as “typical” and “heap” are most common. Inspection of temporal cluster coverage of the test-bed surface shows that the proportion of clusters present on the surface tends to grow with time. Maximum cluster surface coverage of between 5% and 34% is observed. In addition, particles entering and departing from clusters are monitored. Most commonly, particles enter from directly upstream of the cluster, however >20% of particles approach from a direction >20 deg from the streamwise direction. Approximately 35% of all particles directly upstream of a cluster bypass the cluster.

1. Introduction

The term “cluster” describes the form of an elevated group of bed particles, which is generally structured such that smaller particles accumulate around a larger, central stone [Brayshaw, 1984; Strom and Papanicolaou, 2008]. Cluster forms are thus characterized by the deposition of bed material onto that specifically structured group, being more stable than the surrounding bed [Wittenberg et al., 2007]. It is generally accepted that clusters improve bed stability [Brayshaw, 1984; Papanicolaou and Schuyler, 2003; Reid et al., 1992; Strom and Papanicolaou, 2002a; Strom et al., 2004], however there has been some contradictory thought on this [Billi, 1988]. The stability of clusters relative to the surrounding bed has been observed, providing in-stream shelter during flood events for periphyton and invertebrates, while other bed sediments are washed downstream [Biggs et al., 1997a]. Increased knowledge of clusters is thus essential for the monitoring and protection of aquatic life [Biggs et al., 1997a, 1997b].

Cluster forms are common in gravel-bed rivers and play an important role in the armoring process [Chin, 1985; Mao et al., 2011]. Clusters are known to influence the interaction of the flow structure, entrainable sediment and stable bed morphology [Strom and Papanicolaou, 2002a; Strom et al., 2004]. A complete mechanistic model of cluster formation and disintegration dynamics has eluded researchers to date, but is necessary for the progression of sediment transport models for graded gravels [Wilcock and Detemple, 2005]. An improved understanding of cluster dynamics will play an important role in helping to understand gravel-bed stability, bed load transport rates, downstream particle movement, overall flow resistance, and local flow field characteristics [Strom and Papanicolaou, 2008].

Typical cluster forms comprise three distinct sections; obstacle, stoss, and wake. The anchor stone (or obstacle) is an unusually large particle that is deposited on the river bed. This provides an anchor for the cluster and initiates cluster formation [Brayshaw, 1984]. The anchor stone is usually in the $D_{95}$ to $D_{99}$ fraction of the bed gravel [Brayshaw, 1984], but has also been reported to be larger than $D_{95}$ [Papanicolaou et al., 2003],...
where $D_i$ is the size of grain at which $\%$ of the sample is finer. The area upstream of the anchor stone is referred to as the stoss, and usually contains particles of medium size, within the range of $D_{10}$ to $D_{50}$ [Brayshaw, 1984]. The area downstream of the anchor stone is termed the wake, with sediment sizes in the range of $D_5$ to $D_{10}$ [Brayshaw et al., 1983]. In addition to typical cluster forms, the existence of other types of cluster forms, in particular, line and heap clusters, has been reported in a number of studies [De Jong, 1995; Strom, 2006; Wittenberg, 2002; Wittenberg and Newson, 2005].

Image analysis is emerging as a practical, unobtrusive method for gathering detailed data from sedimentary motion [Moore, 1976; Black et al., 2007; Radice et al., 2006; Schuyler and Papanicolaou, 2000]. Using photogrammetry, image analysis provides in-depth information regarding the surface and particle characteristics of river beds [Keshavarzy and Ball, 1999; Lane et al., 2001; Schuyler and Papanicolaou, 2000]. A thresholding technique allows the visual identification of the moving particles, enabled by using moveable colored particles upon a fixed bed [Piedra et al., 2012; Schuyler and Papanicolaou, 2000; Strom and Papanicolaou, 2002b]. This technique is excellent for the study of individual particles; however, study of the dynamics of the entire bed is not permitted, as it relies on a static background of known and constant color property. Major advances in using image analysis to quantify sediment transport have been made in recent years [Drake et al., 1988; Nokes, 2007; Radice et al., 2006, 2010; Hergault et al., 2010; Lajeunesse et al., 2010; Papanicolaou et al., 1999; Zimmermann et al., 2008]. Most recently, Piedra et al. [2012] used UV paint to color sediment in order to determine clusters of larger particles forming on the test section. This technique was effective at isolating individual groups of sediment based on their color, enabling the study of groups of particles.

The aim of the present study is to investigate the development of naturally formed clusters from a flattened bed of graded gravel at constant flow rate. These experiments act as a bridge between the group of laboratory experiments conducted on idealized glass spheres [e.g., Papanicolaou and Schuyler, 2003] and field studies conducted on naturally formed clusters [e.g., Billi, 1988; Hendrick et al., 2010; Strom and Papanicolaou, 2009; Brayshaw, 1984; Reid et al., 1992]. Field studies are often limited by the practicalities of continuously monitoring bed conditions during flood events. Additionally, gaining a complete and detailed picture of cluster behavior is difficult due to quantity and scale issues that are inherent in field studies. Laboratory studies that use idealized particles, such as glass spheres, have a limitation, in that the clusters formed in these experiments are less influenced by particle size and shape than clusters formed in natural environments. Thus the aims of our study were to set up a physical model capable of mimicking complex natural processes, such as the dynamic evolution of cluster formation and disintegration, and apply image analysis to monitor cluster development and sediment motion over a long period of time, while maintaining a high level of detail in measurement. This study fits into a broader objective of developing a mechanistic model of cluster formation and disintegration, which can be applied in prediction of scour, sediment transport, and in-stream habitat evaluation.

