THE INFILTRATION OF AND INFLUENCE OF SAND PULSES INTRODUCED INTO MOBILE GRAVEL SUBSTRATES

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Abstract Six sand infiltration flume experiments were conducted with mobile gravel substrates. Each experiment had two phases. In the first phase gravel transport was allowed to reach equilibrium. In the second phase, a sand pulse was introduced into the equilibrium gravel transport system. Bed slope measurements, bed form statistics and substrate cores were collected after each phase of each experiment. Results from two mobile gravel experiments were compared to experiments that used the same substrate and sand pulse materials, but were conducted at shear stresses below the critical shear threshold of the gravel (static bed experiments).

Bed slope decreased during the sand pulse phase for three experiments, indicating that the sand increased gravel transport more than enough to offset the increased mass of the sand-gravel mixture. When the 'sand pulse' material was silt or fine gravel, however, the bed slope increased. In most cases, bed form amplitude increased during the sand pulse phase and decreased during the cleansing flow phase. The bed form wavelength trends were less conclusive. Substantially more sand infiltrated into the mobile gravel bed than the static substrate. Even in mobile gravel experiments that used identical materials but different hydrodynamic conditions, more sand infiltration was measured in the runs with a higher gravel transport rate.

INTRODUCTION

Several natural and anthropogenic processes release large, relatively sudden pulses of sediment into a river that are substantially finer than the ambient river substrate. Dam removal, watershed fires, land use changes, mass wasting events and gravel augmentation all change quantity and gradation of source sediments. These pulses can have dramatic impacts on the geomorphic and ecological processes of the system. This work investigated the effects of a pulse of introduced fine sediment on transporting gravel and the effects of mobilizing the grave on the infiltration of sand into the framework. The experiments had three primary objectives:

1. Examine the influence of a sand pulse on gravel transport.
2. Measure the impact of bimodality on bed form statistics.
3. Quantify the effect of gravel transport on sand infiltration.

EXPERIMENTAL METHOD

Six mobile gravel flume experiments were conducted (Table 1). A 22.5 m long, 1 m wide, 0.3 m deep, upstream feed (Parker and Wilcock, 1992; Gibson, 2009), adjustable slope flume at the U. S. Army Corps of Engineers', Coastal and Hydraulics Lab was selected. Three different gravel substrates and five different load materials (Figure 1) were used for the six experiments. Gravel was introduced with a gravel feed piston at the upstream end of the flume that gradually lifted a 1m by 1m reservoir of gravel into the field of flow at a specified rate. Experiments were

conducted in two phases. First, the flume was operated with just the constant gravel feed until gravel transport was in equilibrium (i.e. the measured rate of gravel exiting the flume was roughly the same as the rate introduced by the gravel piston). Then sand was introduced using a conical, vibratory feed hopper. Pictures taken near the end of each experiment at a window 11 m downstream of the hopper are depicted in Figure 2.

Bed profiles were recorded after the equilibrium stage and sand pulse stage of each experiment using a point gage. Cores were also collected after the sand pulse phase. Portions of the flume were lined with a 1 cm thick layer of clay before the gravel substrate was placed. After the sand pulse, a 5 cm diameter acrylic tube was advanced through the substrate until it pushed through the clay, sealing the bottom of the tube and allowing extraction of the sample without further disturbance (Gibson *et al.*, 2009, Gibson 2009). The cores were then extruded in approximately 1 cm layers and each layer was sieved to determine how much of the feed material had infiltrated into the framework as a function of depth. In two of the experiments some of the gravel particles introduced by the gravel feed piston were painted to track their longitudinal dispersion and depth of burial.

Table 1 List of mobile gravel experiments.

Ex #	Q (cms)	S	Substrate Material	Substrate Feed Rate (kg/min)	Feed Material	Feed Rate (kg/min)	Notes
1	0.085	0.002	G1	2.0	FM 1	3.2	Feed material sand and silt
2	0.085	0.00475	G2	0.9	FM2	6.6	Multi colored gravel tracer particles
3	0.099	0.005	G2	2.7	FM2	6.6	
4	0.123	0.0055	G3	2.3	FM3	7.7	Slug of red gravel clasts
5	0.123	0.0055	G3	2.3	FM4	6.8	Colored sand
6	0.133	0.0055	G3	2.3	FM5	4.1	Gravel feed material (same as substrate G1)

