Patterns in Gravel Bedload Transport from Impact Plates in a Laboratory Flume

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Abstract

Bedload remains difficult to measure, and finding patterns in bedload transport, such as those caused by the passage of a hydrograph or from a change in sediment supply, is particularly difficult because manual sampling methods are laborious and limit temporal resolution and total monitoring time. The use of accelerometer-equipped steel plates installed in the bottom of a channel allows the impact of particles on the plates to be continuously recorded. Using a calibration process, the data can be converted to particle size, and the sum of the particle masses can be used to quantify transport rate over a range of time scales. Impact plates in a 30 m laboratory flume were used to record gravel transport over a range of antecedent shear stresses for a gravel/sand mixture. The data were processed to reveal patterns in mass transport and gravel particle size resulting from different antecedent conditions for repeated experiments with the same flow conditions. Both initial transport rate and variability in transport rate were found to be higher when starting from a screeded bed and when following flows with larger excess shear stresses.

Introduction

Temporal variability in bedload makes continuous monitoring attractive in rivers where coarse bedload may have impacts on flooding, navigation, and fisheries management. In recent years, the use of metal plates equipped with accelerometers or geophones to detect impacts of particles transported as bedload has expanded (e. g., Wyss et al., 2016; Barrière et al. 2015; and Rickenmann et al., 2014). Based on the calibration and testing of the impact plates in Kuhnle et al. (2017), which describes cooperation with the U.S. Bureau of Reclamation on research aimed at providing a calibration for instrumented plates installed in the Elwha River, a new series of experiments was focused on investigating the effect of antecedent conditions or stress history on sediment transport. The effect of antecedent flow conditions on bedload transport has been previously considered. For example, Ockelford and Haynes (2012), studied the effects of sub-critical shear stresses on the bed structure for gravel beds in an effort to explain why critical shear stresses for mobilizing gravels have been shown to increase after extended periods of flow with sub-critical shear stresses. Mao et al. (2011) identified structural difference in static and mobile armor layers, and Mao (2012 and 2018) examined the effects of flow hydrographs and stress history on sediment load. The present work is focused on the effect of antecedent conditions on sediment transport for a sand/gravel mixture, with emphasis here on gravel bedload transport.

Methods

A range of bedload transport rates for a sand/gravel mix was created in the flume at USDA-ARS-National Sedimentation Laboratory, and the signal generated by gravel particles as they impacted steel plates in the flume channel was recorded. Using procedures similar to those described in Wyss et al. (2016a) and detailed in Kuhnle et al. (2017), particle impacts were identified in the voltage signal. The data packets representing the impacts were converted to particle size based on the calibration procedure in Kuhnle et al. (2017), and the time series of particle sizes was used to find gravel load by particle size class.

The experiments were run in a tilting, recirculating 30-m x 1.22-m x 0.61-m flume with adjustable slope. The flume can recirculate water and sediment up to 80 mm in diameter. A 0.25-m thick gravel bed with a median grain diameter of 8.12 mm was screeded flat for the first experiment of this series. The bed material was a bimodal sand/gravel mixture, and the median size of the sand was approximately 0.5 mm. The gravel was 2-45 mm in diameter. The 15.9-mm thick impact plates (0.349 m x 0.501 m in the cross-channel direction) were at the same elevation as the gravel bed, 28-m from the channel origin. Each plate had a CMCP-1100 accelerometer (STI Vibration Monitoring, League City, Texas) mounted to the center of the underside of the plate. Deformation of the plate by impacts induced a voltage that was recorded at 50 kHz. The lower limit of detection for the impact plates was 4 mm gravel.