The present study uses sediment, partly painted in bright colors, according to their size fraction. The digital particle tracking (DPT) algorithm, using image analysis specifically targeted at interrogating cluster formation, is presented in detail in Heays et al. [2014]. The algorithm enables the measurement of physical properties of clusters, as they form on the bed surface, to be quantified under varying sediment and flow conditions. It also allows the preliminary investigation of the self-organizing nature of cluster formations by exploring their origin and relationship with the surrounding bed. Using the DPT information, a cluster identification tool (CIT) is presented, which allows studying of a variety of aspects of the cluster formation process. In particular, questions are addressed that are focused around the form of clusters. How many clusters formed? How long did the clusters last? How were the clusters constituted? How were the clusters related to the surrounding sediment movements? Aspects of the quantification of these characteristics have been conducted in a number of studies to date [Brayshaw, 1984; Hendrick et al., 2010; Papanicolaou et al., 2012; Papanicolaou and Schuyler, 2003; Reid et al., 1992; Strom and Papanicolaou, 2002a; Strom et al., 2004; Strom and Papanicolaou, 2008]. The present study differs from previous investigations either through the experimental setup, where idealized glass beads have been monitored using image analysis, or in relation to the sampling method, where manual surveys of cluster position in natural river bed situations have been conducted. The use of natural sediment and frequent high resolution imaging of the test section, over an extended timeframe, provides an unusual insight into the development of natural clusters in a laboratory situation.
2. Experimental Setup

The experimental work and analysis were conducted in the Fluid Mechanics Laboratory at the University of Auckland. A series of experiments was conducted, testing the response of cluster formation to different flow and sediment conditions. Three main variables were investigated for their role in cluster formation; flow rate, grain size distribution, and the addition of a significantly larger anchor stone on the bed. Each experiment was conducted over a number of hours to allow for clusters to develop fully. The test section of the experiment was captured continually to record the behavior of the sediment. Post processing of the photogrammetric data provided the information for this study.

2.1. Flume

Experiments were conducted within a 19 m long, glass-walled rectangular flume with dimensions 0.45 m wide by 0.5 m deep, with adjustable slope kept constant at 1% (Figure 1). Water was supplied to the flume using pumps that draw from a constant head reservoir. Temperature was kept constant at 21°C, using a cooling system within the reservoir. The water entered the flume through a flow straightener, and the water level was controlled by an adjustable sharp crested weir at the end of the flume.

The flume was equipped with a 130 mm high false floor, leading up to a recess in which the sediment can be placed. The volume required to fill the sediment recess was relatively small, which reduced the volume of sediment required for these experiments. The sediment recess was situated 10.4 m downstream of the flow straightener. The recess was 1 m long, 0.45 m wide, and its depth was the full thickness of the false floor. Fitted within the recess was a 5 mm thick plastic table, with foam at the interface between the table and the side walls, to prevent sediment falling through the cracks. The plastic table was supported by four mechanical screw jacks, which were connected to a motor below the flume. The motor would drive a chain around cogs attached to the screw jack, enabling the jacks to adjust the height of the plastic table within the recess. The speed of the motor was adjustable, with a minimum speed equating to a vertical rise of 0.17 mm/min and maximum speed delivering a vertical rise of 1.4 mm/min. The adjustable bed allowed the test section surface to remain level with the upstream fixed bed, as the section eroded. This ensured the bed shear stress was kept relatively constant and reduced the complicated flow structures that would have exaggerated scour if the levels were to become uneven. The adjustment of the sediment recess, while experiments were underway, was undertaken manually.

2.2. Flow Conditions

The flow rate was controlled using an orifice plate and was measured using a differential manometer. The calibration of the orifice plate was checked in situ using the laboratory calibration tanks that enable flow measurement to better than 1% accuracy. Additionally, using an Acoustic Doppler Velocimeter (ADV), a velocity profile was taken 1 m upstream of the test section (over the fixed bed) at the centerline of the flume to determine the flow characteristics. The profile was collected using 60 s samples from 10 measuring elevations. In a preparatory experiment, under the same experimental conditions, multiple velocity profiles were collected upstream and within the test section, and those confirmed that the flow was uniform and steady. The time-averaged streamwise velocity profile of the flow was found to satisfy the logarithmic law. The shear velocity ($u_*$) was calculated by applying the logarithmic law of the wall to the velocity profile ($u/u* = 1/k \ln(z/z')$), where $u$ is the time averaged streamwise velocity, $k$ is the Von Karman constant (0.41), $z$ is the measurement height above the bed, and the roughness parameter, $z' = k_s/30.2$, where $k_s$ is the characteristic roughness length), and was assumed to be $2D_{50}$. The dimensionless shear stress (Shields’ parameter, $\tau_{*c}$) was calculated for each experiment (Shields et al., 1936):
where \( sg \) is the specific gravity of the gravel. The Reynolds number \( Re = \frac{\bar{u}L}{v}, \) where \( L \) is the hydraulic diameter, \( \bar{u} \) is the depth averaged streamwise velocity, and \( v \) is the kinematic viscosity) indicated fully turbulent flow for all experiments.