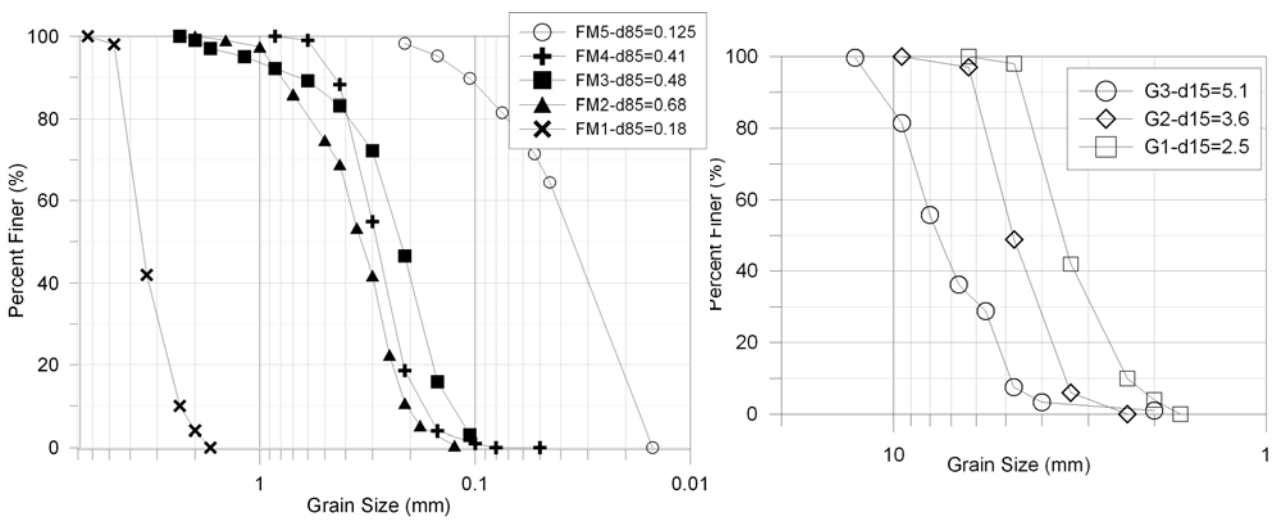


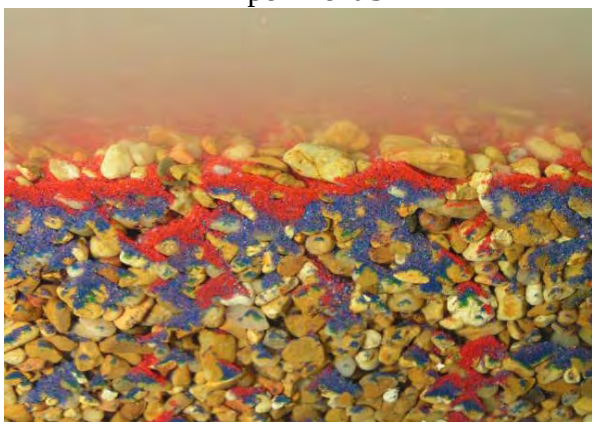
Figure 1 Sand and gravel gradations used in experiments.

Experiment 1

Experiment 2

Experiment 3

Experiment 4



Experiment 5

Experiment 6

Figure 2 Photographs taken at the window 11 m downstream of the source near the end of the sand pulse phase of each mobile gravel experiment.

For comparison, two 'static gravel' experiments were also conducted (Table 2). These experiments used the same substrate and feed materials as mobile gravel experiments 4 and 5 but were run at shear stresses below the critical shear of the substrate.

Table 2 List of comparable stable gravel experiments.

Ex #	Q (cms)	S	Substrate Material	Substrate Feed Rate (kg/min)	Feed Material	Feed Rate (kg/min)	Notes
iv_{LS}	0.085	0.002	G3	0.0	FM3	7.0	same materials as ex 4 (low shear)
v_{LS}	0.085	0.005	G3	0.0	FM4	5.8	same materials as ex 5 (low shear)

RESULTS

Bed Form Statistics Analyzing a bed profile for bed form statistics can be a subjective process (Chickmore, 1970). The primary complicating factor is the differentiation between local perturbations or micro-features and the primary bed form peaks and troughs. In order to minimize the subjectivity of this process a "perturbation threshold" was selected for each bed profile. From an identified trough (local minimum) a new peak was identified at the highest point that exceeded the perturbation threshold before the profile dropped to a new trough that was likewise, lower than the peak by at least the perturbation threshold (Figure 3). Local minimums were determined by a similar process. This approach does not eliminate subjectivity from the determination of bed form statistics because the threshold can be adjusted to include more or fewer minor oscillations as distinct bed forms. Smaller thresholds will detect more bed forms and decrease both the average wavelength (λ) and amplitude. However, because bed form geometry differed dramatically between experiments based on the hydrodynamics and materials, different thresholds were appropriate for each experiment. Therefore, each bed profile was analyzed with a threshold deemed appropriate based on physical observation of the bed and visual inspection of the profile.

