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Characterizing Clustering in Boulder Bed Channels and the Impact on Shear Stress Equations

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Abstract

Boulders and cobbles are often used in stream restoration projects to increase flow resistance and enhance channel stability and habitat diversity. Particle size metrics determined from the particle distribution are often used as a proxy for shear stress in field equations. Clustering of large particles has been thought to contribute to shear stress, but the effect of clustering is not accounted for in equations that use a representative particle size, such as the D_{84}. In this paper, clustering is defined using the upper tail (≥84%) in a variable called Topsum. The number of clusters, average size of clusters, and shear stress are evaluated using the proposed definition of cluster. Findings suggest that the upper tail represents the roughness height better than the commonly used proxy of D_{84} for boulder bed streams (streams which have a D_{84} particle 0.05 - 0.15 meters).

Keywords

Boulder Bed, Shear Stress, Particle Distribution, D_{84}

1. Introduction

Boulders and cobbles are often used in stream restoration projects as a way to increase flow resistance and enhance channel stability and habitat diversity [1] [2] [3] [4] [5]. The size of the particles applied to the project is often determined by the desired flow resistance; however, flow resistance equations do not account for particle clustering or what is known as small-scale particle organization [6] [7] [8] [9]. Conversely, large-scale particle organization or bed forms such as dunes, riffle-pool sequences, and step-pool sequences are well characterized and recognized as a significant factor in flow resistance [1] [10] [11] [12] [13].

Small-scale particle organizations such as particle clusters are either poorly characterized or unknown [11] [12] [13] [14] [15]. Particle flow resistance in natural channels is often determined using the Wolman pebble count method [16]. The Wolman pebble count requires sampling 100 particles along a stream cross section and measuring the intermediate axis. A particle size distribution is derived from this technique using bins (log based two bin size). The distribution is linked to the flow hydraulics using the following equation [16]

$$\frac{\bar{u}}{u^*} = 2.8\log\left(\frac{d}{D_{84}}\right) \quad (1)$$

where $\bar{u}$ is average velocity, u^* is shear velocity, d is flow depth, and D_{84} is the 84th percentile in the particle distribution sample. Shear velocity is related to shear stress by the following equation:

$$u^* = \sqrt{\tau/\rho} \quad (2)$$

where ρ is fluid density. A more thorough analysis of the particle distribution's heterogeneity and its contribution to flow resistance is described in [13].

Under the premise that the D_{84} represents the larger particles that occur frequently (compared to the D_{95} which might occur too infrequently to have as great an impact), all flow resistance is assumed to come from particle size distribution. For engineering applications of stream restoration, it is an appealing equation, because it collapses the flow resistance variable to the particle size metric. This equation does not account for resistance in bed forms, sinuosity, vegetation or micro bedforms such as clusters.

$$\tau = \tau_{D_{84}} + \tau_{\text{bedform}} \quad (3)$$

Step-pools, riffle-pool, and dunes are examples of large-scale particle organization that have a significant impact on flow resistance. In Equation (3), τ is the total shear stress. In the scenario that Equation (1) assumes, the τ_{bedform} in Equation (3) is negligible. For stream beds without well-defined bedforms, they can exhibit small-scale particle organization such as clustering that increases shear stress. Equation (1) would underestimate flow resistance when clusters are present.

To evaluate small scale particle organization (clustering) shear stress and compare these values to Equation (1), quantitative definitions of clusters are required. Reference to clusters are found in the geomorphology literature [1] [2] [3] [4] [10], but these definitions are not easily translated to reproducible field techniques. Specifically, there are no definitions to guide field measurements of where a cluster begins or ends, or which particles are on the bed should be considered clustered.

Roughness is associated with the size of the particles and the heterogeneity of the particle distribution itself. Boulders bed particle distributions (**Figure 1**) show a range of particles from sand size to particles exceeding 70 mm. Designating the upper tail of the distribution as equal or greater than 84 percent, the sum of these particle lengths can exceed half a meter. While the sum of the lower

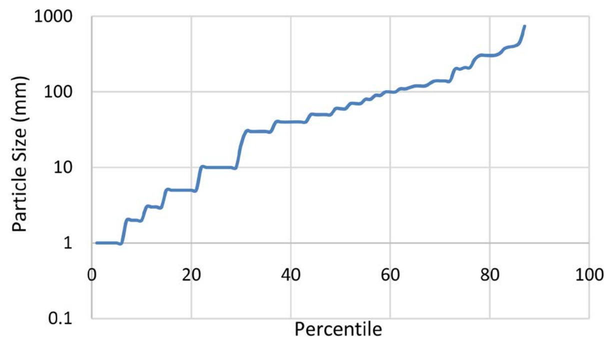

Figure 1. Boulder bed particle distribution.

tail (all particles in the lower 16%) may have a cumulative sum less than 0.01 meter. The upper tail is of greater interest in how it may affect shear stress.

