Effect of cluster spatial interaction and coactions on a turbulent flow field in a gravel river bed

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Abstract
In gravel bed rivers, low flows generate shear stresses less than what is needed to entrain the largest particles but large enough to transport the fines. During sustained low flows, fine sediment winnows from the bed surface and an armored surface layer forms. As the surface armor forms, a surface structure develops that increases bed roughness and flow resistance and can be characterized by the presence of clusters. Individual clusters are known to exert a significant influence over the spatial and temporal flow processes acting in the vicinity of the bed. However, clusters do not always form in isolation on the bed surface, but instead vary in spatial density and distribution. Where multiple clusters are adjacent but distinct bed features, they can be considered double or triple clusters, affecting larger bed and flow areas than a single cluster. Spatially adjacent clusters can interfere with flow patterns, which leads to a different pattern of turbulent structures upstream, downstream, and over the clusters.

A series of flume experiments have been conducted to investigate the magnitudes of flow interactions and the types of turbulent structures forming around clusters where coactions can affect the dominant turbulent structures. Flow were measured around isolated and multiple clusters, all naturally developed during bed armoring. Instantaneous velocities and Reynolds shear stresses were measured by deployment of an Acoustic Doppler Velocimeter during steady flow rates of 0.055 cm/s. Results show a significant change in the flow profiles over a single cluster when compared to multiple clusters. Reynolds shear stresses and turbulence intensity reached a peak value at 35cm downstream from the isolated cluster and their magnitudes decrease as the number of cluster increase. The results also suggest the effects of the single cluster on the surrounding flow dynamics are quite localized. Only clusters formed within 30cm of each other, was there interaction between the flow fields. Quadrant analyzes of the three-dimensional velocities sampled from single, double, and triple clusters suggests turbulence intensity was lowered in the flow field between closely spaced clusters over the centerline of the cluster groups. Large burst and sweep events were dampened and instead outward events became dominant.

Methodology
1. Two distinct flow rates were used in the experiment. The initial flow rate of 0.11cm/s fully mobilized the sediment and was employed to create a gravel bed underwater transport condition. Once equilibrium transport conditions were established, the flow was lowered to 0.055cm/s and held constant for 36 hours while the bed surface armored.
2. Clusters of different spatial arrangements on the armored bed were identified through the combined use of the DEM, the photo panorama, and visual inspection of the sediment bed. Cluster spacing parameter is defined as the distance from an individual cluster to the nearest cluster along a downstream diagonal. If $D = S$, the clusters are determined to be multiple clusters, where $D$ is the key cluster size.

$\lambda = \sqrt{(S)^2}$

3. High resolution and frequency (200Hz) 3-D velocity measurements using a Nortek Vectrino Acoustic Doppler Velocimeter (ADV) were taken around clusters on the armored bed.
4. Reynolds shear stress, Turbulence intensity, TKE and Quadrant Analysis were calculated and analyzed to investigate the effect of cluster spatial arrangement on turbulence characteristics.

Findings
Isolated Cluster (Figure 3a)
The centerline transition plane is a plane of average streamwise velocity $U_{1}$ at $Z = 0$, where a turbulent structure is shed from the center of the cluster. Interaction between structures and sweeps indicates the formation of intense lateral vortices around the cluster, which sweep events dominate the outer layer downstream and dominate the area of intense turbulence. A dead zone forms immediately downstream of the isolated cluster and is characterized by a decrease of Reynolds shear stress and Turbulence intensity (TI). This is the region where the cluster provides shelter to the sediment in its wake.

Double Cluster (Figure 3b)
Ejections (Q2) around the center of both clusters are paired with sweeps (Q3) on either side of both clusters at $Z = 1.0$, indicating vortices shedding from the cluster core. This area corresponds to the transition between core regions of the TI and Reynolds stresses. The wake attach structure is a dead zone near the core of the TI and Q3 events dominant. Within the wake of TI ejection events, there is an isolated area of Q3 dominance at the downstream cluster core.

Triple Cluster (Figure 3c)
The centerline transition plane is a plane of average streamwise velocity $U_{1}$ at $Z = 0$, where a turbulent structure is shed from the center of the cluster. Interaction between structures and sweeps indicates the formation of intense lateral vortices around the cluster, which sweep events dominate the outer layer downstream and dominate the area of intense turbulence. A dead zone forms immediately downstream of the isolated cluster and is characterized by a decrease of Reynolds shear stress and Turbulence intensity (TI). This is the region where the cluster provides shelter to the sediment in its wake.

Conclusion
The present study illustrates a similar pattern for the triple cluster as was observed for the double cluster. Spatially-averaged Reynolds stress, Turbulence intensity and TI around triple cluster are reduced around the triple cluster when compared to the double cluster and the net of the right cluster which is not aligned with the other two clusters. Areas of peak TI and Q2 are consistent with TI events in Quadrant plot. Ejections (Q2) are dominant closer to the bed and sweeps (Q3) dominant further away from the bed. All Q3 events are present in the immediate region around each cluster, indicating formation of a dead zone and an area where the isolated clusters provide shelter for moving sediment.

A turbulent structure is shed from the crest of each cluster and travels upstream in the flow profile. This pattern occurs at the single, double, and triple clusters. The prevalence of Q2 and Q3 events indicates the turbulent structure is not robust for the clusters. The magnitude of these turbulent structures decrease with increasing distance from the streambed. The region between the double clusters has lower Reynolds stress closures, TI, and TKE as compared to the isolated cluster and the region around the triple cluster has lower Reynolds stress, TI and TKE as compared to the isolated cluster and the region around the triple cluster.

Figure 3. Side and plan view of Reynolds shear stresses defined as $\tau = \rho/\rho_0 U^2$, Turbulence Intensity, TKE and Quadrant Dominance for a) isolated cluster; b) double cluster; c) triple cluster at distinct nondimensionalized elevation $Z^* = z/h$. Grid nodes represent sampling locations for velocity measurements. Flow is from left to right. Cluster locations are represented by the solid black area on Reynolds stresses, TI and TKE plots and by the dark blue areas on the Quadrant plots.