AN INVESTIGATION OF BED ARMORING PROCESS AND THE FORMATION OF MICROCLUSTERS

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Abstract Armoring is a recognized phenomenon in gravel bed rivers that have been subject to periods of extended low flows. Coarsening creates a bed surface where greater intergranular friction angles increase the surface stability and the stress necessary to entrain the bed. We will present results from a series of flume experiments investigating the processes of bed armoring and microcluster formation with the purpose of quantifying the change in overall bed stability.

Where a gravel bed river incorporates structure in its bed surface, overall bed stability increases. This structure forms a microtopography that increases the roughness of the bed. Microclusters, or discrete particle groupings on the bed surface, are common features in surface microtopography. The influence and interaction of the sediment grains and channel flow hydraulics during the armoring process has yet to be fully defined. Recent research on microclusters has focused on how the turbulent flow field is affected by their presence. Where 2D flow fields have been measured, the results point to a strong 3D component to turbulence around microforms, which has not been fully elucidated.

The flume experiments presented here are designed to quantify the influence of independent variables over bed armoring, link the bed armoring process to the occurrence and distribution of microclusters on the armored bed, and measure the stability of the final, armored beds. The flume experiments created armored beds testing 4 sediment mixtures against 4 flow rates. The microcluster density on each bed is measured through the creation of DEMs from laser profile scans of the bed surface. Acoustic Doppler Velocimeters measure 3D point velocities over the armored bed and around microcluster groups of varying densities. The effect of bed substrate grain size distributions and flow rate during armor layer formation is linked to the creation of structure in the armor layer topography. Continued data analyses will compute the shear stresses associated with each of the armored bed surfaces.

The bed surface mediates interaction between the flow and the bed sediments and determines the sediment available for transport. It also defines the habitat for aquatic insects, salmonid spawning, and juvenile fish. The formation of rough topography on the bed surface creates areas of variable flow with the regions directly downstream of large clasts acting as a refuge for aquatic organisms. When the armor layer breaks, the channel bed erodes and incision may occur. This may negatively impact aquatic life in the channel that is dependent on stability of the bed surface. An improved understanding of armored channel bed formation and stability will aid predictions of the effect of controlled flow releases on the downstream channel morphology.

INTRODUCTION

The bed surface mediates interaction between the flow and the bed sediments and determines the sediment available for transport. It also defines the habitat for aquatic insects, salmonid spawning, and juvenile fish. Channel bed topographic diversity has been linked to biological diversity in stream systems and has been applied as an indicator of stream health (Bartley and Rutherford, 2005). The formation of rough topography on the bed surface creates areas of variable flow with the regions directly downstream of large clasts acting as a refuge for aquatic organisms (Cardinale and Palmer, 2002).

The static armored bed condition exists as a result of an extended period of flows over a mixed gravel bed. The flows generate shear stresses less than that needed to entrain the largest particles but large enough to transport the fines and over time the fines sediment is winnowed from the bed surface (Figure 1). A coarse surface layer forms on the bed surface, effectively sheltering the finer substrate grains from entrainment (Jain, 1990; Parker and Sutherland, 1990). The presence of an armor layer on the bed surface is a common phenomena in rivers, particularly in the reach downstream of a dam and upstream of a significant tributary input (Shen and Lu, 1983; Williams and Wolman, 1984; Richards and Clifford, 1991; Lamberti and Paris, 1992; Kondolf, 1997; Brandt, 2000; Grant, 2001; Vericat et al., 2006).

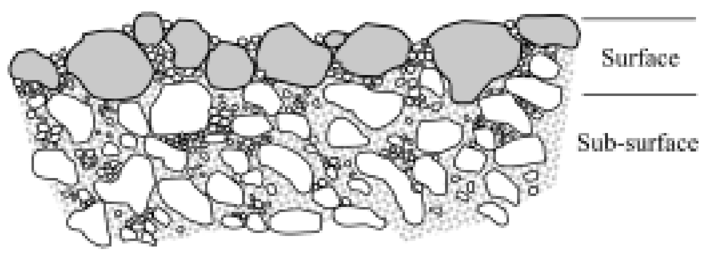

Figure 1 Illustration of an armored bed surface (Almedeij, 2005).