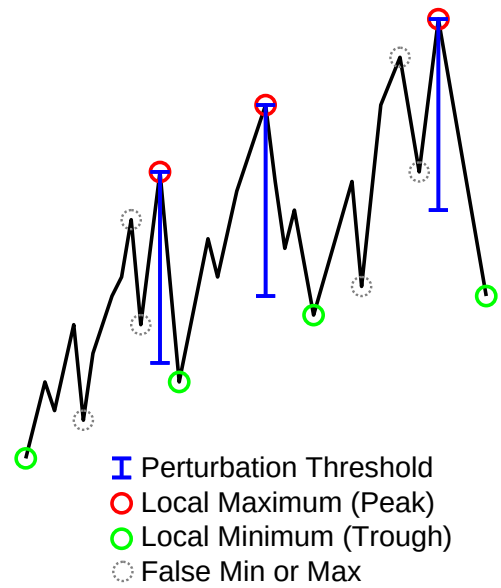


Figure 3 Perturbation threshold process used to determine local minimums and maximums (bed form peaks and troughs).

For all cases, bed form amplitude increased in response to the sand pulse (Table 3). The sand pulse bed form heights were between 11% and 73% (average ~39%) larger. Sand increased bed form amplitude (experiments 3, 4 and 5) more than silt (experiment 1) or gravel (experiment 6). Nearly all of the samples taken of the bed form material following the sand pulse phase, however, contained less than 40% sand. This indicates that the bed forms were still, for the most part, framework supported. Therefore, the amplitude change did not simply represent a layer of sand transporting over a mobile gravel substrate. The bimodal bedload transported as a mixture which developed higher amplitude bed forms than the gravel alone (Figure 4).

Table 3 Bed form statistics for the equilibrium and sand pulse phases of the mobile gravel experiments. Sand pulse experiments all had larger amplitudes than their equilibrium corollaries.

	Equilibrium Phase			Sand Pulse Phase				
	Perturbation Threshold (cm)	λ (m)	Height (cm)	Perturbation Threshold (cm)	λ (m)	Height (cm)	Δλ (%)	ΔHeight (%)
Experiment 1	0.5	2.0	1.0	0.7	1.8	1.3	-8%	25%
Experiment 2				1	1.7	1.5		
Experiment 3	0.7	1.8	1.0	0.7	0.9	1.4	-49%	41%
Experiment 4	0.8	1.7	1.4	0.8	2.2	2.0	32%	46%
Experiment 5	0.5	1.1	1.0	0.7	1.4	1.8	18%	73%
Experiment 6	0.7	1.2	1.6	0.7	1.3	1.8	5%	11%

The influence of the sand pulses on wavelength was not as conclusive. The wavelengths measured after the sand pulse phase of the three experiments that utilized coarser, gravel substrates (experiments 4, 5 and 6 – all used substrate G3 from Figure 1) were longer than those measured after the equilibrium phase. These experiments started off with shorter wavelengths (1.1 to 1.7 m) after the equilibrium phase. The other two experiments (18 and 21) that utilized finer substrates had higher wavelengths after the equilibrium phase (1.8 to 2.0 m) that decreased during the sand/silt pulse phase.

Figure 4 Increased bed form amplitude during the sand pulse phase of experiment 19.

Bed Slope Profiles Bed slope also shifted between the equilibrium and sand pulse phases (Figure 5). Gravel feed rates and hydrodynamics were held constant for both experimental phases. The only difference between the phases was the introduction of the feed material. By simple continuity principles, increased mass with unchanged capacity should result in overall deposition and a base level rise in the sand pulse phase. However when the slopes of the profiles were computed and compared (Table 4) the slope decreased following the sand pulse phase for experiments 3, 4 and 5. This demonstrates the effect of sand content on gravel transport (Curran and Wilcock, 2005; Wilcock and Crowe, 2003). The sand pulse increased the gravel (and, for that mater, total) transport capacity. Material from the bed was entrained to satisfy the sediment deficit due to the increased capacity, and the slope relaxed to achieve a new equilibrium.

