River Flow 2010 - Dittrich, Koll, Aberle & Geisenhainer (eds) - © 2010 Bundesanstalt für Wasserbau ISBN 978-3-939230-00-7

Enhanced insight on the effects of boulders on bedload transport

D. Dermisis & A. (Thanos) Papanicolaou
IIHR-Hydroscience and Engineering, Dept. of Civil and Environmental Engineering, The University of Iowa, Iowa City, IA, USA

ABSTRACT: In this study the effects of partially submerged boulders on sand transport over and within a gravel bed were examined thoroughly in a tiltable water re-circulating flume. These effects were evaluated by providing: (i) qualitative descriptions of the sand depositional patterns around the boulders; (ii) quantitative analysis of the bedload rates; and (iii) determination of the infiltrated sediment within the gravel bed. Results showed that the presence of boulders regulated the depositional patterns of the incoming sand particles. Characteristic sand patches were formed in the stoss region of the individual boulders, whereas the wake region remained free of incoming particles. A depositional, V-shaped, sand bed feature was created upstream of the boulder region, along the longitudinal direction of the flume bed. It was determined that under moderate and high bed shear stress conditions ~ 75 % and ~ 40 %, respectively, of the incoming sediment was captured by the boulders in the form of these bed features. The time series of the bedload rates revealed that the existence of the boulders and the sand depositional features directly affected the movement of the sand particles during the progression of the experiments. Significant variations in the transport rate were clearly observed during the initial periods of the experiments. Finally, less sand accumulated within the bed when boulders were present.

Keywords: Boulders, Bedload, Deposition, Patches, Sand ridge

1 INTRODUCTION

The bed morphology of mountain rivers is characterized primarily by the presence of distinguishable isolated roughness elements, such as boulders or clasts (e.g., Wohl 2000). The sizes of these boulders can range from a few meters at the headwaters of mountain streams to a couple of centimeters at the downstream regions (i.e., transition from a gravel to a sand bed river). Downstream fining of boulder size has been attributed to sorting, abrasion, and differential mobility of various grain size fractions. Due to their size, boulders are rarely entrained and tend to be mobilized predominately under extreme flow events.

The transport of bed material in gravel bed rivers has been found to be either in the form of individual particles or characteristic bed features, such as ripples, dunes, bars (e.g., Bennett & Bridge 1995). Although numerous studies have investigated the transport of sediment over gravel bed rivers (e.g., Smith & Ferguson 1996; Almedeij & Diplas 2003; Grams & Wilcock 2007), little attention has been given on the effects of boulders on the movement of bed material. Recently, artificial boulders have been installed in many gravel bed rivers by hydraulic engineers and fish biologists to restore degraded waterways by stabilizing the streambed as well as to enhance aquatic habitats by damping the kinetic energy of flow (e.g., Saldi-Caromile et al. 2004).

Building upon the foregoing research, the overarching objective of this study was to examine, through flume experiments, the effects of the presence of an array of isolated boulders on the movement of sand over and within a gravel bed under low relative submergence conditions (i.e., $H/d_b < 1$, where H is the flow depth and d_b the diameter of the boulder). The relative submergence has been reported to control the flow and sediment patterns in the vicinity of boulders (e.g., Papanicolaou & Kramer 2005). The study aimed at achieving the following goals: (1) provide a qualitative description of the sediment depositional patterns around the boulders; (2) illustrate the effects of boulders on bedload rates; and (3) determine the amount of the infiltrated sediment within the bed.