An armor layer increases the resistance to entrainment of the bed surface. Coarsening creates a rougher surface with greater intergranular friction angles which increase the stresses necessary to entrain the bed surface (Parker et al., 1982; Buffington and Montgomery, 1999; Vericat et al., 2006). Armor layers break-up with large flood events and are re-formed during the falling limb of the flood hydrograph (Parker and Klingeman, 1982; Vericat et al., 2006). When the mobility of a gravel bed is estimated from the grain size distribution of the bed surface without consideration of the surface structure, the results often over-predict fractional transport rates (Measures and Tait, 2008). Under static armor, which is common downstream of dam and the subject of this research, the fluid forces apply unevenly, with a higher proportion of total stress acting on the larger grains.

Where a gravel bed river incorporates structure in its bed surface, the stability of the overall bed increases (Iseya and Ikeda, 1987; Hassan and Reid, 1990; De Jong, 1991; Strom et al., 2004; Lamarre and Roy, 2005). This structure forms a microtopography that increases the roughness of the bed. Microclusters are common features in surface microtopography. We use the definition of microclusters put forward by Strom and Papanicolaou (2004; 2007) that they are ‘discrete, organized groupings of particles that sit above the average elevation of the surrounding bed surface.' Microclusters increase overall bed resistance (Brayshaw, 1984; Canovaro et al., 2007) which has been documented as an increased time to entrainment of the grains within the cluster microform (Iseya and Ikeda, 1987; De Jong, 1991).

Microclusters may be part of a feedback system through which the density of microforms adjusts to local flow conditions to maintain a maximum flow resistance (Hassan and Reid, 1990). Estimates of the percent bed area covered by by microforms range from 5% (Brayshaw, 1984; Clifford, 1996) to 75% (De Jong, 1991). Flow resistance is increased by alteration of the flow field and formation of turbulent flow patterns that include vortex shedding (Buffin-Belanger and Roy, 1998; Hassan and Church, 2000; Lamarre and Roy, 2005). Field studies have focused on defining the role of microforms in bed stability and have recognized their presence in armored beds (Brayshaw et al., 1983; Hassan and Reid, 1990; Wittenberg et al., 2007; Strom and Papanicolau, 2008; Strom and Papanicolaou, 2009). In the field, the dominant independent variables controlling microcluster formation are the flow rate during cluster formation and the sediment as described by D_{50} and D_{84} grain sizes (Strom and Papanicolaou, 2009). 2D field measurements show a 10-fold increase in turbulence in the wake area immediately downstream of a microform. Counter rotating vertical vortices around microforms are indicated by large amounts of horizontal turbulent momentum exchange (Lacey and Roy, 2008).

An improved understanding of armored channel bed stability is necessary to predict the effect of controlled flow releases on the downstream channel morphology. Break-up of the armor layer may or may not be a goal of a given flow release. Flushing flows are designed to remove fines from the channel bed and leave the armor layer intact (Kondolf and Wilcock, 1996; Batalla and Vericat, 2009). When the armor layer breaks, the channel bed erodes and incision may occur. This may negatively impact aquatic life in the channel that is dependent on stability of the bed surface. In some cases, gravel augmentation is pursued to replace the gravel lost following removal of the armor layer.

This paper presents the preliminary results of flume experiments designed to connect the processes of bed armoring, microcluster formation, and bed stability. The hypotheses being addressed in this research are: the density of microclusters on the armored bed increases as the sand fraction in the bed sediment increases; the density of microclusters on the armored bed increases as the flow rate during armor formation increases; the stability of the bed surface increases with the density of microclusters on the bed.