2.3. Sediment
Rounded river gravels ranging from 0.15 to 27 mm were used in the experiments. There was no upstream sediment source. The sediment was separated into five size groups, approximating the important fractions involved in cluster formation. The average properties of these sizes are shown in Table 1, the grain sizes presented relate to the subsurface material, sieved prior to placement in the test section. The colors red, white, yellow, and green were used, leaving the smallest size group (<2.8 mm) unpainted, defining it as gray color.

The painted gravels were mixed manually and then transferred into the test section. After each experiment, all the gravel that had been transported downstream was carefully removed; the sediment was remixed, and then placed back in the test section. Sieve samples were taken regularly, after experimentation, to ensure the grading curve remained the same.

The shape factor is defined as \( SF = \frac{a}{bg^{2}} \), where \( a \) (longest), \( b \) (medium), and \( c \) (shortest) are mutually orthogonal dimensions of a particular grain (Table 1). A vernier caliper was used to measure the grain dimensions of a sample of 100 grains. Grains smaller than 2.8 mm were not measured; however, observation showed they were similar in shape to the coarser grains.

2.4. Photography
An overhead camera was used to continuously capture images of the test section below. The camera used was a Nikon D90 digital SLR camera with an AF-S Nikkor 18–105 mm lens. The Nikon was connected to a computer to allow remote control and immediate transfer of the image to the computer’s hard drive. The camera captured still photos at a rate of approximately 0.67 fps for the duration of the experiment. The recording rate was restricted by the data transfer capabilities of software and hardware, and allowed continuous recording for several hours, while maintaining good image resolution of the entire test section. The recording frequency was high enough to capture the movement of larger (white and red) particles. Four dual flood lights were positioned to illuminate the test section.

To minimize image noise caused by reflection and refraction from the fluctuations of the water surface, a 1 m long Perspex skimmer was installed. This “flow skimmer” was positioned on the surface of the water, so that any surface waves were flattened, with minimal alterations to the flow channel and pressurization.

2.5. Experimental Conditions
The variable experimental conditions comprised a range of flow rates (60–72 L/s), the addition of a single large anchor stone, and the addition of several anchor stones. A summary of the experiments is presented in Table 2, where \( t_{\text{max}} \) is the experiment time. Water depth was kept constant at 0.2 m for all experiments. The experimental nomenclature is based on the following method; the presence of an artificially placed anchor stone is denoted by an “A,” where \( A_{0} \) indicates no anchor stone was placed, \( A_{1} \) indicates a large round type anchor stone, and \( A_{4} \) indicates a large oval flat anchor stone and the final two numbers refer to the flow rate at which the experiment was run.

2.5.1 Flow Rate
The different flow rates chosen for this experiment were based on Chin [1985], who observed the formation of armor layers using the same flume as in the present study.
Table 2. Summary of Experiments