Table 4 Slope after each phase of each experiment

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	Equilibrium Slope	Sand Pulse Slope	Slope Change
Experiment 1	-3.4E-03	-4.4E-03	1.0E-03
Experiment 2		-5.1E-03	
Experiment 3	-5.1E-03	-4.2E-03	-9.0E-04
Experiment 4	-4.0E-03	-3.1E-03	-9.0E-04
Experiment 5	-5.4E-03	-4.3E-03	-1.1E-03
Experiment 6	-5.8E-03	-6.2E-03	4.0E-04

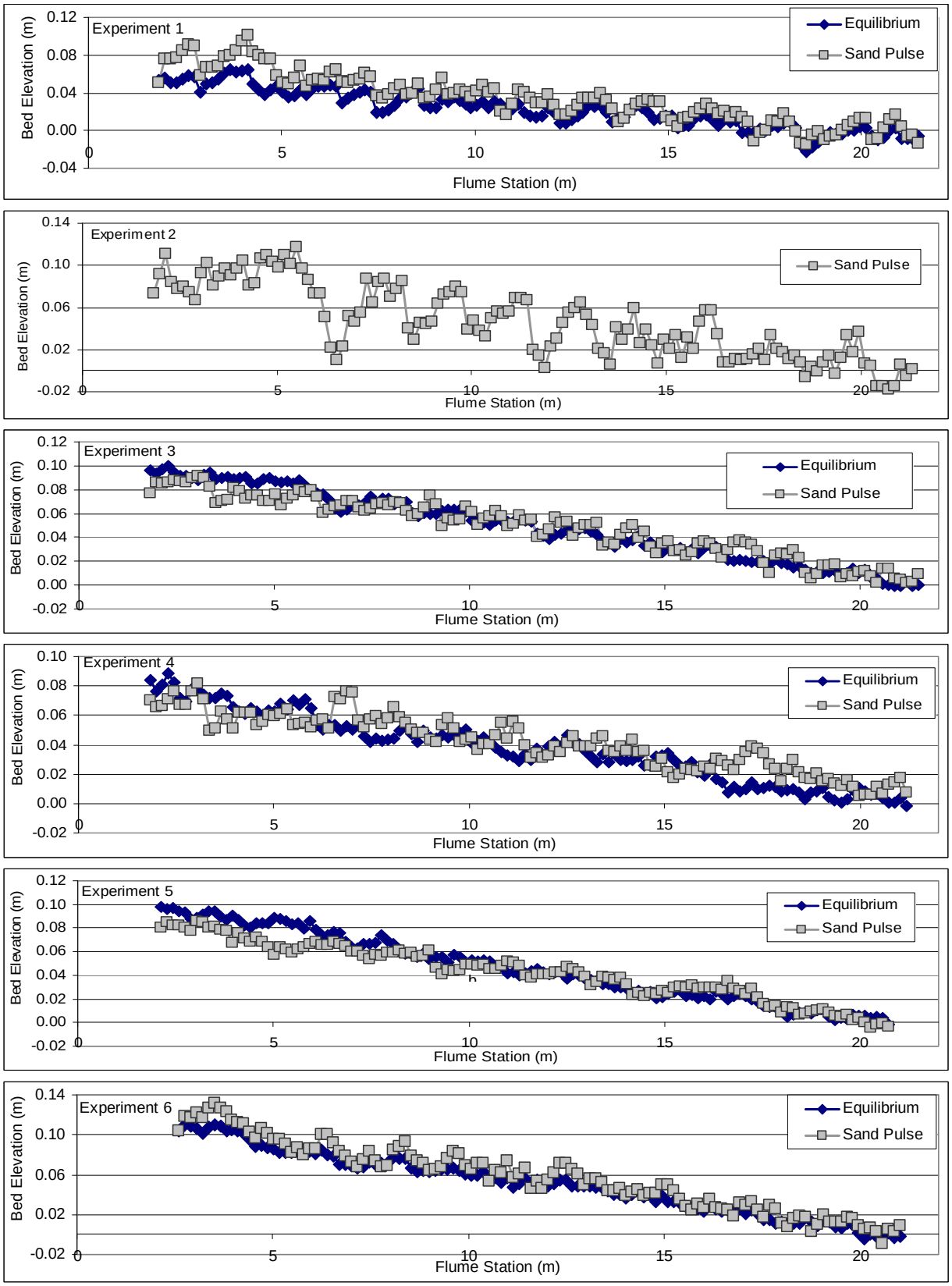

Figure 3 Bed profiles after the equilibrium and sand pulse phases.