EXPERIMENTAL METHODS

The research is being performed in a sediment and water recirculating flume. The experimental channel is 9 meters long, 0.6 meters wide, and 0.5 meters deep. Laboratory flumes allow for detailed measurements of the flow field and sediment transport rates in a controlled physical model. The flume represents a mid-section of a channel (Sharp, 1981; Peakall et al., 1996), so that the influence of flow rate and channel sediment distribution during bed armoring is measured directly. This is a commonly employed approach in both engineering (Davies, 1980; i.e. Canovaro et al., 2007) and river geomorphology (Wilcock, 2001; i.e. Curran and Wilcock, 2005).

Sediment The sediment mixture used consists entirely of coarse grains, from 2mm-64mm (Figure 2). The largest grain size fractions have been painted to aid in their identification in the flume: 11.3mm-16.0mm, rose; 16.0mm-22.6mm, yellow; 22.6mm-32.0mm, green; 32.0mm-45.3mm, red; 45.3mm-64.0mm, blue. Direct clast size measurements are not possible from an armored bed as the process would necessarily destroy the armored surface. By painting the largest size fractions distinct colors, the sizes of the grains in the clusters can be readily identified by eye. The pea gravel sizes were not painted as they are not expected to act as keystone clasts.

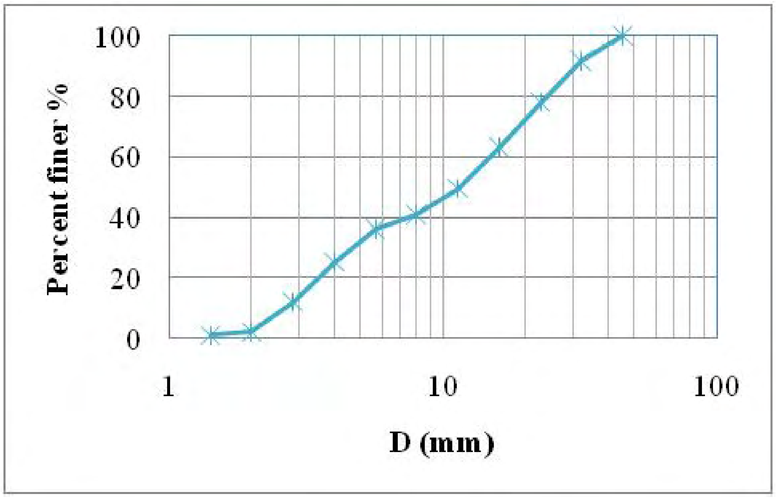

Figure 2 The cumulative grain size distribution for the bed sediment.

Each experiment begins with a 10 cm thick sediment bed over the length and width of the flume that is screeded flat. This thickness is more than twice the a-axis and one and a half times the b-axis of the largest grain size. The channel bed slope is free to adjust during all experiments. After each flow segment, the length of the bed is scanned using a laser profiler. Using this process, the bed cross-section topography is measured every 2 mm using laser scans and the individual cross sections stacked to create a Digital Elevation Model (DEM) (Darboux and Huang, 2003). Where this method has been used, bed elevations can be determined to within 0.7mm (Zimmermann, 2009). These DEMs are used to depict the distribution of bed elevations above a standardized arbitrary reference datum and derive statistical metrics describing the surface roughness and geomorphic variability of the bed surface. After the bed scan, the grain size distribution of the bed surface is measured using the grid by number method (Wolman, 1954).

After armoring the bed during Segment 2, the bed surface is examined for the presence of clusters. Microclusters are identified from the DEMs created from bed scans, and their geometric properties measured, including cluster length, height, and width. The bed surface is photographed, and the grain sizes creating each cluster identified by clast color and the size of the key clast in each cluster determined. The spatial location of each cluster is identified and measured relative to other clusters on the bed using the DEMs. Spatial identification over the horizontal plane defined by the sediment bed requires a means of locating patterns that may be regular or irregular within a 2D space. The correlation functions defined by Strom and Papanicolaou (2008) were used in this research. Spacing parameters are defined as λ_x, average downstream cluster spacing for which $\Delta y=0$; λ_y, average transverse cluster spacing for which $\Delta x=0$; (λ_{x1}, λ_{y1}), average coordinates of the nearest downstream cluster for which $\Delta x>\Delta y$ and neither Δx nor Δy is 0. From these parameters, λ is defined as:

$$\lambda = \sqrt{\lambda_{x1}^2 + \lambda_{y1}^2} \tag{1}$$

λ is the distance to the nearest cluster in a diagonal direction and therefore the minimum possible spacing between clusters on the bed surface.