Table 1 shows the basic hydraulic parameters for the experiments, including the antecedent shear stress at the beginning of each series of experiments. Four experiments with the same shear stress are reported, but each one had a different stress history. Bed shear stress was determined from $\tau_b = \rho g h S$, where ρ is fluid density, g is acceleration due to gravity, h is water depth, and S is water surface slope. The bed shear stress data were wall corrected based on modifications of the Vanoni and Brooks (1957) method described in Vanoni (1975) with further modification by Chiew and Parker (1994), which resulted in an explicit relationship for wall friction. The first experiment was run on a screeded, randomized bed. The second experiment was begun after approximately 40 hours for a flow with approximately 6.3 Pa of shear stress. Each subsequent experiment inherited its bed from previous runs with increasing shear stresses. Note that the final series (Shear 1d) inherited the entire stress history of all previous runs. The bed was not randomized and screeded again before each set of experiments. This implies the assumption that the higher shear stresses applied before each of the low shear runs was able to create its own equilibrium bed and transport rate that was independent of previous experiments at lower shear stresses.

Table 1. Hydraulic parameters

Designation	Shear stress for antecedent condition (Pa)	Mean shear stress (Pa)	Mean depth (m)	Froude number
Shear1a	0 (screeded bed)	5.31	0.253	0.51
Shear1b	6.3	5.21	0.260	0.49
Shear1c	7.0	4.84	0.262	0.48
Shear1d	7.4	5.40	0.264	0.48

Results

Figure 1 summarizes the results obtained during the flume experiments. The first two hours of data for Shear1a (antecedent stress 0 pa) is not present because of a temporary equipment malfunction. Figure 1A shows the time series of the gravel size class centered at 6 mm (4-8 mm) for each of the antecedent shear stresses. The most evident effect of antecedent condition in Figure 1A is the period of increased load in the first 10 hours of the 0 pa (Shear1a) and 7.4 pa (Shear1d) experiments, which was likely caused by particles being exposed to the flow on beds that were not in equilibrium with flow conditions. Figure 1B shows that the mean load for the 6 mm class (calculated with the first 2 hours removed to match Shear1a) decreased across the experiments, while Figure 1C shows that the standard deviation of the load (again calculated with the first 2 hours removed to match Shear1a) decreased with increasing antecedent shear until the highest antecedent shear stress, which resulted in increased variability. This effect may have been caused by patterns in particle arrangement generated by the preceding flow, which persisted for the subsequent shear stress condition. Similar patterns were found for the 12 mm size class (8-16 mm), with higher mean loads (Figure 1E) that reflect the greater amount of the 12 mm class in the bed material. The standard deviation for the 7.4 pa antecedent condition was nearly as high as for the 0 pa condition (Figure 1F). The relative infrequency of 24 mm motion, along with the decreased load, resulted in a sparse dataset (Figure 1G). The lowest mean loads (Figure 1H) were found for the 24 mm class across the antecedent conditions, which may account for the opposite trend in standard deviation (Figure 1I) relative to the 6- and 12-mm classes.

The results contribute to efforts to understand the effects of antecedent conditions on bed load transport. For example, Mao (2018) studied the effects flood history on sediment transport and bed topography, finding that transport rates were greater on the rising limb of a flood flow hydrograph, with decreasing hysteresis for repeated hydrographs. The present work continued each flow for extended periods and adds capability for separating the bed load by particle-size class, which enables examination of preferential movement by size class. In future work, detailed measurements and analysis of bed topography and its effect on transport rate will be incorporated (e.g., Hodge et al., 2009 and Cooper and Tait, 2009).

Conclusions

Measurements of fractional transport made with impact plates showed that antecedent conditions affected the rate of gravel transport, and the effect varied across particle size classes. The effect of beginning an experiment with a screeded bed was similar to the effect of the highest shear stress antecedent condition, resulting in initially high transport rates that gradually decreased as the bed was reworked into equilibrium with the new, lower flow rate. Variability in gravel transport also appeared to be influenced by the prior stress history, with transport rates following screeded bed and high shear stress flows showing increased standard deviation relative to flows that had lower antecedent shear stress conditions.