<table>
<thead>
<tr>
<th>Code</th>
<th>Q (m³/s)</th>
<th>u* (m/s)</th>
<th>$\tau_{cr}$</th>
<th>Re</th>
<th>$t_{max}$ (min)</th>
<th>% Surface Cluster Coverage at $t_{max}$ (%)</th>
<th>Maximum % Surface Cluster Coverage (%)</th>
<th>Time of Maximum % Surface Coverage (min)</th>
<th>Time to Reach 80% Surface Coverage (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plain Bed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A060</td>
<td>0.06</td>
<td>0.0703</td>
<td>0.070</td>
<td>282,353</td>
<td>167</td>
<td>4</td>
<td>5.1</td>
<td>145</td>
<td>120</td>
</tr>
<tr>
<td>A060a</td>
<td>0.066</td>
<td>0.0763</td>
<td>0.074</td>
<td>310,588</td>
<td>296</td>
<td>4</td>
<td>7</td>
<td>110</td>
<td>100</td>
</tr>
<tr>
<td>A060b</td>
<td>0.066</td>
<td>0.0704</td>
<td>0.070</td>
<td>310,588</td>
<td>310</td>
<td>18</td>
<td>18</td>
<td>240</td>
<td></td>
</tr>
<tr>
<td>A072</td>
<td>0.072</td>
<td>0.0796</td>
<td>0.090</td>
<td>338,824</td>
<td>290</td>
<td>13.8</td>
<td>13.8</td>
<td>120</td>
<td></td>
</tr>
<tr>
<td>A072a</td>
<td>0.072</td>
<td>0.084</td>
<td>0.100</td>
<td>338,824</td>
<td>285</td>
<td>6.5</td>
<td>6.5</td>
<td>250</td>
<td></td>
</tr>
<tr>
<td>A072b</td>
<td>0.072</td>
<td>0.087</td>
<td>0.107</td>
<td>338,824</td>
<td>310</td>
<td>6</td>
<td>26</td>
<td>170</td>
<td>140</td>
</tr>
<tr>
<td>Anchor Stone</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A166</td>
<td>0.066</td>
<td>0.074</td>
<td>0.078</td>
<td>310,588</td>
<td>237</td>
<td>19.5</td>
<td>19.5</td>
<td>$t_{max}$</td>
<td>165</td>
</tr>
<tr>
<td>A172</td>
<td>0.072</td>
<td>0.0791</td>
<td>0.089</td>
<td>338,824</td>
<td>285</td>
<td>21.8</td>
<td>21.8</td>
<td>$t_{max}$</td>
<td>220</td>
</tr>
<tr>
<td>A172a</td>
<td>0.072</td>
<td>0.0874</td>
<td>0.108</td>
<td>338,824</td>
<td>198</td>
<td>20</td>
<td>29</td>
<td>175</td>
<td>155</td>
</tr>
<tr>
<td>A172b</td>
<td>0.072</td>
<td>0.085</td>
<td>0.103</td>
<td>338,824</td>
<td>295</td>
<td>34</td>
<td>32</td>
<td>140</td>
<td>90</td>
</tr>
<tr>
<td>A466</td>
<td>0.066</td>
<td>0.0741</td>
<td>0.078</td>
<td>310,588</td>
<td>205</td>
<td>10.4</td>
<td>18.1</td>
<td>130</td>
<td>90</td>
</tr>
<tr>
<td>A472</td>
<td>0.072</td>
<td>0.0843</td>
<td>0.101</td>
<td>338,824</td>
<td>190</td>
<td>6.7</td>
<td>10</td>
<td>120</td>
<td>80</td>
</tr>
<tr>
<td>Multiple Anchor Stones</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M466</td>
<td>0.066</td>
<td>0.077</td>
<td>0.084</td>
<td>310,588</td>
<td>250</td>
<td>13.5</td>
<td>13.5</td>
<td>$t_{max}$</td>
<td>250</td>
</tr>
<tr>
<td>M472</td>
<td>0.072</td>
<td>0.0882</td>
<td>0.110</td>
<td>338,824</td>
<td>255</td>
<td>10.8</td>
<td>12.1</td>
<td>160</td>
<td>100</td>
</tr>
</tbody>
</table>

The lowest flow rate (60 L/s) did not transport enough of the bed particles to form clusters. This can be explained by observing the shear stresses of the experiment. The threshold for initial motion of a grain of a particular grain size ($i$) was calculated using the equations proposed by Petit [1994]

$$\tau_{cr}^i = 0.5 \frac{D_i}{D_{50}}^{-0.7},$$  \hspace{1cm} (2)

where $D_i$ is the particle size of a particular size fraction. Using equation (2) to calculate the thresholds for each grain size, the theoretical thresholds for grain size motion can be compared with the measured dimensionless shear stress. The calculated critical shear stress for the average grain size was $\tau_{cr50} = 0.05$ and for the $D_{50}$ was $\tau_{cr50} = 0.03$ [Petit, 1994]. The measured dimensionless shear stress (equation (1)) at the lowest flow rate was $\tau_{cr}^50 = 0.07$, which can be expressed in terms of the critical shear stress as $1.4 \tau_{cr}$ and $2.3 \tau_{cr}$ for the $D_{50}$ and $D_{90}$ sizes, respectively. In their laboratory studies of uniform spherical particles, Strom et al. [2004] observed that clusters form at shear stresses between $1.25 \tau_{cr}$ and $2 \tau_{cr}$. Assuming cluster formation is dependent on the transport of $D_{50}$ sized particles, comparison of the present shear stresses with those of Strom et al. [2004] indicates that the possibility of cluster formation lies at the lower threshold for cluster initiation. Assuming cluster formation is dependent on the transport of $D_{50}$ sized particles, then cluster formation is improbable.

The midrange of flow rates (66 L/s) transported enough of the bed load that clusters were able to form. The flow condition at this flow rate produced shear stresses of around $1.8 \tau_{cr}$ to $3 \tau_{cr}$ for the $D_{50}$ and $D_{90}$ size, respectively, which is within the expected range for cluster formation [Strom and Papanicolaou, 2002a].

The highest flow rate (72 L/s) was such that clusters could form, but the bed load transport was high and approached the condition where all grains were in motion. Values of around $2.1 \tau_{cr}$ for the $D_{50}$ size and 3.56 $\tau_{cr}$ for the $D_{90}$ size were reached in those experiments. Considering that in natural environments $\tau_{cr}$ rarely exceeds $2 \tau_{cr}$ and that the bed appeared to be unstable at flow rates higher than this, no higher flow rates were used.