Flows The flow rates are chosen to create transport rates and shear stresses that test the effect of flow rate on armoring. These flow rates maintain subcritical flow. Each experiment consists of three segments, defined by segment discharge. In Segment 1, the flow rate creates active transport of the sediment bed, with each size fraction either fully or partially mobile. This segment eliminates any bias introduced with the creation and screeding of the initial bed (Cooper and Tait, 2009). Segment 1 is continued until bed and water surface profiles are parallel over the length of the flume, indicating that the channel bed is no longer aggrading or degrading. In Segment 2 the flow rate is reduced by half from the rate used in Segment 1 and held constant while the bed armors. It is not possible to know with absolute certainty the point at which all particles have stabilized and will not transport, therefore a very low transport rate is used as a cut-off. Armoring continues in these experiments until the rate of sediment transport measured at the downstream end of the flume is less than 1% of the rate measured at the end of Segment 1 and for a minimum of 10 hours. Segment 3 determines the stability of the armored bed by increasing the flow rate back to what it was during Segment 1 with the goal of breaking the armor layer and creating active sediment transport. In the event that the discharge is no longer sufficient to mobilize the bed, the flow rate is incrementally increased by 10% until the armor breaks.

To describe accurately the flow field generated around microclusters, high spatial resolution is needed for both velocity and topographic measurements (Lamarre and Roy, 2005). For this research, we employed the Nortek Vectrino Acoustic Doppler Velocimeters (ADV), which measures the 3D velocity in a cell column with diameter 15mm and height 5mm and can measure flow within 1mm of the bed. After Segment 2, the flow is maintained over the armored bed surface at the same depth and Reynolds number used during the armoring process and the 3-dimensional flow field created by the armored bed both with and without microclusters is measured. The ADV is used to measure sequential cells in the x, y, and z directions, forming a grid of measurements around each cluster. The grid extended in each direction until the effect of the cluster's presence is no longer visible in the velocity data. The time period of data collection at each location is determined experimentally and set to achieve statistical independence between turbulence and record length. Previous research has shown that a stationary time series develops in turbulent flow within 1 minute (Buffin-Belanger and Roy, 2005; Thoroddsen et al., 2008; Hardy et al., 2009). Flow measurements were taken in locations with single microclusters, where microclusters were absent, and where microclusters were grouped with different densities.

ANALYTICAL METHODS

Bed stability is evaluated through the shear stress created by the armored bed, the time to armor surface break, and the sediment transport rate following armor break. The time that elapses between the increase in discharge with the initiation of Segment 3 and the initiation of sediment movement from the armored bed provides a qualitative measure of the resistance (hence, stability) created by the armored bed as a whole.

To evaluate the resistance to transport created by the different armored beds, the Shields stress of the bed is calculated both in localized areas around clusters and for the bed as a whole. A comparison of Shields stresses for the median surface grain size for beds with and without clusters has been used in field research to illustrate an increase in bed stability when structures were present on the bed surface (Oldmeadow and Church, 2006). Where detailed velocity measurements have been taken around clusters, an increase in turbulence as characterized by the Reynolds stresses has been measured (Lacey and Roy, 2008).