An important step in understanding particle cluster effect on shear stress is to develop a definition of clusters that is related to the particle size distribution, especially the upper tail. The second step is to evaluate how the definition of particle clusters affects the hydraulics and may be used to adjust Equation (1).

2. Cluster Definition

Particles in the upper tail (≥84%) of particle size distribution along the cross section protrude 2 - 3 times above the baseflow in most cases, so they are substantial obstacles to flow. Particles that protrude above the bed, constrict the channel width locally and possibly enhance shear stress. Clustering is hypothesized as being related to the particle distribution using the following equation:

$$\text{Topsum}_{\text{rank}} = \sum\nolimits_{84}^{\infty} y_i \tag{4}$$

where y_i is the width of the intermediate axis. Topsum is the defined as the sum of the particle diameter for the upper tail. Particles are considered clustered when there are two or more that are closer than the D_{84}.

3. Methods

To test the hypothesis that clustering decreases with particle size, six streams from the Maryland Piedmont and Coastal Plains with a range of particle size from coarse gravel to boulder were chosen. This selection ensured sampling would occur across a range of particle distribution sizes. For each stream reach, particle size data were collected from a minimum of three cross sections; however, many streams were sampled along 6 or more cross sections. Sites were selected that exhibited little or no bedforms along straight portions of the stream. The D_{84} range for the data set is 5 - 30 cm with stream width range of 6 to 17 meters.

To collect information about particle organization, the Wolman pebble count was revised to include recording the article diameter size (not frequency of occurrence in a bin size), and particle position along the cross section. To ensure adequate and uniform sampling, particle measurements were taken every 20 mm. For streams with particles larger than 20 mm, the particles occupancy on the bed was recorded.

Clusters were characterized two ways. First the total cluster size or Topsum was calculated. As mentioned in Equation (3), this is a measure of the total amount of particles along the bed that can be considered clustered. The second examination is average cluster size which is the total cluster size divided by the number of clusters. Average cluster size is indicative of the general size of these clusters and is useful to compare to particle size statistics such as the D_{84}.

Channels cross sections and longitudinal profiles were surveyed using a geodetic total station at 0.2-meter intervals. Both the bed and water elevation were measured. Average velocity and velocity profiles were measured at 0.2-meter stations along the stream using a topsetting wading rod and Sontek flow meter.

Average velocity measurements along the stream were taken at 60 percent of the depth. Velocity profiles consisted of 6 - 8 measurements along the water column at each station. From the derived velocity profiles, shear stress was calculated using the change in velocity over the change in depth. The depth integrated velocity was used to calculated shear velocity (a shear stress value dimensionally comparable to velocity) using the "law of the wall" turbulent flow equation [17] [18] [19].

$$\frac{u}{u^*} = 5.75 \log\left(\frac{z}{k}\right) \tag{5}$$

where u (m/s) is velocity, u^* is shear velocity (m/s), z is depth and k is a roughness constant. An example of this analysis and calculation are shown in **Figure 2**. To effectively calculate u^* the velocity measurements are plotted on a log linear graph. The log trendline slope is obtained. The slope value is divided by 5.75 to calculate shear velocity.

4. Results

Overall, the results were promising. **Figure 3** shows an aggregate of all field data. In **Figure 3**, the average cluster size was found to show a positive correlation with the D_{84} as expected. Average particle clusters were roughly a third larger than the D_{84}. The correlation coefficient of 0.64 is not considered to be highly significant, but it indicates further investigation is warranted. As the D_{84} is larger

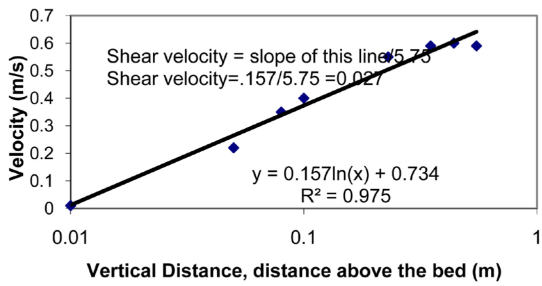

Figure 2. Example of velocity profile at a stream station. Velocity was measured in the vertical water column eight times to a height of 0.59 above the bed.