2.5.2. Anchor Stone Placement

The difference in the effect of two different artificially placed anchor stones on cluster formation was investigated for the two higher flow rates. The anchor stones were of a similar $a$ axis dimension, but the oval flat anchor stone was much flatter and more elongated ($A4, a = 64 \text{ mm}, b = 42 \text{ mm}, c = 18 \text{ mm}$) than the round anchor stone ($A1, a = 62 \text{ mm}, b = 55 \text{ mm}, c = 50 \text{ mm}$; shorter $b$ and $c$ axes). Four other stones of similar dimensions to the elongated stone were used for the multiple anchor stone studies ($M4$), the layout of these experiments featuring a stone in the center of the bed, with the remaining four stones placed midway toward each corner of the test section.
3. Image Analysis Methodology

For each experiment, an image of the test section was captured every 1.5 s, for approximately 5 h, resulting in over 10,000 images per experiment. An example of a raw image of the test section is shown in Figure 2. The Matlab Image Analysis Toolbox was used for all image processing.

The process used for the complete photogrammetric analysis of clusters required initial calibration of the images, and subsequent digital identification of each colored particle. Complete cluster analysis was achieved in a three-step process: (1) observing clusters in a known location with a boundary identification tool, (2) tracking particles with DPT [Heays et al., 2014], and (3) locating and observing mobile-bed clusters as they formed and disintegrated with CIT. The image processing for CIT was completed using the steps discussed in the following sections.

3.1. Image Calibration

Close-range photography results in image distortion due to the curvature of the lens. This shows in the image as either barrel or pin cushion distortion, the effect being exaggerated the closer the subject is to the camera [Blair and Dufresne, 2005]. If used for photogrammetry, a distorted image will yield inaccurate results and must be calibrated before analysis. Where barrel distortion of the image was >2 mm (0.5% section width) at the test section boundary, a calibration algorithm was developed in Matlab and applied to the images to correct the distortion. With the help of a calibration checkerboard, a calibration image was obtained for each experiment, and an image distortion equation was developed and applied. As the camera position was fixed for each experiment, the same distortion correction could then be applied to the rest of the images.

3.2. Color Separation

Stream-bed armoring effectively changes the grading curve of the sediment on the surface of the bed, reducing the amount of fines on the surface and generally coarsening the sediment. Photogrammetry allowed measuring this change in grading, through observing the change in grading composition over time. Digital color separation was required to isolate each different colored particle in the images, with subsequent analysis of individual size fractions. Colors were similar between runs, with slight variation due to lighting fluctuation.

The RGB intensity values for each pixel were observed, and the different color combinations for each colored rock were determined. As each color has a distinctly different combination of RGB values, each color group can be digitally isolated.

3.3. Cluster Identification Tool

3.3.1. Concept of Stability

Analysis of the behavior of clusters requires definition of the spatial boundary of the cluster. Strom and Papanicolaou [2008] conducted a field analysis to identify natural cluster formations and classify them according to shape, their geometric properties, and their spatial arrangement. In their study, identification of clusters was done visually, using the broad definition of a cluster which is “a discrete organized grouping of particles that sits above the average elevation of the surrounding bed surface.” Brayshaw [1984] suggested that clusters generally consist of accumulations of particles, typically formed around an exceptionally large clast above the level of an otherwise planar bed. Hendrick et al. [2010] used a broad definition when surveying a mountain stream for clusters, classifying a cluster as one or more clasts which impede the progress of two or more sediment particles and protrude above the normal gravel-bed surface of the immediate surrounding area. They defined the surrounding area as the 50 cm radius surrounding the cluster, and...
imposed a size limit on the minimum anchor stone size as 5 cm, which was equal to the mean grain size in the study [Hendrick et al., 2010].

The use of photogrammetry enables automation of the survey process. The definition of clusters by others was taken into consideration and additionally, the philosophy that a cluster is more stable than the surrounding bed was used. This concept of stability was used to isolate the areas of the bed that were stationary over extended durations.

### 3.3.2. Removal of Moving Particles

The image analysis process uses image subtraction between subsequent images to identify any moving particles between frames; the particles that had moved are then digitally subtracted from the first image in the sequence; we term this technique “digital erosion.” Figure 3 shows a selection of images from this process. Repetition of this process results in a mainly black image, with only a small number of particles remaining in place; these are the stationary particles. If a cluster forms, it is these stationary particles that anchor the formation.

This digital erosion process was applied to a sequence of images obtained over an observation period. For this technique to work effectively, the observation period must be long enough that bed entrainment can be observed, to provide a visible contrast with the stable area of the cluster. The observation period was intended to target clusters that were stable for a significant proportion of the experiment duration. Preliminary analysis of cluster formation, and monitoring of the percentage of the bed that did not move, resulted in setting an observation period of 1 h for all experiments. Consequently, all clusters identified herein formed for a minimum duration of 1 h. This fixed time digital erosion process was applied to multiple sequences of images in each experiment, with one digital erosion sequence commencing every 10 min for the duration of the experiment. The 10 min interval was chosen as a short enough duration, relative to the transport rate of the sediment, to detect any major changes in the bed. This method provides one 60 min
integration window starting every 10 min. Therefore, there is a 50 min overlap between successive stability windows.