The ADV records point velocities (u,v,w) and fluctuations (u',v',w'). From the measurements, it is possible to calculate mean fluid velocities, variances (or root-mean squares), skewness, flatness, turbulence intensity, vorticity components (ω_x, ω_y, and ω_z), Turbulent Kinetic Energy (from the normal turbulent stresses ($\overline{u^2}$, $\overline{v^2}$, and $\overline{w^2}$), and Reynolds shear stresses ($\overline{uv}$, $\overline{vw}$, and $\overline{uw}$) acting on the bed and on the cluster. Nikora et al (2007) present a Double Averaged Navier-Stokes (DANS) approach whereby the turbulent flow characteristics are averaged over time and space. Flow data collected with the ADV are being analyzed using the DANS approach and quadrant analysis, which together will provide insight into the momentum transfers occurring and the coherent flow structures present in the flow field at specific locations. When coupled with detailed bed topography, it will be possible to differentiate the boundary stresses due to bedform, armor surface, viscous stress, or flow interaction as a result of multiple bedforms. Cooper and Tait (2009) provide further insight into the construction of boundary force equations for 2D flows following the DANS approach. A detailed measure of the bed stability will be completed using this analysis, enabling quantification of the shear stress of an armored bed with microclusters of varying density.

RESULTS

The research is in progress and the results of one experiment are presented to illustrate the processes being measured. The flume experiment was conducted using the gravel mixture already detailed and shown in Figure 2. The flow rates were constant during each segment at 0.07 cms during Segments 1 and 3, 0.035 cms during Segment 2. Segment 1 was run for 125 minutes, at which point the transport rate was consistently 430 grams, or 1.2 g/ms. Following this, during Segment 2, the bed underwent an armoring flow for 10 hours. The armored bed surface was scanned, and the DEM from that scan is shown in Figure 3. Cluster density was measured over individual sections of the bed and the overall bed surface (Figure 4). The ADV is used to define a minimum distance from the side walls of the flume for which data analysis is possible. This distance was initially set at 10 cm from the flume walls.

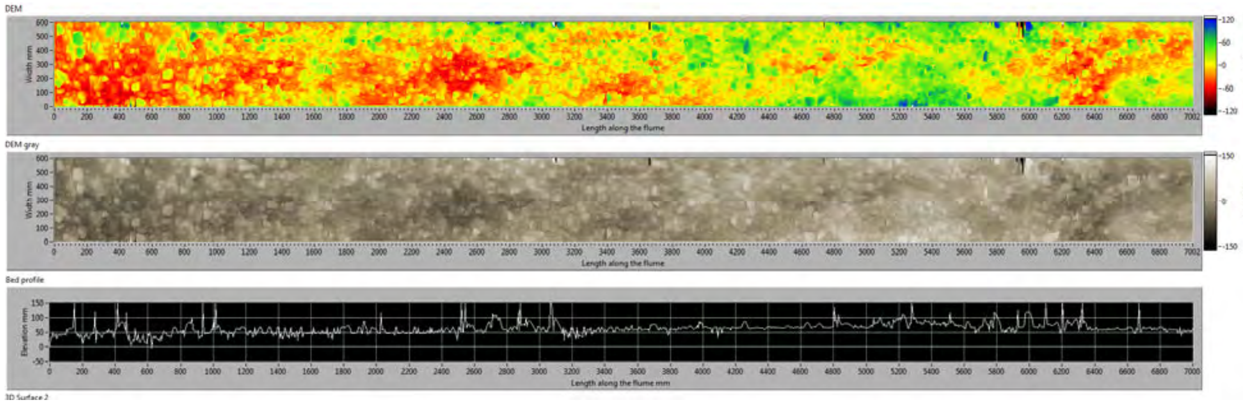

Figure 3 Results of a laser scan following Segment 2. The color image at the top is a color DEM where blue represents a maximum elevation and red a minimum. The middle image is a grey scale DEM of the same bed. The lowest image is the longitudinal bed elevation profile as measured down the middle of the flume.