2 METHODOLOGY

There are two experimental scenarios considered for this study: scenario A consists of tests performed with the presence of boulders atop a gravel bed, whereas scenario B is tested without the presence of boulders. The experimental tests, representing scenarios A and B, were conducted under identical flow conditions. These conditions were determined based on the dimensionless applied bed shear stress, τ^*, which was selected to be ~ $2.5\tau_c^*$ (corresponding to moderate applied bed shear stress conditions) and ~ $5.5\tau_c^*$ (corresponding to high applied bed shear stress conditions), where, τ_c^* is the reference dimensionless critical bed shear stress for the incipient motion of the sand particles. The incipient motion criterion for the individual sand particles was determined using the probability of entrainment concept by Papanicolaou et al. (2002). This concept takes into account the near-bed turbulent effects (cycle of turbulent bursts) and frequency of their occurrence, thus it does not overestimate the critical flow conditions under which commencement of sediment motion occurs. The incipient condition of the sand particles was considered for a 2.0 % probability of entrainment (i.e., during a bursting cycle 1 out of 100 particles is transported by near-bed turbulence). By utilizing the methodological procedure of image analysis described in the study by Papanicolaou et al. (1999) the dimensionless critical shear stress τ_c^*, corresponding to 2.0 % sand entrainment, was determined to be 0.022. Using a combination of scenarios A and B with the two selected τ^* values, four tests were performed, namely tests A-1, B-1 and A-2, B-2 (1: moderate τ^*, 2: high τ^*).

3 EXPERIMENTAL SET-UP

3.1 *Facilities and instrumentation*

The experiments were carried out in the IIHR-Hydroscience and Engineering facilities located at the University of Iowa in Iowa City, USA. A state-of-the-art water-recirculating, tilting flume was used, having a useful length of 21.6 m, width of 0.90 m and depth of 0.50 m. The slope of the flume was adjustable using a screw jack, driven by an electric motor, with a precision of 0.01 %.

The flow rate was measured using a digital flowmeter with an accuracy ± 0.25 % of the actual flow rate. A carriage was equipped with five point gauges (precision 0.0003 m), equally spaced at a distance of 0.15 m across the y (transverse) direction of the flume, for mapping the bed surface. To obtain the topography of the bed at different cross-sections, the carriage was manually moved along the x (longitudinal) direction of the flume. To calculate the bedload rate, a sediment trap was used to collect the material at the exit of the flume. The sampling period for sediment collection varied between few minutes to 12 hrs, depending on the duration of each experiment; A-1 experiment lasted ~ 90 days, B-1 ~ 60 hrs, A-2 ~ 2.0 hrs, and B-2 experiment ~ 1.0 hr. Consequently, bedload material was collected in the sediment trap at a sampling period of ~ 12 hrs, ~ 1 hr, ~ 2 min and ~ 1 min, respectively.

3.2 *Test sections*

The flume consisted of three sections (see Figure 1): (a) the "sand bed section" as a feeding section of sand particles; (b) the "glass bead bed section" which constituted the main test section; and (c) the "exit section" including the sediment trap.

The sand bed section, 9.6 m in length, consisted of uniform size quartz sand with a mean particle diameter of d_m = 0.19 cm (subscript m denotes matrix, adopted by Lisle 1989). Prior to the experimental run the sand bed was leveled to its final height of ~ 8 cm using a screed board. Sand was not re-circulated or fed into the flume.

The gravel bed section, 4.5 m in length, was comprised of 5 layers (~ 8 cm thick) of immobile, well packed, uniform glass-beads (Strom et al. 2004) with an average porosity of η = 0.24 and a diameter of d_f = 1.91 cm (subscript f denotes framework, adopted by Lisle 1989). To enable monitoring of sediment infiltration beyond the 8 cm bed-layer, part of the flume bed was modified to form a 30 cm-deep rectangular recess (namely "spawning box"), as shown in detail in Figure 1. The spawning box (dimensions 90x60x30 cm) was filled with 20 layers of glass-beads. Determination of the amount of sand within the streambed was performed by sweeping the bed during the removal of the 25 glass-bead layers at the end of each test.

Spherical particles simulating the boulders with a diameter of d_b = 5.5 cm were placed atop the immobile glass-bead bed. The boulder size was defined as $d_b \approx 3d_{armour}$ (Reid et al. 1992), where $d_{armour} = d_f$ = 19.1 mm is the median size particle of the armoured bed. The spacing between the boulders was $6d_b$ (i.e., 2% packing density), resulting in an isolated roughness regime (Morris 1955).