### 3.3.3. Cluster Isolation

The images showing the stationary particles were then transformed so that only the largest particles and groups of particles were shown (any particle size greater than $D_{80}$). The basis for limiting observation to this fraction of the bed was to target anchor stones, which have been found to be particles greater than $D_{84}$ [Papanicolaou et al., 2003]. Only the stable areas that were identified in at least two consecutive sequences were kept. These were then labeled as clusters. Figure 4 shows one complete iteration of CIT. Groups of particles identified between consecutive frames were defined as belonging to the same cluster if their centroids were $<40$ mm (approximately equal to the long axis of the maximum grain size) apart from each other. The image was digitally eroded to remove any small particles and enable identification of any large (white or red) particles that were adjacent to each other in groups larger than the average particle size. These groups were compared with those identified in the previous two sequences and only clusters that were at least partially present in one of the two previous sequences were considered to be clusters. The cluster location and dimensions were tracked between sequences to give a history of the evolution of the cluster.

### 3.3.4. Cluster Identification Error

This method of cluster identification does not take into account the elevation of the bed. A three-dimensional surface elevation of the bed was taken using an acoustic depth sounder. Figures 5 and 6 show the comparison of the positions of identified clusters using the photogrammetry method, with the surface elevation of the test section (taken at the cessation of the experiment). There is reasonable agreement between the position of the detected clusters, and the most elevated sections of the bed. Difficulty arises in determining the extent of the cluster, because, if based on elevation alone, the surface area of the cluster...
would be much greater. Surface elevation data were not available continuously for the experiment, therefore CIT is not able to take elevation into account. The cluster forms identified with CIT can be said to be the “core” of the cluster.

3.4. CIT Application

CIT produced large volumes of data regarding the time and position of the clusters. The preprocessing of the images produces an output of a series of images that are cropped to show only the test section, and are not distorted. The color separation thresholding must be done on each set of images, as lighting between experiments varies, changing the detected RGB values slightly. CIT outputs contain information about the position, size, shape, and orientation of the tracked particle or cluster. CIT thus allows obtaining the essential quantitative information to document the behavior of formation and disintegration of patterns on the river-bed surface. Particles can be approximated to an elliptical shape, and it is assumed that the particle lies with its shortest axis vertical. Therefore, the long and short axes obtained with CIT are assumed to be the $a$ and $b$ axes, and changes in the orientation of the particle that might alter the effective width of the particle when observed from above are neglected.

3.5. CIT Limitation

The precise nature of CIT means that any small variation in the experimental setup will affect the processing. All possible steps were taken to minimize the variation between setup conditions for experimental runs; however, this remained a challenge. The slightest change in conditions is detected in the image, and any differences between images will affect the image analysis process. Because of this, great care was taken to ensure that the lighting and water clarity were consistent in each run and that the skimmer plate was free of water and bubbles. When automating analysis of a complex process, such as cluster evolution, it is necessary to make assumptions and generalizations. Taking overhead photographs of the bed provided only a 2-D perspective of the bed mechanics. This places a limit on the accuracy of the cluster identification, as other studies have shown that the bed form should be raised above the average bed surface to be considered a cluster. Because this was not an option in this analysis, the cluster was identified according to grain-size and stability.

The division of particle sizes to be painted was based on the size thresholds observed by previous authors, which play significant roles in the cluster formation. The red particles ($>D_{90}$) were intended to act as anchor stones, the white particles ($D_{90} - D_{98}$) were intended to form the stoss and the yellow ($D_{36} - D_{55}$) and gray particles were intended to form the wake ($<D_{36}$). The medium green particles are not mentioned as playing a significant role in cluster formations. In practice, the roles played by the particles were less clearly defined. In particular, many white particles played major roles in the initiation of clusters, and many green particles formed a part of the stoss. When identifying clusters, only red and white colored particles were considered, representing the “core” of the cluster. If the green particles were included in the cluster search, it would be difficult to isolate clusters, as the green particles filled much of the space between clusters. Therefore, some clusters that were formed with a majority of green particles are excluded in identification of clusters. These types of clusters were in the vast minority, and through the visual survey were estimated to be <5% of all clusters that formed. In future experiments, the division of the bed into smaller size fractions is recommended to assist in determining more precise differentiation of the cluster extent.

4. Results and Discussion

4.1. General Cluster Formation

As the bed was water worked, coherent bed structures began to form...
appear. A visual survey of six experiments, conducted thrice within the experiments (50, 150, and 250 min), was taken to identify the occurrence of cluster types that formed (Figure 7). Out of all of the anchor stones thought to be available to form clusters (those on the bed surface that were coarser than the $D_{98}$), only around 22% actually formed clusters. The existence of different types of cluster formations, in particular, line and heap clusters, has been noticed in a number of studies [De Jong, 1995; Strom, 2006; Wittenberg, 2002; Wittenberg and Newson, 2005]. Throughout the experiments, the anchor and heap clusters were the most common, with line clusters generally occurring less frequently, and ring clusters seldom occurring. The survey results are consistent with those for two natural stream beds conducted by Strom [2006]. Over time, typical clusters become increasingly predominant relative to the heap clusters. These results verify the sediment grading and flow thresholds for cluster formation that have been developed through observation of both natural conditions and using spherical beads. The present results show that clusters form under the predicted conditions in graded gravel laboratory conditions. Additionally, they show that the use of graded gravels in an artificial environment can synthesize the diversity of clusters that has been observed in natural streams.