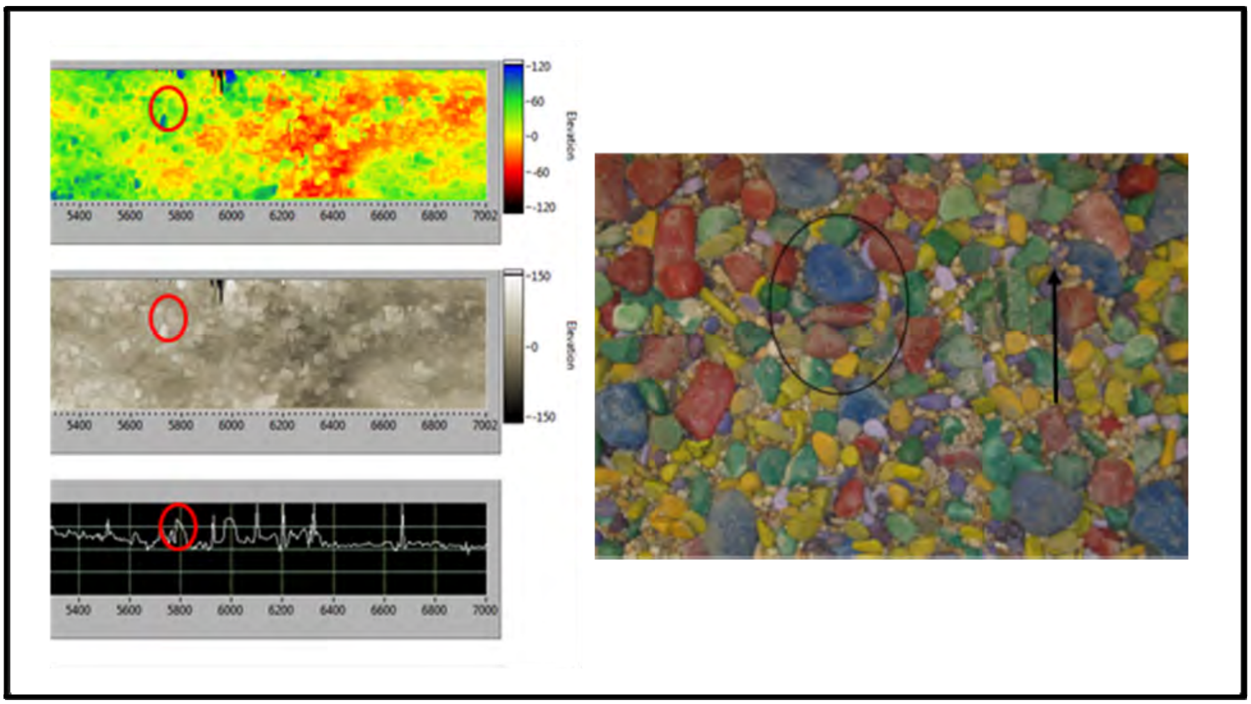

Figure 4 On the left are enlarged portions of the DEMs and the topographic profile shown in the preceding figure. The red circles identify a cluster on each of the images. To the right is a photo of the armored surface with a cluster circled. The photo shows the plan view, masking the elevation of the cluster. The flow direction is indicated by the arrow.

The flume bed is analyzed both in sections and as a whole. Each section is 1m in longitudinal length and 0.4m wide, which encompasses the middle 0.4m of flume width and excludes the 10cm adjacent to the side walls. The number of clusters in each bed section bed is divided by the area of the bed section (0.4m^2) to produce a measure of the cluster density per bed section. The density of clusters over the entire bed area (2.8m^2) is also calculated. Through these measures, any change in cluster density with distance downstream can be identified along with the overall cluster density for the experiment.

The cluster shown in Figure 4 has an anchor clast in the largest grain size category, 45-64mm. The other grains making up the cluster are in the next largest grain size category with diameters between 32-45mm. The flow has been measured around the bed cluster using the ADV and the flow profiles reconstructed. Point velocities were measured in 3D at 3mm intervals over the flow depth to create velocity profiles. From these measurements, the directional mean and fluctuating velocities are measured. The Reynolds stress, turbulence intensity, and tubulent kinetic energy are calculated for each profile. Profiles were measured following this process across the flume width in 20mm increments where clusters were located as well as longitudinally upstream and downstream of each cluster. In this manner, a grid of points is measured around and over the cluster.

The results from profiles around the cluster shown in Figure 4 are presented here. The cluster is located in the middle section of the flume, approximately 250mm from the flume wall. Streamwise velocities around the cluster illustrate the influence of the cluster and associated change in bed surface level on the local velocities (Figure 5).