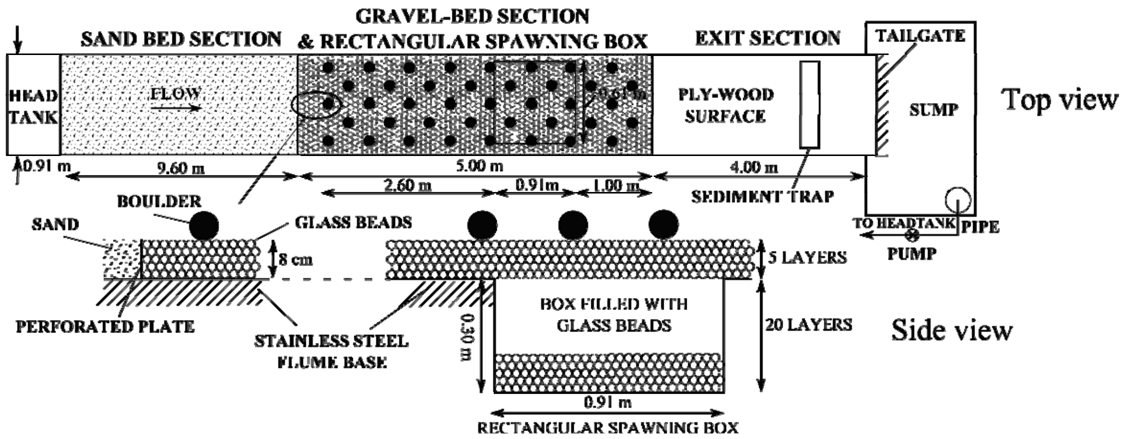


Figure 1. IIHR's state-of-the-art recirculating tilting flume.

Lastly, the exit section, 4.0 m in length, incorporated a sediment trap to collect the sand particles and a tailgate to control the flow depth.

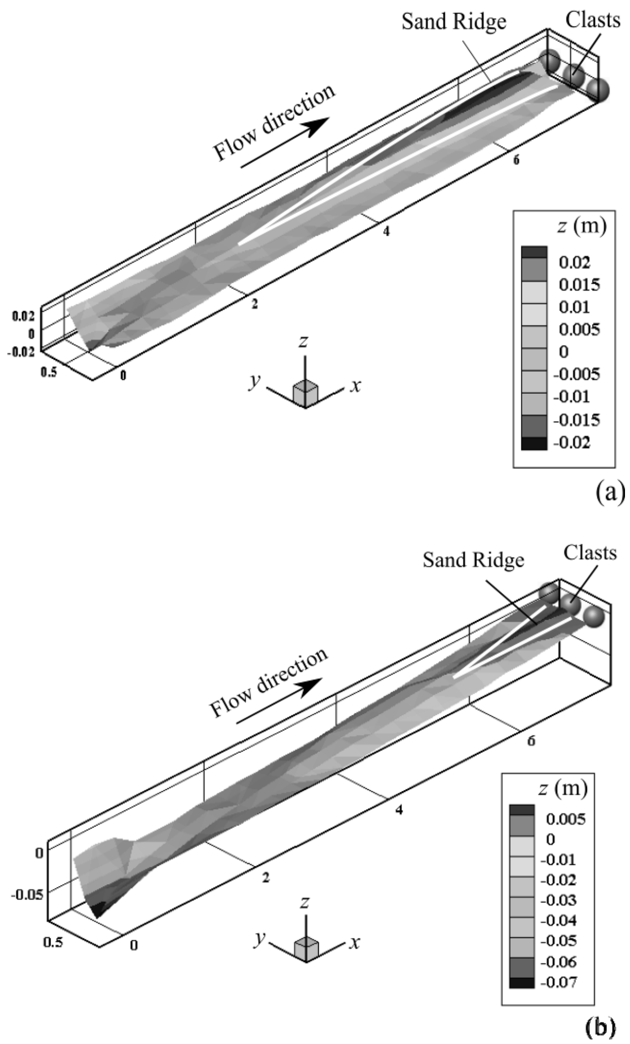
Table 1 shows a summary of the hydraulic conditions for the 4 experiments and includes: 1) the applied dimensionless bed shear stress τ^*; 2) relative submergence H/d_b; 3) flow depth H; 4) aspect ratio B/H; 5) ratio of the d_f/d_m of the diameter of the framework to the diameter of the matrix; 6) slope of the bed S; 7) flow discharge Q; 8) bulk velocity U_{bulk}; 9) Froude number Fr; and 10) Reynolds number Re. Experiments were performed for a fixed low relative submerge of $H/d_b = 0.8$, a benchmark value adopted from the experimental study of Bettess (1984). It should be noted that the selected τ^* was larger than the τ_c^* for the glass beads with no protrusion, which has been documented to be greater than 0.2 (Fenton and Abbot 1977).

