Equal-Mobility Bedload Transport in a Small, Step-pool Channel in the Ouachita Mountains

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Introduction

Equal-Mobility Transport Theory: The equal-mobility transport (EMT) theory states that larger grains are more easily entrained than smaller ones in a heterogeneous bed because they are relatively more exposed to lift and drag forces (Parker and others 1982, Andrews 1983). It challenges the traditional, size-selective transport theory (SST) (Shields 1936) that holds that bedload size is directly proportional to displacement forces (e.g., shear stress, discharge, stream power).

Step-pool Applications: Only Blizard and Wohl (1998) have directly examined whether EMT occurs in step-pool channels. They found a general trend towards EMT but also found evidence suggesting size-selective transport occurred, too.

Study objectives: The objective of this study is to assess whether EMT or SST occurs in step-pool channel during near-bankfull streamflow events. Four different testing methods are used to evaluate which bedload transport mode occurs.

Methods

Site Description: Bedload was measured in a typical step-pool stream (Toots Cr) located within the Ouachita Mountains (Figure 1-2). Weighted (by channel length) mean gradient is 8.8% and bankfull widths average 4.2 m. Banks are composed of mixed colluvial and alluvial deposits while surface bed material ranges from silts to boulders with an overall D_{50} of 56 mm (Figure 4). See handout for additional information.

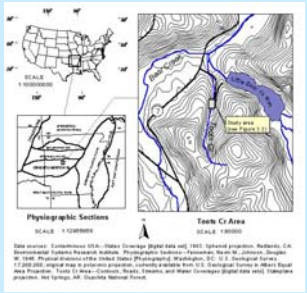

Figure 1. Location of the Toots Cr basin and the study reach.

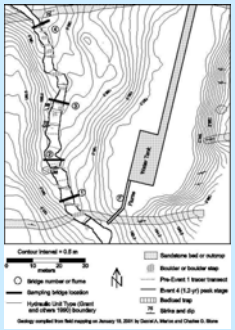

Figure 2. The Toots Cr study reach features.

Figure 3. Aerial view of storage tank and flume.

Figure 4. Downstream portion of Toots Cr study reach looking upstream.

Experimental design: Five individual flow events with peak discharges ranging from 0.25 to 1.34 m^3/sec (1.0- to 1.6-yr recurrence intervals) were simulated using controlled releases from a storage tank (Figure 3) (Marion and Weirich 1997). All bedload sampling was done at Bridge 2 (Figure 2) using a 73-mm Helley-Smith sampler. See handout for additional information.

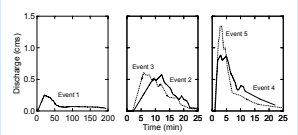

Figure 5. Hydrographs for all five simulated events used at Toots Cr.

Testing Methods

Several approaches have been advanced for determining whether EMT occurs. See handout for additional information.

Critical Dimensionless Shear Stress (τ_c*) vs. Maximum Grain Size (D_{max}): Parker and others (1982) theorize that an inverse relationship (i.e., regression slope coefficient [b_1] = -1) between τ_c* and D_{max} indicates EMT. Andrews (1983) tested this by regressing τ_c* against D_{max}/D_{50sub} where D_{50sub} is the median subsurface grain size. **We tested the relationship between τ_c* and D_{95}/D_{50b}** where D_{50b} is the bed surface D_{50}. The surface D_{50} was used because extensive pavement break down did not occur (Ashworth and Ferguson 1989).

Displacement Distance vs. Grain Size: Ashworth and Ferguson (1989) reason that if EMT occurs, then $b_1 = 0$ in the linear regression between displacement distance and grain size, and $b_1 < 0$ if SST occurs. We computed models for both grain weight and b-axis length (two measures of size) for each event and cumulative displacement over all events.

Grain Size of Selected Bedload Distribution Percentiles (D_x) vs. Shear Stress (τ): Komar and Shih (1992) regressed selected D_x against τ. If $b_1 = 0$, then EMT is defined as occurring; whereas if $b_1 > 0$, then SST occurs. We derived models for bedload D_{05}, D_{16}, D_{50}, D_{84}, and D_{95}.

Grain-Size Skewness vs. τ: Komar and Shih (1992) contend that bedload grain-size skewness should increase with τ (i.e., $b_1 > 0$) if SST occurs. We derived models for all five events.

All of these approaches were developed using data from gravel-bed channels that lacked significant structural roughness features such as isolated boulders or steps that are common in step-pool channels.

Results

Critical Dimensionless Shear Stress vs. Relative Grain Size: EMT is indicated, however confidence in this conclusion is not high. This relationship does not vary with event magnitude (P = 0.46) so data from all five events was used together. Two models were tested: one using all data and one excluding the one case where $D_{95} > 32$ mm (see Figure 6). The probability that $b_1 \neq -1$ is quite low (0.04) for both models, indicating that EMT occurred. However, both model slopes have very low R^2 values (0.33 and 0.18). Thus, while the occurrence of EMT is more evident than SST (where $b_1 = 0$), is not conclusively demonstrated by these models.