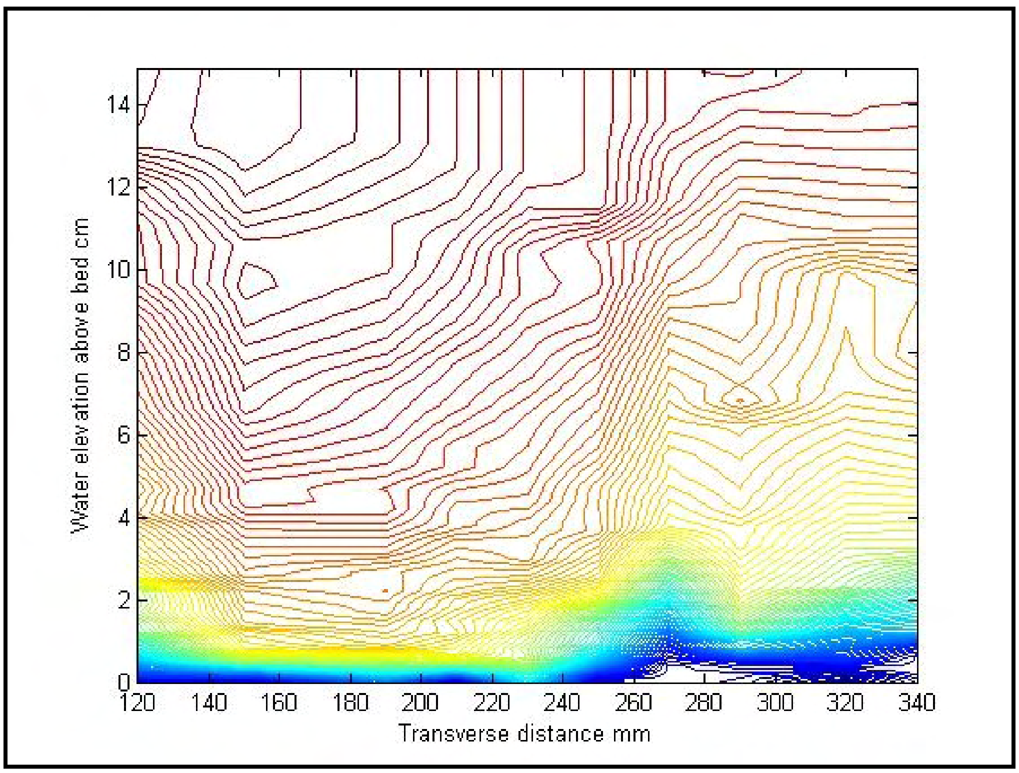

Figure 5 Sharp velocity increase on left side of the cluster.

There are is a second cluster located at approximately 100mm, and the velocity contours around the first cluster do not appear to be influenced by the presence of the second cluster. Figure 5 illustrates where the velocity increases sharply on the left side of the cluster, as the flow approaches the cluster crest. All profiles were analyzed for Reynolds shear stress and turbulent kinetic energy, and two of the resulting profiles are show in Figure 6.