Table 1. Hydraulic parameters for the four tests

	A-1	B-1	A-2	B-2
τ^*	0.056	0.056	0.120	0.120
H/d_b	0.8	-	0.8	-
H (m)	0.044	0.040	0.044	0.039
B/H	21	23	21	23
d_f/d_m	10	10	10	10
S	0.0036	0.0040	0.0078	0.0088
Q (m^3/s)	0.014	0.014	0.017	0.017
U_{bulk} (m/s)	0.35	0.39	0.43	0.48
Fr	0.54	0.62	0.65	0.78
Re	61600	61600	74000	74000

4 RESULTS

4.1 *Distribution of sand particles over the flume bed*



Figures 2(a), 2(b) provide the morphology of the sand bed section recorded at the end of tests A-1 and A-2, respectively.

Figure 2(a) illustrates the creation of a longitudinal bed feature, namely "sand ridge". The sand ridge constituted a funnel shaped (V-shape) depositional pattern that gradually formed during the

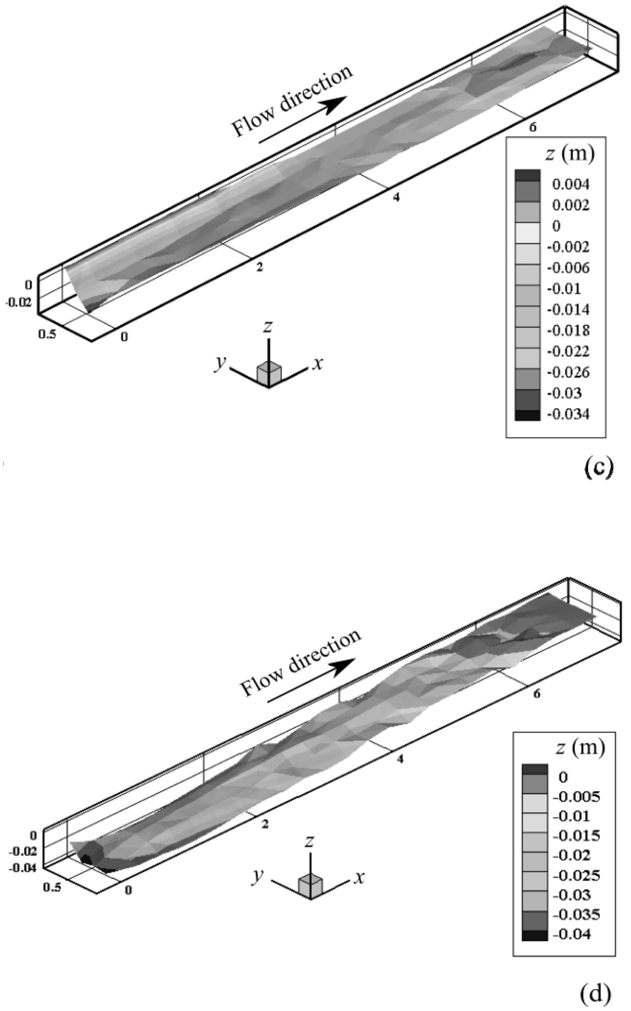


Figure 2(c, d). The morphology of the sand bed section for (c) B-1 and (d) B-2 tests (without boulders).

