Experiments were performed in a sediment and water recirculating flume at the University of Virginia. Turbulence over the unclustered bed area was most similar to the 24% sand bed case. Quadrant analysis showed sweep events dominant in the flow over the cluster. The bed armored during the second portion of the experiment when the flow rate was reduced to half of the equilibrium flow rate. An initial run segment that established equilibrium sediment transport and full bed mobility, the flow rate in the flume was reduced and the bed surface fully armored. Once armored, clusters were identified using a combination of bed DEM, vertical profile, and visual analysis. Instantaneous three-dimensional flow velocities were measured around the clusters using an Acoustic Doppler Velocimeter, and these values were used to calculate Reynolds shear stresses, turbulence intensities, and turbulent kinetic energy in the flow field. Results show a significant change in the flow profiles over a cluster when compared to an open area of the armored bed. Reynolds shear stresses doubled over the cluster and turbulence kinetic energy within the surrounding flow dynamics are quite localized and limited to 30mm in lateral orientation. Quadrant analysis shows large ejection and sweep events around clusters indicates vortex formation at the cluster crest. The magnitudes of the coherent structures formed around clusters at a single variable flow rate are compared across the grain size distributions.

Methodology

1. Experiments were performed in a sediment and water recirculating flume at the University of Virginia Sustainable Rivers Lab. The experimental channel is 11 meters long, 0.6 meters wide, and 0.5 meters deep. The flume slope was kept constant while the sediment bed slope was free to adjust.

2. For all experiments, a 10 cm thick bed was screeded flat. This thickness is more than twice the length of the axis of the largest grain size. While the gravel size fraction remained constant, the sand content increased such that separate clusters were formed from layers of sediment with sand contents of 9%, 24%, and 38%.

3. An initial flow rate of 0.11 cms fully mobilized the sediment and was employed to create an equilibrium transport condition. Dynamic equilibrium was determined to exist when the channel bed was no longer changing, and as measured by parallel water and bed surface profiles over the length of the flume. This portion of the run was performed to eliminate any bed loss from initial bed creation.

4. The bed armored during the second portion of the experiment when the flow rate was reduced to half of the initial value. This flow rate, Q=0.055 cms, was held constant while the bed surface armored. Armoring was considered complete when the transport rate was less than 1% of the rate measured during the equilibrium condition. Because it was not possible to know with absolute certainty the point at which all particles had stabilized, a very low transport rate was used to define the armored bed condition.

5. The flow depth was maintained at 15 cm during both run segments by adjusting a tail gate on the flume.

Cluster Identification

1. A Digital Elevation Model (DEM) was generated from bed elevation data collected with a Micro-Epsilon laser profiler, which has an accuracy of ±2mm. A photo panorama of the armored bed surface was also acquired, and the bed surface grain size distribution determined from the panorama by identifying the color of 400 surface grains, and hence their sizes, using the modified grid by number method.

2. Clusters and any other bedforms present on the armored bed were identified through the combined use of the DEM, the photo panorama, and visual inspection of the armored sediment bed. Each cluster consisted of a key class (clast) surrounded by two smaller grains deposited. Cluster beds were also identified above the surrounding bed area, making the DEM a particularly useful tool in identification. The geometric properties of the clusters were measured from the photos and DEMs, including cluster length, maximum bed width, and key class diameter.

3. Earlier experiments using the same key class size showed the area of influence of a cluster over the flow field to be 30 cm, which is approximately seven times the maximum cluster size (45 mm, blue grains). Clusters separated by a greater distance are considered isolated.

Findings

1. Roughness features on the armored bed surface generate small scale turbulence flow structures, but the overall impact on the flow remains limited to the near bed region. The flow structure, identifiable by peak values of TKE, and u' over a height of Z=0.02 and did not transfer momentum or energy to the outer flow field.

2. Energy and momentum are most balanced for the 9% sand bed conditions. Reynolds shear stress increases over 24%, most turbulent energy remains near the bed and 38% sand has the largest decreases in TKE and u' from inner to outer flow areas.

3. A net transfer of mass and momentum from inner to outer flow areas occurs only for the 24% sand bed case. This is also the cluster extending leeward into the flow profile which may influence the transfer.

4. Turbulence over the unclustered bed area was most similar to the 24% sand bed case.

5. Mean profile of TKE was spiked using the mean and standard deviations. Data with a correlation between 65% and 70% was maintained in the velocity time series to account for lower correlation measurements caused by high turbulent events occurring in near bed regions.

Flow Measurements

1. 3D flows are measured in a grid pattern around each bed area with a Nortek Acoustic Doppler Velocimeter (ADV) under a sampling rate of 200Hz. The grid extended in the vertical as well as horizontal and transverse directions. Thus, the same Cartesian grid pattern was followed over the vertical flow profile. Flow measurements were taken at each grid node for a duration of 120 seconds to allow the velocimetry to sample at a frequency that maintained equipment error of less than 1 mm/s.

2. Velocity time series were inspected by eye for abnormalities and then de-spiked using the mean and standard deviations. Data values greater or lower than the mean velocity ± standard deviation were truncated to achieve a relatively clean and regular time series. The ADV signal correlation Rc was used to detect unreliable data points. A low pass filter designed to discard instantaneous velocity data points was applied when the correlation R< 65%. Data with a correlation between 65% and 70% was maintained in the velocity time series to account for lower correlation measurements caused by high turbulent events occurring in near bed regions.

Conclusions

1. Flow separates when forced over a cluster crest, creating an increase in the turbulent flow properties and formation of a vortex where the flow re-attaches downstream.

2. Quadrant analysis showed sweep events dominate in the near bed region that switch with ejection events in the outer portion of the flow. Neither upward nor outward events were dominant at any location in the profile.

3. The association between flow lines, vortex formation, and cluster presence indicates a physical interpretation for turbulent flows over clustered, armored beds.

4. The sand content affects the influence of turbulent flows generated by clusters on the bed. As the bed sand content increases over 24%, most turbulent energy remains near the bed and TKE is low. For bed sand content at and below 24%, turbulent energy is more evenly distributed through the flow profile. The lowest sand content has the highest TKE values.