Slope increased during the sand pulse phase of the experiments 1 and 6. Experiment 1 was the only mobile gravel experiment that resulted in unimpeded static percolation (i.e. where the infiltrating material completely filled the interstitial framework space from the bottom up – Kleinhans, 2002). The flow kept a thin upper layer of pore spaces free of deposited material and over passing gravel bed forms remained relatively silt free compared to the framework. Interstitial fines probably did not accumulate in the surficial gravels because of the interstitial currents. Therefore the fines did not increase gravel transport. It was also hypothesized that filling the gravel framework with silt might have a stabilizing or strengthening effect, decreasing gravel transport. This could explain the slope increase but cannot be verified from the data.

Adding 4 kg/min of very fine gravel to an equilibrium load of 2.3 kg/min of very fine to medium gravel (experiment 6) to the system, did not drop the gravel transport capacity sufficiently to off set the additional mass. At some point the feed material to framework size ratio ($d_{15gravel}$/ d_{85sand}) would become sufficiently small that the increases in transport capacity disappear. For example, a 'pulse' of identical material added to a system in equilibrium, would require a slope increase from a straight forward continuity perspective. The load material gradation in experiment 6 was close enough to the transporting gravel that it increased the required transport capacity and resulted in a mild slope increase.

Influence of Gravel Mobility on Infiltration More infiltration was observed in the mobile gravel experiments than in the static gravel experiments conducted with the same materials. Infiltration profiles are plotted in Figures 6, 7 and 8. In these plots the percentage of infiltrated feed material after the sand pulse phase for each layer of the core is plotted against the depth of the layer. Infiltration profiles taken at different positions along the flume after experiments 4 and 5 are plotted with data from cores taken at similar locations after experiments iv_{LS} and v_{LS} respectively (experiments conducted with the same substrate and feed materials but at low shears with stable frameworks) in Figures 6 and 7. In both cases, substantially more infiltration was measured after the mobile gravel experiments.

Likewise, infiltration profiles from experiments 2 and 3 are plotted together in Figure 8. These were both mobile gravel experiments conducted with identical substrate and feed materials. However, experiment 3 was conducted with a higher shear stress and more gravel transport. More sand infiltration was measured after the higher shear experiment. This difference in total infiltration between experiments 2 and 3 can actually be resolved visually in Figure 2.

Gravel transport consistently reworks an active layer of approximately one to five large (~d_{90}) gravel particle thicknesses. In most cases, however, temporary sand bridges also formed in this zone. Because the sand bridge formed in the gravel active layer it was subject to constant agitation as the flow reworked the bed. This inhibited the permanent formation of a bridge layer, pushing the bridging front farther into the substrate. This 'dilation' process (Middleton *et* al. 2000; Allen and Frostick, 1999) also delayed the clogging of interstitial pathways to the deep pores and allows more total interstitial deposition throughout the framework.