experiments. In A-2 experiment the presence of higher bed shear stress reduced the length and height of the sand ridge [see Figure 2(b)].

Figures 2(c, d) suggest that for tests B-1 and B-2 erosion occurred in most parts of the sand bed section, without the formation of any characteristic bed features.

Figure 3 illustrates a plan and side view picture of the bed morphology over the glass-bead bed section for test A-1. The incoming sand particles were mainly deposited in the stoss region of the boulders forming short and wide bed features, which is in agreement with the flow patterns reported in literature for low relative submergence conditions (e.g., Shamloo et al., 2001). In the wake region of the boulders there were few particles trapped due to flow recirculation, but for the most part this region remained free of incoming sand. The side view picture in Figure 3 shows that the sand patches between subsequent boulders along the x- direction of the flume, obtained a similar geometry with the sand ridge recorded in the sand bed section. For test A-2, elongated and narrow sand patches were recorded in the stoss region of the boulders. On the contrary, in tests B-1 and B-2 it was visually observed that sand particles gradually filled the interstices of the glass beads and then moved atop the fully covered bed without creating characteristic depositional patterns.

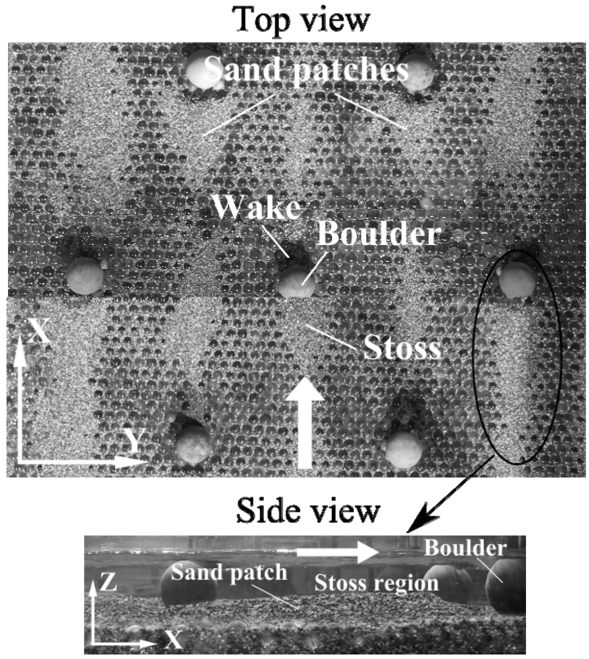


Figure 3. A top and side view picture of the sand patches formed upstream of the boulders (test A-1). White arrow shows the flow direction.

4.2 *Time series of the bedload rates*

Figures 4 and 5 present the time series of the dimensionless bedload rates, q_b^*, defined as:

$$q_b^* = \frac{q_b}{\rho_s \left[g\left(\gamma_s / \gamma - 1\right) d_m^3 \right]^{1/2}} \quad (1)$$

where, q_b = dimensional bedload rate; ρ_s = density of the sand particles; and γ_s/γ = ratio of the specific weights of the sand particles to the specific weight of the water. For all tests there was an initial period when no bedload was measured because sand did not reach the sediment trap.