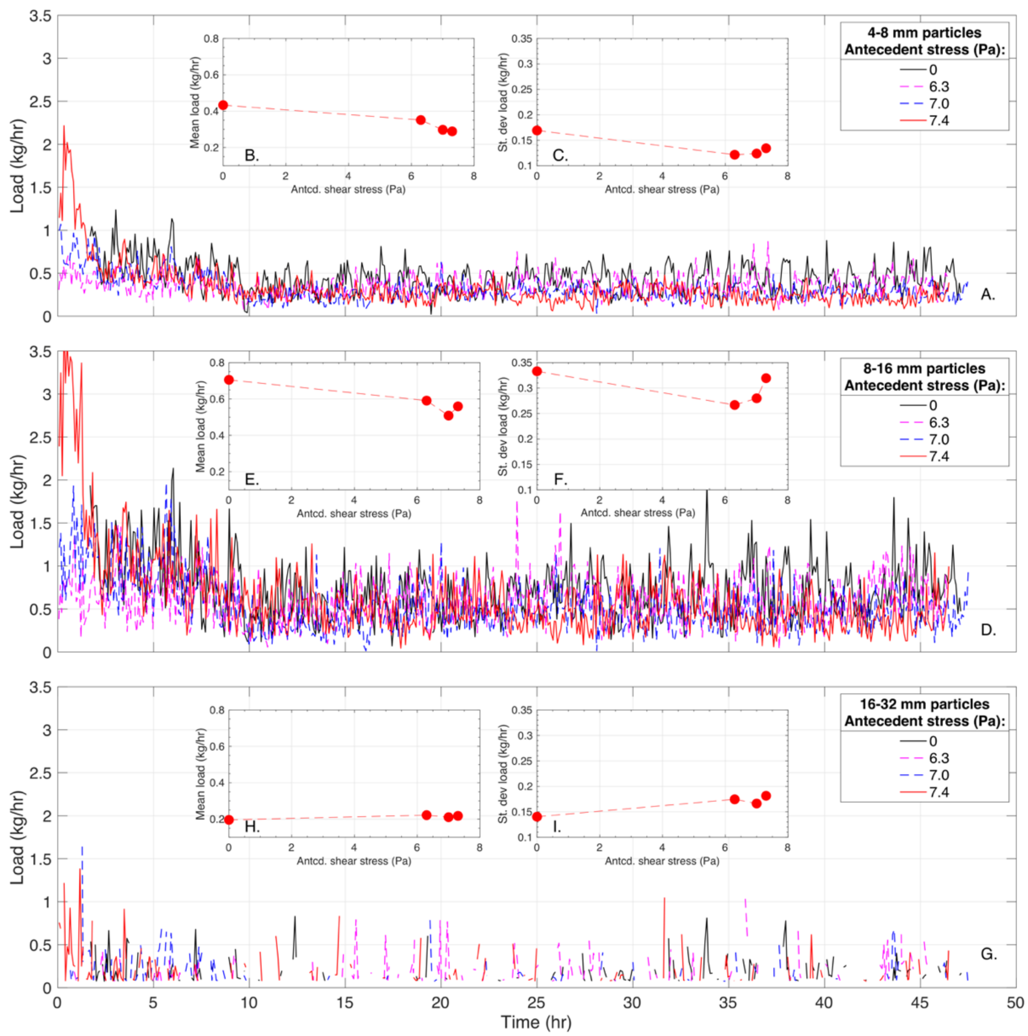

Figure 1. Fractional gravel load from impact plate experiments. A. load for the 6 mm size class (4-8 mm); B. mean load for 6 mm class; C. Standard deviation for the 6 mm size class; D. load for the 12 mm size class (8-16 mm); E. mean load for 12 mm size class; F. standard deviation for 12 mm size class; G. load for the 24 mm size class (16-32 mm); H. mean load for the 24 mm size class; I. standard deviation for the 24 mm size class.

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