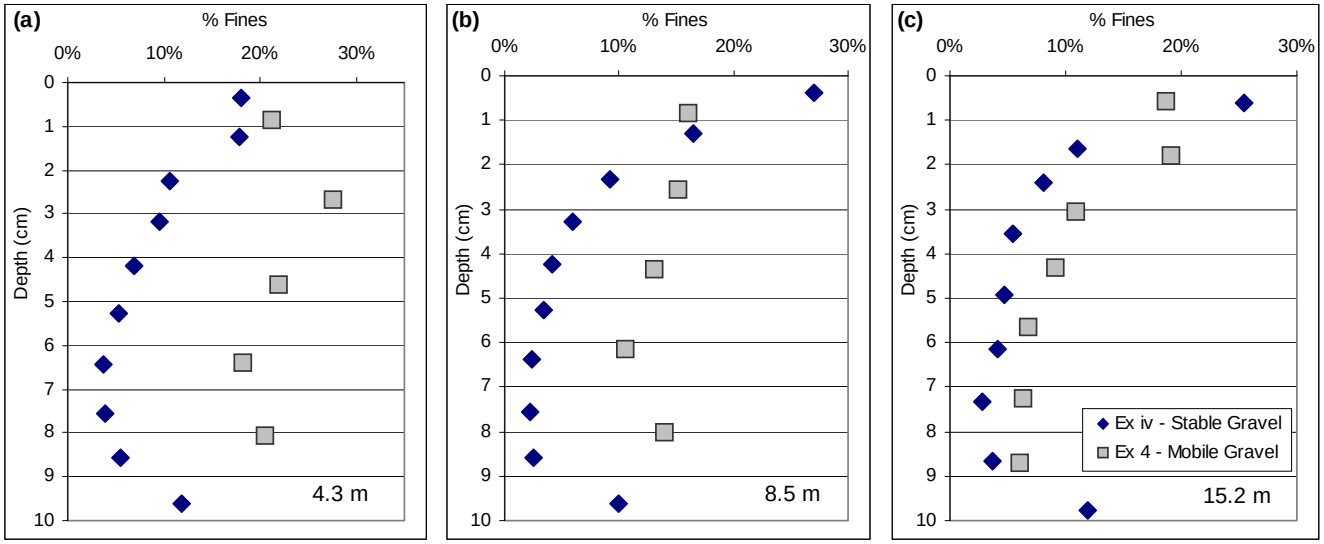

Figure 4: Comparison of fine content profiles between experiment 4 (mobile gravel) and experiment iv_{LS} (stable gravel) at three flume locations.

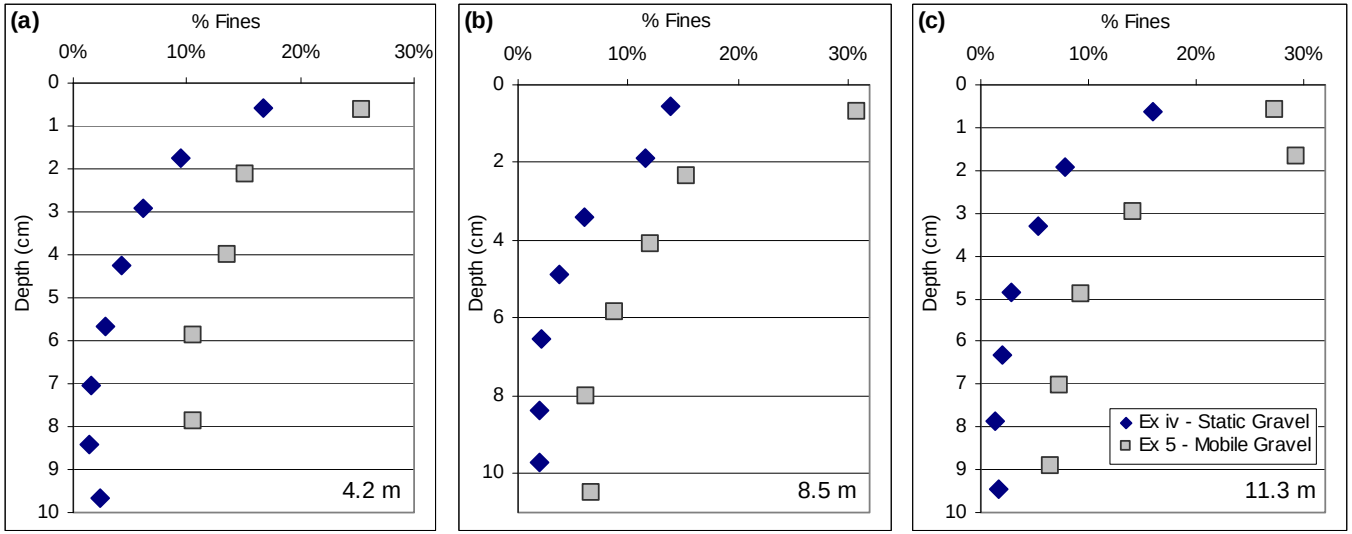

Figure 5: Comparison of fine content profiles between experiment 5 (mobile gravel) and experiment v_{LS} (stable gravel) at three flume locations.