Figure 4(a) illustrates 3 distinct periods of bedload movement for test A-1. During period 1 (duration ~ 150 hrs) the effects that boulders and sand patches had on the bedload rate were insignificant. On the contrary, period 2 (~ 470 hrs) illustrates the time interval that the cumulative effects of boulders and sand ridge were significant on bedload movement. During this period, the bedload rate was gradually reduced due to: (i) accumulation of the sand particles upstream of the boulder region; (ii) formation of the sand patches around the individual boulders (i.e. significant reduction in τ^*); and (iii) sand infiltration within the porous structure of the glass bead bed. At the end of period 2 equilibrium conditions were found to be present, i.e., the geometrical characteristics of the bed features (sand ridge and patches) remained unchanged with time. Period 3 (~ 1,300 hrs) clearly illustrates a significant reduction on bedload rates due to starvation conditions (i.e. no sediment feeding).

Figure 4(b) presents the time series of the bedload rates for test A-2. A comparison between Figures 4(a) and 4(b) illustrated that there were two discernable differences between A-1 and A-2 tests.

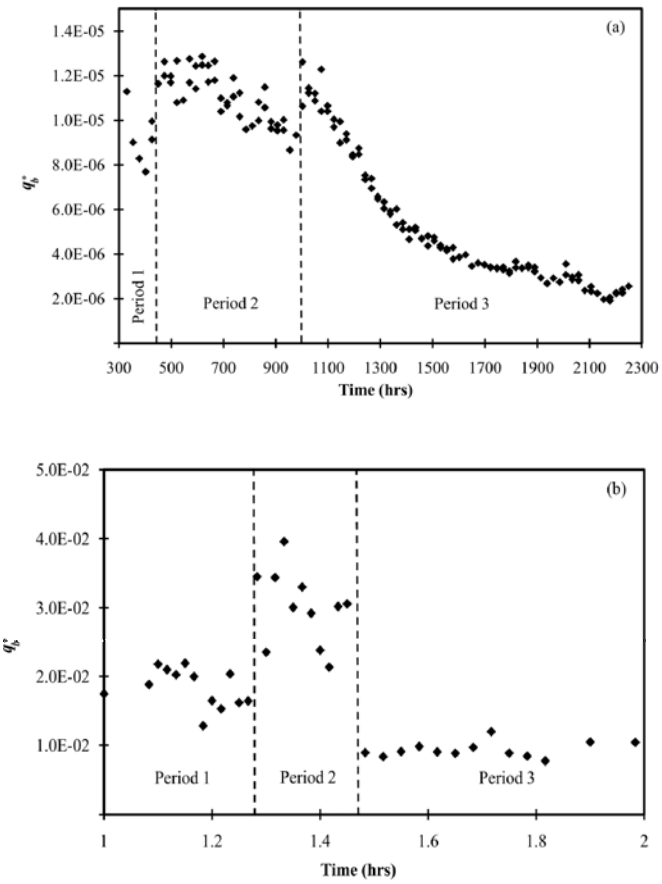


Figure 4. The bedload time series for tests (a) A-1 and (b) A-2 (with boulders).

First, equilibrium conditions were reached much faster for the A-2 test than for A-1. Second, the reduction in the bedload rate between periods 2 and 3 in A-2 was abrupt compared to the one in A-1 test where the reduction was gradual. Tests A-1 and A-2, however, presented some similarities too. Both had an induction period (period 1) where the bedload rate was lower in magnitude than period 2. Secondly, both included a section where the sedigraph was highly fluctuating (i.e., periods 1-2 for both tests) as well as a section where fluctuations were less prominent (i.e., period 3 for both tests). It is suggested that the highly fluctuating periods corresponded to conditions where formation of the ridge and patches was continuously evolving ("immature" bed formations). On the contrary, throughout the last period of A-1 and A-2 tests, where the bed features obtained a "mature" planform geometry and starvation conditions in the flume occurred, the fluctuations observed in the bedload rates were significantly reduced.