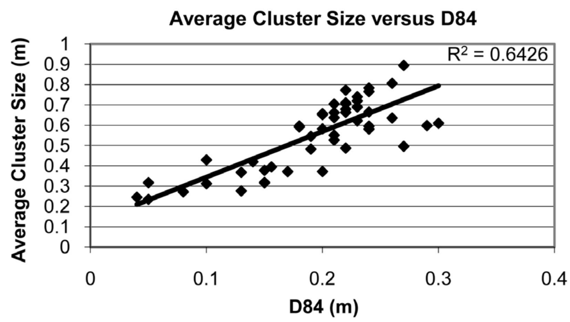

Figure 3. Average cluster size vs D_{84} for six watersheds in Maryland coastal plains and piedmont.

in the stream, note that the range of average cluster size increases by over 0.5 m in some cases.

In **Figure 4**, the total cluster size versus D_{84} is illustrated. The total cluster size increased until the D_{84} reached approximately 0.15 m, and then it decreased. This dual trend relationship between total cluster size and D_{84} is unexpected. The total cluster size is always larger by almost at least a magnitude of order. D_{84} particles around size 0.14 - 0.16 have total particles clustered from 4 - 6 meters.

The number of clusters was compared to the D_{84} particle (**Figure 5**). As the D_{84} particle increased, the number of clusters (as defined in this study) decreased. The correlation coefficient is not very significant for this relationship. Part of the reason for the low correlation coefficient is that cluster numbers are discrete data. There are also multiple values of the number of clusters for each D_{84} value. For example, streams with three clusters were found to have D_{84} values from 0.15 to 3 meters.

The number of clusters per cross section decreased as the D_{84} increased, as shown in **Figure 5**. The relationship between D_{84} is not significant with a correlation coefficient of 0.42, but the graph is instructive. The values of the cluster numbers are only reported as integers, so cluster values are not unique. For example, for particles ranging from 0.15 to 0.3 meters may have 3 clusters. Also, a D_{84} of 0.2 meters may have 3, 4 or 5 clusters.

Hydraulic Data Results

Shear velocity was determined from the method described above and average velocity was measured. To evaluate how well the ratio compared to the field-based equation that relates shear velocity to (Equation (1)) to the flume derived equation (Equation (5)) data were graphically compared to the following ratios: d/D_{84} and the d/Topsum (where d is depth), top channel width/D_{84}, and width channel/Topsum.

A low correlation coefficient was found between all relationships. Of interest is the relatively low correlation found in **Figure 6** for an established field equation (Equation (1)). Also of note is the relationship between u/u^* versus d/D_{84} shown in **Figure 6** and u/u^* versus d/Topsum shown in **Figure 7**. The Topsum shows a higher correlation coefficient by more than fifty percent, which is

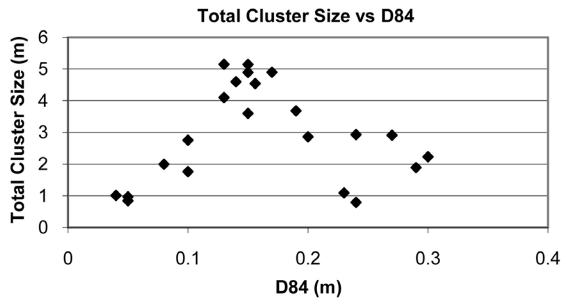

Figure 4. Total cluster size vs D_{84} for six watersheds in Maryland coastal plains and piedmont.

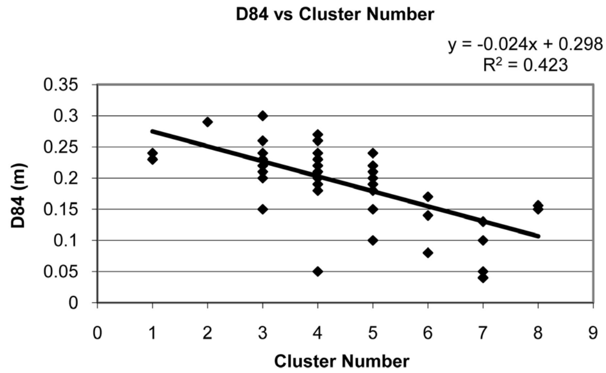

Figure 5. D_{84} versus cluster number for six watersheds in Maryland coastal plains and piedmont.