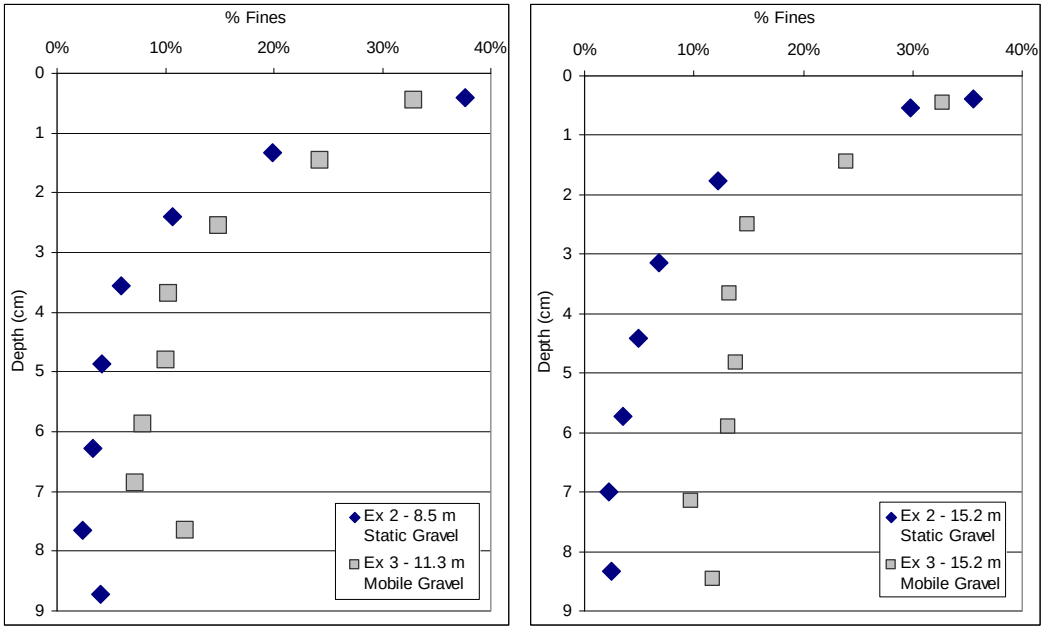

Figure 6 Comparison of samples taken from experiment 2 and 3. There is more total infiltration in the profiles from experiment 3 which had higher shear and more bed movement.

Advection and Diffusion of Tracer Gravel In two experiments (3 and 4) painted gravel particles were released to provide temporal information on longitudinal gravel movement and active layer mechanics (Gibson, 2009).

Before experiment 3, four different layers of tracer gravel (red, yellow, blue, and purple) were placed at known depths in the gravel feed piston. Each layer was < 1 kg and was released into the flume when the gravel piston eroded to the depth at which it had been placed. This released small pulses of distinctly colored gravel into the flume at different times throughout the experiment. Red and yellow particles were released during the equilibrium phase. Blue and purple grains were released during the sand pulse phase. After the sand pulse phase of the experiments the tracer particles were counted and recorded for each 0.6 m long section of the flume (Figure 9).

By the end of the sand phase of experiment 3, most of the first introduced colored grave (red) had passed through the system or deeper into the bed with just a few observations until the final 5 m of the flume. Gravel #2 (yellow) was more abundant but also mainly limited to the downstream half of the flume, increasing prevalent toward the downstream end. Gravel #3 (blue) was relatively evenly distributed throughout the flume with a noticeable spike around 12 m. Finally, gravel #4 (purple) was concentrated in the upstream half of the flume though purple clasts were spotted throughout the flume length.

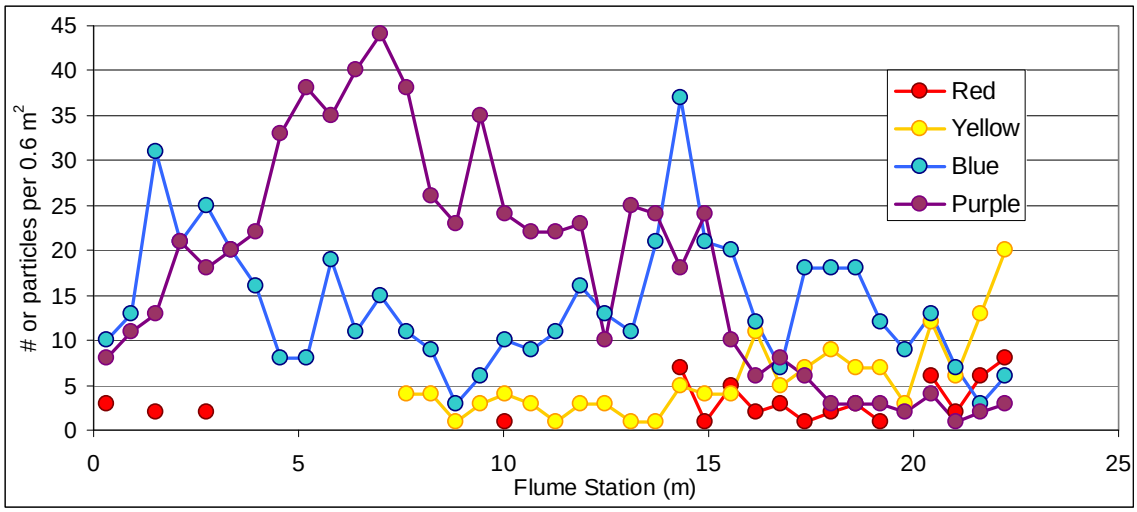

Figure 9 Colored particle count after the sand pulse phase of experiment 3.