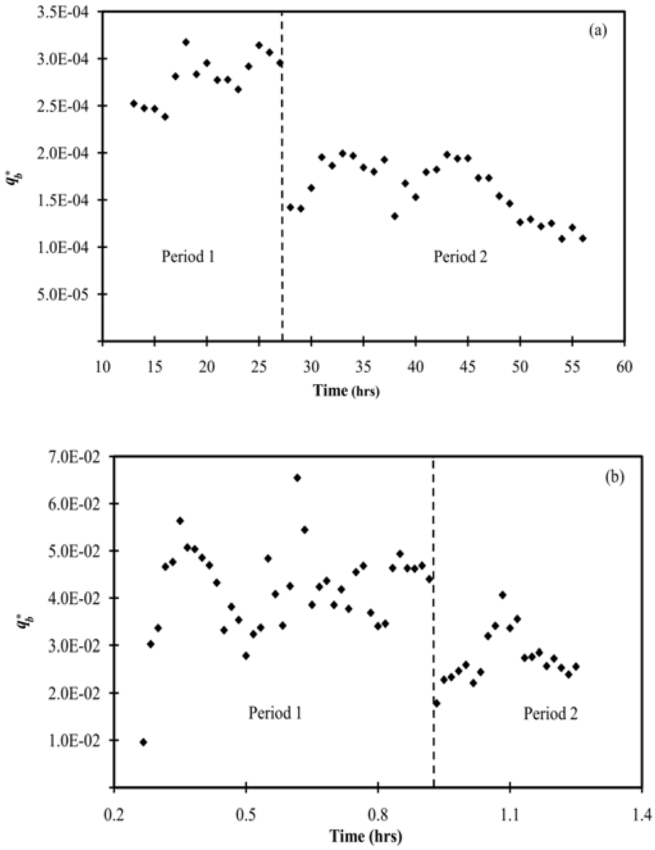


Figure 5. The bedload time series for tests (a) B-1 and (b) B-2 (without boulders).

Figures 5(a) and 5(b) show the sedigraphs for B-1 and B-2 experiments, whose duration was less than the one for A-1 and A-2 tests. An induction period did not exist for these experiments, suggesting that the induction time related to the presence of the boulders and the associated formation and evolution of the ridge and sand patches. Also, similarly to A-1 and A-2 tests, a reduction in the bedload rate was observed during period 2 for B-1 and B-2 experiments due to no sediment feeding. Since A and B set of experiments were performed for identical hydraulic conditions, it was expected that the bedload rates would fall within the same range. By comparing, though, the bedload rates corresponding to period 2 for A-1/A-2 and period 1 for B-1/B-2 experiments, one can surmise that for moderate shear stress conditions the presence of boulders reduced the bedload rate on average by a factor of ~ 20, while for higher shear stress conditions by a factor of ~ 1.5.

The qualitative descriptions of Figures 4 and 5 were complemented with a mass balance, control volume (CV) approach, where the CV included the sand bed section and the boulder region. The mass balance was performed between the incoming, depositing (in the form of the sand ridge and patches), infiltrating and exiting sediment. It was concluded that for A-1 experiment, ~ 63 % of the eroded material from the sand bed section deposited in the form of the sand ridge, ~ 18 % infiltrated within the porous glass bead bed, ~ 11 % deposited upstream of the individual boulders and ~ 8 % exited the boulder region. Along the same lines, for A-2 experiment, ~ 32 % of the eroded material from the sand bed section deposited in the form of the sand ridge, ~ 11 % infiltrated within the porous glass bead bed, ~ 6 % deposited upstream of the individual boulders and ~ 51 % exited the boulder region. Consequently, one can surmise that the formation of the sand ridge had a significant impact on controlling the incoming sediment.

4.3 *Distribution of sand particles within the gravel bed section*

Figure 6 displays the bar graphs of the subsurface sand distribution at the end of the four tests. By comparing the sand distributions between conditions with vs. without boulders, one can conclude that the presence of boulders atop the bed reduced the sand fraction into the substrate, especially for the moderate applied bed shear stress conditions ($\tau^* = 2.5\tau_c^*$).