The clusters that formed were identified using CIT as presented in section 3. Examples of the development of the surface coverage of the clusters for two similar experimental runs are presented in Figure 8. Additionally, the depth of erosion and number of white particles that moved within the bed at each time step are plotted. The depth of erosion was measured by recording the change in elevation in the raising bed, when it was in operation. The number of moving particles was obtained from DPT, and is presented in units of g/m² s. This rate is determined by multiplying the volume of moving sediment by the average particle density, and dividing by the time step and test section area. These three parameters were monitored for all experimental runs. To summarize the results, the peak cluster coverage, time at which the peak coverage is reached, cluster coverage at the final cluster detection measurement and time at which 80% of the peak cluster coverage is reached are presented in Table 2. The boundary where a clustered surface becomes a fully armored surface remains unclear. In this series of experiments, the peak cluster coverage ranged between 5% and 34%. The peak surface coverage was not always observed at the end of an experiment; in 50% of the experimental runs, the cluster surface coverage pattern shown in Figure 8b was observed, where the surface coverage increased early in the experiment, then sharply declined at some point during the experiment, then subsequently began increasing again. A decline in surface coverage, such as that at minute 100 in Figure 8b, is the result of one or many clusters disintegrating, typically in a localized area of the test section. This indicates that there is a limit to the proportion of clusters that are able to be formed on the bed; the limit is dependent on the sediment transport or degree of armoring of the bed. To explore this concept further, the relationship between maximum surface coverage and shear velocity is plotted in Figure 9. This relationship shows that the maximum surface coverage increases with shear velocity. The higher sediment transport rates that accompany the higher shear velocity experiments most likely provide more opportunity for particle motion to contribute to cluster formation. This trend may continue until an upper limit is set by the critical armor condition, where no stable armor layer will form. This may coincide with the theoretical maximum surface coverage of 40% that was suggested by Wittenberg et al. [2007].

The wide range in surface coverage of clusters at the higher shear velocity experiments shows there is considerable variability in the occurrence of clusters. Cluster formation is heavily dependent on the surrounding bed surface, where high shear zones can arise due to changes in bed levels, therefore reducing the chance of sediment depositing within or nearby a cluster. Also contributing to the variability in cluster formation is the bed load, which is a stochastic supply of constituent particles to the cluster. Because of this, the absence of an upstream sediment supply in these experiments may have decreased the number or size of clusters that formed.
4.2. Particles Entering Leaving and Bypassing Clusters

This section addresses the effect of clusters on sediment transport from a slightly different perspective, that of the sediment moving as bed load. Due to the localized impact of the cluster disintegration, it is difficult to infer what effect clusters have on the sediment transport of the bed when observing bed load over the entire test section. Knowing the time and location of all clusters and white particle movements allowed for the development of a database focused on the individual particle interactions with clusters. The bed surrounding each identified cluster was examined in time steps relative to the time at which the cluster formed. An example of the types of movements that were detected for each individual cluster from one experiment is shown in Figure 10. All particle movements for particles that landed inside the cluster region within 50 min prior to the first detection of the cluster were collected for each cluster in each experiment. These movements were considered to be the cluster-forming movements. Each particle track was normalized...
with respect to the cluster position \((x_{ci}, y_{ci})\), enabling the conglomeration of particle tracks into one representative cluster (Figure 11), where each particle track is colored according to whether it is entering or leaving the cluster. In a similar manner, the area around the cluster was monitored from the time that it was identified as a cluster to the time that it was no longer detected. The direction and distance of each of these particle forming tracks is then presented in modified rose diagrams (Figure 12).

The majority of cluster-forming particle movements are aligned with the downstream direction, especially for those particles that came from a greater distance away. Particle movements closer to the cluster feature a much wider range of angles, indicating that the process in forming a cluster includes the attraction of nearby particles moving at angles to congregate together. More than 20% of particle movements approach from a direction greater than 20° from the streamwise direction. In the cluster duration phase, particle movements for both the forming and disintegrating movements enter or leave the cluster at a narrower angle than those of the cluster formation period, with over 30% of particles entering or leaving within ±5° of the streamwise direction. Clusters are known to influence the surrounding flow field, which in turn must influence the trajectories of passing bed load. These results indicate that as the cluster is forming, it has potential to influence passing particles from further away. As the cluster develops, it generally takes on a more streamlined shape, which may result in a reduction of the changes to the flow field surrounding the cluster. Consequently, the streamlined shape is less likely to influence particles.