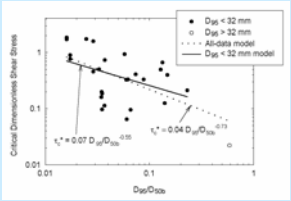

Figure 6. Critical dimensionless shear stress as a function of relative bedload grain size (bedload D_{95}/bed D_{50}) at Bridge 2 during all five events.

Tracer Displacement Distance vs. Grain Size: Initial results indicate that SST does occur in Event 1, but not Events 2, 4, and 5 (see Figure 7). All individual events and cumulative displacement have models with $b_1 < 0$, but only for Event 1 is the coefficient significant at the 0.05 level. Results are very similar for both b-axis length and grain mass. Further analysis indicates that significant relationships can be derived for Events 2 and 5 if a limited number of samples are excluded (see Figure 7). No improvement is achieved for Event 4 by excluding the two most extreme values. The difference between these two sets of results suggests that larger sample sizes may be needed to resolve this question.

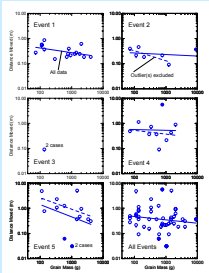

Figure 7. Tracer travel distance vs. grain mass for individual events and total distance over all events. Possible outliers denoted with dot symbol. Models are based on all data (solid line) and with possible outliers excluded (dashed).

Percentile Grain Size vs. Shear Stress: SST is not evident for any except perhaps the largest percentile when data from all events are considered together. P > 0.29 for all percentiles except D_{95} where P = 0.10.

A General Linear Model test indicates that the τ-D_x relationship varies between events. SST does occur during Events 4 and 5, but not during Events 1–3. Figure 8 shows the difference between event groupings for bedload D_{50}, which is typical of all models. For Events 4–5, all but one of the $b_1 > 0$ for the five size percentiles at the 0.05 level, but R^2 values are not very high. EMT is indicated during Events 1–3 (all $b_1 = 0$) (Figure 8).

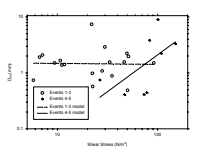

Figure 8. Bedload D_{50} size variation with shear stress at Bridge 2. Model for data taken from Events 1-3 is statistically different than that for Event 4-5.

Blizard and Wohl (1998) obtained significant regressions between τ and three of the four size metrics they tested: D_{max}, D_{84}, and D_{16} (no R^2 values are reported), but results varied greatly by sampling sites. Their data were taken throughout one entire spring runoff season, not individual events like at Toots Cr.

The relationship between τ and bedload grain size evident at Toots Cr is different from that documented by Shih and Komar (1990) at Oak Cr (Figure 9). Oak Cr has finer bed material (D_{50} = 60 and 20 mm for the surface and subsurface, respectively, vs. 100 and 50 mm at Bridge 2). Thus, the different responses might be due to the larger bed grains being relatively more exposed at Oak Cr because the surrounding bed matrix contains more, smaller sizes (Andrews 1983).

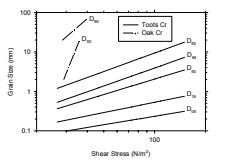

Figure 9. Comparison of bedload grain size-shear stress relationship between Toots Cr and Oak Cr (Komar and Shih 1992). Plot shows models of for given grain-size distribution percentiles.

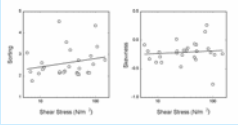

Figure 10. Bedload sorting and skewness variation with shear stress at Bridge 2 for all events. Lines show regression models.

Bedload Grain-size Skewness vs. τ: According to the skewness v. τ test, SST does not occur. The probability is 0.46 that $b_1 = 0$ using data from all events. During the five experimental events, skewness remains essentially constant over the τ range observed (no differences between events). See Figure 10.

Conclusions

Altogether, the results, while not unequivocal, lend greater support to the conclusion that EMT was the predominant mode during the experimental events. Five of the seven tests support the conclusion that EMT occurs or is predominant. Interestingly, EMT is indicated in all four tests when data from all events are used together (cumulative displacement for tracers).

Explanation: Several explanations may account for the seemingly contradictory results between different tests.

- The tests are based upon different assumptions.
- Tracer displacement tests supporting size-selective transport are somewhat suspect .
- Bedload transport modes may be stage dependent.

The inconsistent expression of EMT may indicate that other factors act to confound the effect of bed size heterogeneity on bedload size in Toots Cr. Laronne and Carson (1976) showed that grain packing and infilling of channel structures can greatly affect the entrainment frequency and displacement distance of bed sediment in a step-pool channel. It seems very likely that such processes also occurred during the simulated events at Toots Cr.

Acknowledgments

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A handout with additional information and references is available. Contact Dan Marion at fsmarion@olemiss.edu