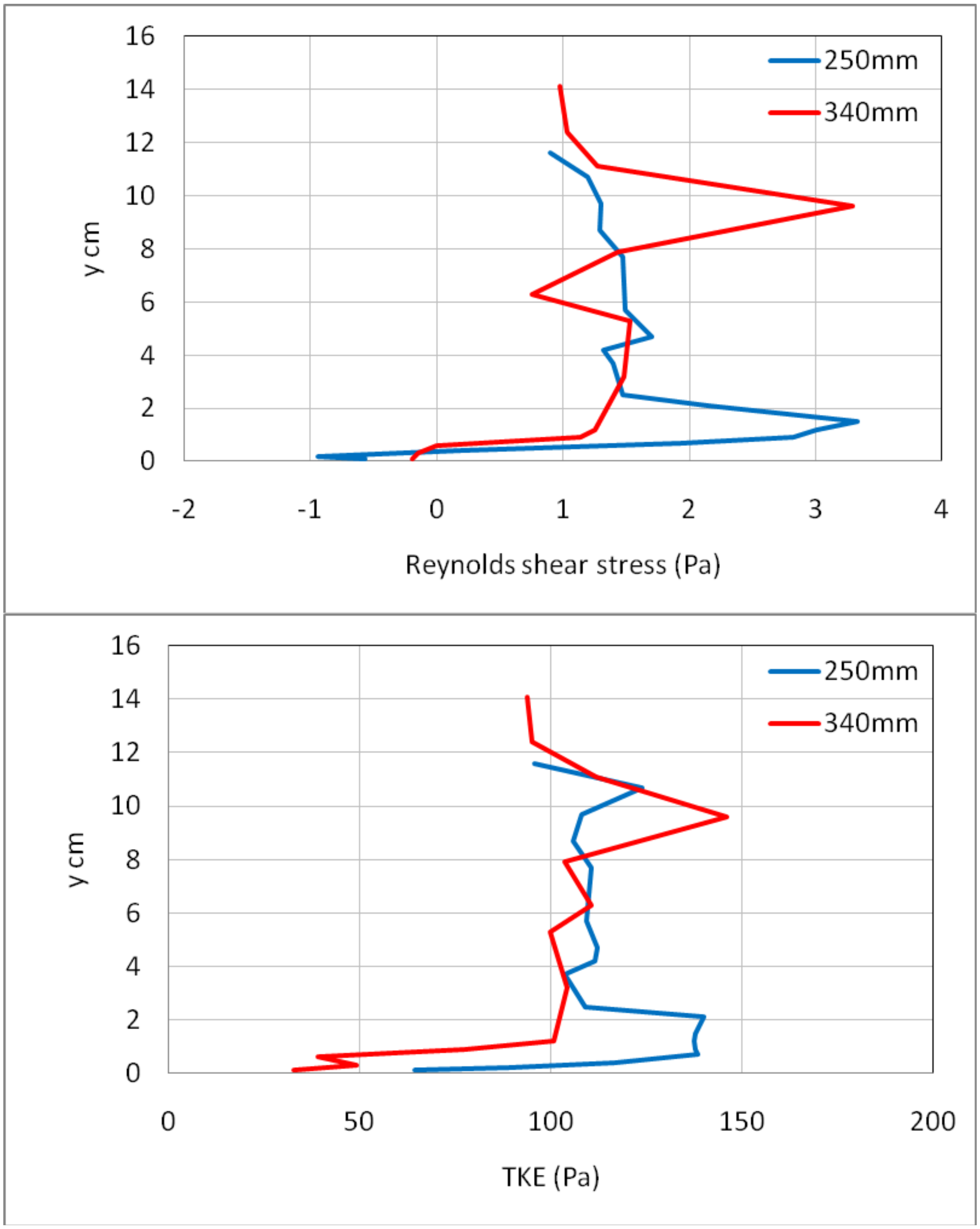

Figure 6 Two resulting profiles.

The influence of the cluster on the turbulent flow properties is evident in the comparison of the profile taken from an area of bed without a cluster (340mm) to that taken at the location of the cluster (250mm). Both the Reynolds shear stress and the turbulent kinetic energy peak in the lower portion of the flow, where the cluster would be extending from the bed surface. The alternative occurs higher in the flow, above the top of the cluster. Reynolds stress and turbulent kinetic energy are reduced over the cluster while over the flat gravel bed, the turbulence increases with distance from the bed.

This situation may be indicative of coherent flow structures forming around the cluster on the armored bed. The analysis of more velocity data around more clusters is needed to make this determination.

As flume experiments are completed, the analysis of cluster densities and turbulent flow profiles will continue. All flume runs follow the same format as presented here but the flow rates will be systematically increased. While the flow depth in the flume will be maintained at 10 cm, the discharge will be 0.09 cms, 0.11 cms, and 0.14 cms for segments 1 and 3. Segment 2 will also armor the bed under a higher discharge rate. The experiments enable a comparison of armored bed stabilities and an analysis of the dependence of that stability on the channel conditions during armoring and the spatial density of microclusters in the armor layer.

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