The proportion of movements involved in forming a cluster was recorded for each experiment. The particle track positions were also inspected to assess whether the respective particles had the opportunity to enter a cluster. Those particles that were entrained from directly upstream from a cluster, but did not join the cluster, were deemed to bypass the cluster. On average, only 25% of all particle movements relate to particles that joined a cluster, with generally very little deviation amongst different experiments (±5%). Approximately 35% of all particle movements bypassed clusters, with a greater deviation between experiments (±17%). The remaining 40% of particle movements had no interaction with clusters, as the particle movement occurred to the side or downstream of the clusters.

These findings highlight the random nature of cluster formation; despite the majority of cluster forming particle movements occurring from directly upstream of the cluster, approximately 35% of particle movements from directly upstream of a cluster travel past the cluster. This indicates that there are factors other than proximity that influence cluster formation. The instantaneous shear stresses and interaction of the flow with the cluster are the likely causes for this bypass of particles.

4.3. Cluster Existence Duration

By observing the lifespan of all of the clusters that were detected, the duration of cluster existence was recorded. This concept is complicated by the ending of the experiment, where some clusters which might have otherwise disintegrated, were not allowed to evolve to completion. For analysis of the cluster formation duration, all experiments were grouped together. Of 875 clusters identified in 11 experiments, 30%
of clusters remained intact for the remainder of the experiment once they had formed. Cluster duration was on average 217 min (Figure 13). Excluding clusters that remained intact for the entire experiment duration, the average cluster duration was 184 min (Figure 14).

5. Conclusions

The study of gravel dynamics using colored particles, coupled with image analysis, has enabled in-depth observation of sediment transport and cluster development. The study bridges a gap between research into clusters conducted in the field and that conducted under idealized conditions in the laboratory. The developed CIT algorithm, based on photogrammetric data, allows detailed study into sediment mechanics, similar to that of the idealized laboratory studies, but under more realistic conditions, due to the use of a graded-gravel bed. The following points summarize the main findings of this study:

1. Objective cluster identification was achieved by monitoring the stationary areas of the bed, and designating clusters as areas with stable groups of large particles. CIT was used in combination with DPT [Heays et al., 2014] to obtain new insights into cluster formation.

2. The variation in cluster types present in the test section was similar to cluster types that have been reported in other studies. Typical and heap clusters were most common, with typical clusters becoming increasingly prominent over time. Of all the anchor stones thought to be available to form clusters (those coarser than $D_{90}$), only around 22% actually formed clusters. These results show that clusters form under the predicted conditions in graded gravel laboratory conditions. Additionally, they show that the use of graded gravels in an artificial environment can synthesize the diversity of clusters that has been observed in natural streams.

3. Inspection of the coverage of the test-bed surface with clusters over time showed that the proportion of clusters present on the surface tends to grow with time, until it reaches a maximum amount. This study indicates that for the range of conditions tested, there is a limit to the proportion of clustering that is possible on the bed surface, which is dependent on the sediment transport rate or degree of armoring of the bed. The maximum surface coverage with clusters for all experiments ranged between 5% and 34%. Overall, the maximum surface coverage increased with increasing shear velocity; however, cluster coverage varied greatly between experiments.

4. Particles entering clusters most commonly enter from directly
upstream of the cluster; however, >20% of particle movements approach from a direction greater than 20° from the streamwise direction. In the cluster duration phase, particle movements for both the forming and disintegrating movements enter or leave the cluster at a narrower angle than those of the cluster formation period, with over 30% of particles entering or leaving within ±5° of the streamwise direction.

5. The proportion of movements involved in forming a cluster was recorded for each experiment. On average, only 25% of all particle movements relate to particles that joined a cluster; additionally, approximately 35% of all particle movements directly upstream of a cluster bypassed the cluster.

6. In a survey of the duration of all the clusters that formed, 30% of clusters remained intact over the duration of the experiment. Of the clusters that disintegrated, the average duration was 184 min.

In the pursuit of a complete study into the formation and disintegration of clusters, it was necessary to develop a new application for photogrammetry and also address aspects of sediment transport and gravel-bed armoring. The relationships between clusters and the surrounding bed are complex, and further work remains to define the mechanics of this phenomenon. In particular, the methodology in this paper could be enhanced with the collection of continuous flow information within the test section, finer division of the sediment sample size fractions, and three-dimensional surface data of the test section.

Acknowledgments
The authors would like to thank the anonymous reviewers, whose comments helped to improve the manuscript.

References
Blair, D., and E. Dufresne (2005), Matlab Particle Tracking Repository, Georgetown Univ., Georgetown, Wash.
Papanicolaou, A. G. Tsakiris, and K. B. Strom (2012), The use of fractals to quantify the morphology of cluster microforms, Geomorphology, 139, 91–108.

Radice, A., S. Malavasi, and F. Ballio (2010), Preliminary results from an application of PTV to bed-load grains, paper presented at River Flow 2010, Braunschweig. IAWR-Fluvial Hydraulics (Braunschweig) Technische Universität Braunschweig (Braunschweig).

Strom, K., and A. N. Papanicolaou (2002a), Monitoring small scale developments in bedforms and bedload transport, paper presented at the Research and Extension Regional Water Quality Conference, Vancouver, Wash, USDA CSREES.