Experiment 4 included a single pulse of tracer gravel. About 3 kg of red gravel, that was otherwise identical in gradation and physical properties to the rest of the substrate, was placed on top of the gravel piston at the beginning of the sand pulse phase. The entire bed was carefully photographed after the sand pulse phase and the particles were counted from the digital photographs. The results are depicted in Figure 10.

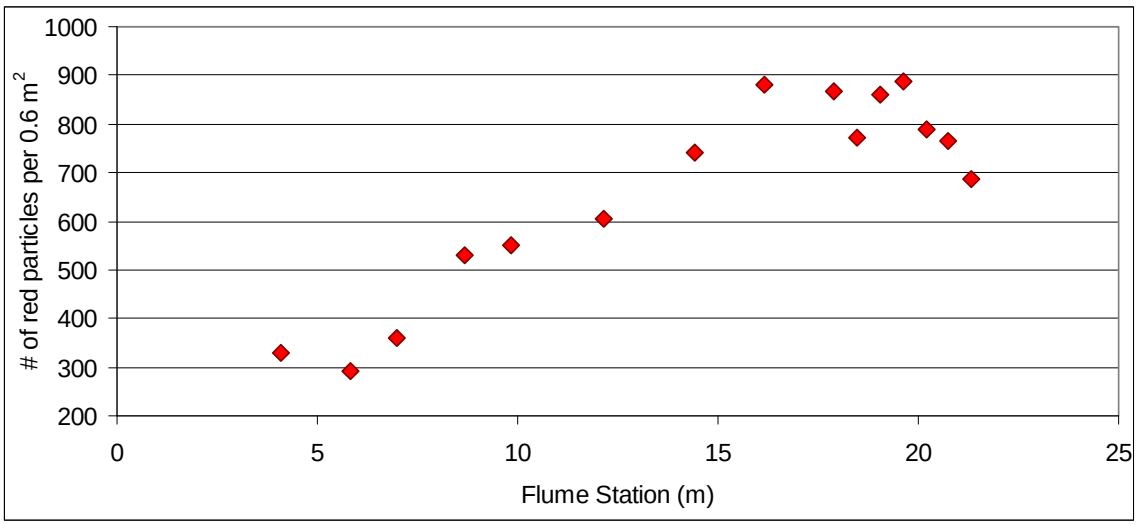

Figure 10 Red particle count after the sand pulse phase of experiment 4.

At the end of experiment 4 red particles were still observable throughout the flume. However, they were concentrated in the downstream section of the flume suggesting that many (even most) of the tracer gravel had passed through the system. At least the center of mass of the trace gravel pulse seems to be at the downstream end of the flume. In contrast, the sand intrusion front extended approximately 15 m downstream by the end of the experiment suggesting that the gravel transported faster then the prograding sand front.

This result is counterintuitive since sand transported in suspension would travel close to the water velocity. However, the progradation of the sand front was attenuated by abstraction into the bed. Before the sand front could pass through a section of the flume enough sand had to infiltrate to form a bridge layer, or subsequent sand would simply continue to disappear into the bed. The tracer particle data suggests that the longitudinal rate of bridge formation (which is the same as the progradation rate of the front of the sand and gravel mixture) was slower than the rate of gravel advection. Both of these tracer studies demonstrate that the length of the sand pulse phase was greater than or equal to the mean time required for the gravel to travel the length of the flume. Therefore, the active layer after the sand pulse phase of each experiment should be composed mostly of gravel introduced during that phase.

SUMMARY AND APPLICATION

Sand pulses increased the transport capacity of the grave sufficiently to offset the mass of the sand and reduce the slope of the transporting mixed bed. Bed slope increased mildly when the 'sand pulse' materials were silt or fine gravel. The amplitude of the bed forms generally increased with the introduction of sand.

Gravel transport increased total infiltration by agitating the bridging layer. Because the bridging layer (which formed in the upper 3 to 5 d_{90}'s of the framework) corresponds almost exactly with the active layer (upper 3 to 5 d_{90}'s of the framework), infiltration will be substantially higher in systems that would easily form bridge layers if the framework remained static.

AKNOWLEDGMENTS

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