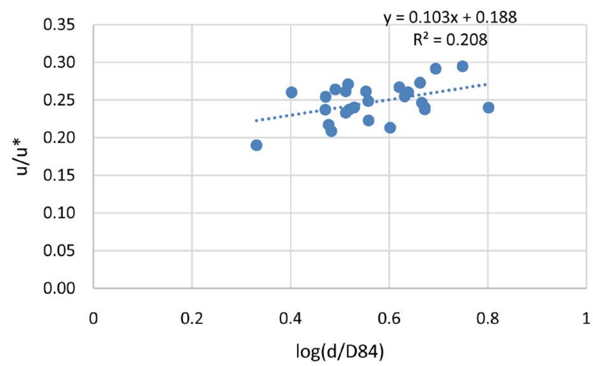

Figure 6. Velocity/shear velocity versus d/D_{84} for six watersheds Maryland coastal plains and piedmont.

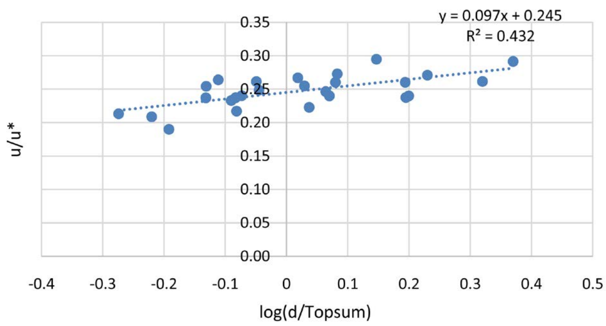

Figure 7. Velocity/shear velocity versus d/D_{84}.

worth further investigation. Of interest is the relatively low correlation found in **Figure 6**.

5. Discussions

The connection of the cluster definition to the particle size works well. For beds with extremely large clasts, all particles could possibly be considered "clusters" by simply their proximity. By excluding the lower distribution from consideration in the cluster definition, it limits clustering to only the largest particles. This definition aids in field scenarios in boulder bed channels (with particles larger than 60 - 90 mm) because the Topsom definition provides a cutoff of what particles should be considered "clustered".

Average particle cluster size and the number of clusters as shown in **Figure 3** and **Figure 5**, respectively convey a similar meaning that overall, the average cluster size will be larger with larger D_{84} particles [20] [21] [22] [23]. Larger cluster sizes may indicate that there are less clusters available to form on the bed [24] [25] [26]. Larger particle sizes may also not be as likely to organize in clusters [23] [25].

As shown in **Figure 4**, the larger D_{84} indicates that less of the overall particles across the bed are likely to be in a cluster when particles are large. Perhaps in streams with large particles (>100 mm) the heterogeneity of the particle distribution is so substantial that there are fewer particles that could be considered in the definition of particle cluster [26] [27]. It also may be more important to identify clustering in streams with "smaller boulder/large cobble" size particles that range from 0.05 - 0.15 m in size. Large particles may also be significant enough to affect the hydraulics with a lower percentage of the particles clustered [28] [29].

The surprising results were found in **Figure 6** where u/u^* did not correlated well with d/D_{84}. This equation was developed for gravel bed streams which range from 0.002 - 0.06 meters. While the relationship in **Figure 7**, was not significant, it is a stronger correlation than found in **Figure 6**. This is highly suggestive the D_{84} is not adequate to account for the shear stress found in boulder bed channels and that addition consideration for micro-particle organization such as clustering needs to be considered to full account for flow resistance.

6. Conclusions

Introducing boulders to natural and engineered streams is a common stabilizing technique to increase flow resistance or to alter the design shear stress. While clustering is widely acknowledged as a potential source of flow resistance in gravel and bounder bed channels, defining clusters is an elusive task. In streams where there are many large particles, most particles appear to form clusters. Using the definition for clusters presented in this paper connects the identification of clusters to the particle distribution and considers only the largest particles to be the most significant. Pebble counts and particle distributions are widely used to estimate shear stress and particle mobility. Topsum uses existing methods to evaluate the impact of clustering in channels with boulder beds but without large scale particle organization such as step-pools. Topsum performs better than the D_{84} in the field flow equation used to link particle size to shear velocity and shear stress.

The definition of clustering appears to work best for particles of size 0.05 to 0.15 m. Streams with larger particles (>100 mm) may have a few very large particles in the upper tail. By the definition, the smaller particles will not be included in the definition of clustering. This observation appears to resonate with what is seen in the field, where isolated large particles may have a significant impact on the flow resistance. For particles greater than 100 mm and larger, a return to using the D_{84} may be appropriate.

Finally, clustering is not considered in flow equations, because determining clustering in a field setting is extremely time consuming, tedious, and requires meticulous field skills. Particle position was recorded for the purposes of evaluating clusters, but to use the variable Topsum in the field, workers would not have to perform extra measurements to obtain Topsum or to use Topsum to estimate clustering boulder bed channels.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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