Boulder effects were prominent within a region that extended ~ 7.5 cm below the bed surface (i.e. $z \approx 4.0d_f$), in which 70-80 % of the total accumulated sand was deposited, creating a surface seal. Below $z \approx 4.0d_f$, sand fraction decreased exponentially with depth. It is believed that the creation of the surface seal close to the bed surface hindered the deposition of sand particles into the underlying layers of glass beads. A similar behavior has been reported by several researchers (e.g., Sakthivadivel & Einstein 1970; Beschta & Jackson 1979; Carling 1984; Diplas & Parker 1985; Lisle 1989). These studies concluded that when the ratio d_f/d_m is between 7 and 15 (in our study d_f/d_m = 10) fine particles bridge the openings between adjacent gravel particles and prevent the downward movement of additional fines into deeper parts of the substrate.

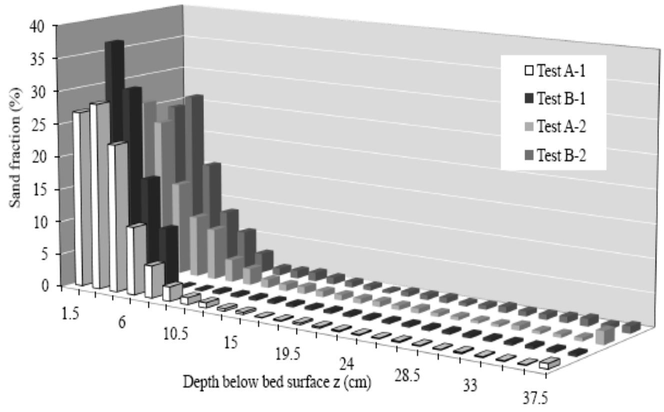


Figure 6. Sand fraction within the bed for the four tests.

5 CONCLUSIONS

Results from this study provided valuable insight on the effectiveness of the boulders in regulating bedload movement. Boulders regulated the incoming sediment and bedload rates by the formation of: (i) a sand ridge upstream of the boulder region; and (ii) distinguishable sediment patches in the stoss region of each boulder. The sediment budget in the flume provided quantitative insight for the role of the boulders as sediment sinks. It was determined that ~ 75 % and ~ 40 % of the eroded sediment was captured by the boulders in the form of the sand ridge and patches under moderate and high applied bed shear stress conditions, respectively. With respect to sand infiltration, boulders seemed to be effective in reducing the sand fraction under moderate applied bed shear stress conditions. An improved understanding of the role of boulders will allow the design of more sophisticated river restoration techniques.

REFERENCES

Almedeij, J.H., & Diplas, P. 2003. Bedload transport in gravel-bed streams with unimodal sediment. *J. Hydraul. Eng.*, 129: 896 - 904.

Bennett, S.J., & Bridge, J.S. 1995. The geometry and dynamics of low relief bed forms in heterogeneous sediment in a laboratory channel, and their relationship to water flow and sediment transport. *J. Sediment. Res.*, A65 (1): 29 - 39.

Beschta, R.L., & Jackson, W.L. 1979. The intrusion of fine sediments into a stable gravel bed. *J. Fish Res Bd Can.*, 36: 204 - 210.

Bettess, R. 1984. Initiation of sediment transport in gravel streams. *Proc., Institute of the Civil Engineering*, Part 2, March, 79–88.

Carling, P.A. 1984. Deposition of fine and coarse sand in an open-work gravel bed. *Canadian Journal of Fisheries and Aquatic Sciences*, 41: 263 - 270.

Diplas, P., & Parker, G., 1985. Pollution of gravel spawning grounds due to fine sediment. *St. Anthony Falls Hydraul. Lab. Proj. Rep. 240*, 145 pp., Univ. of Minn., Minneapolis.

Fenton, J.D. & Abbott, J.E. 1977. Initial movement of grains on a stream bed: the effect of relative protrusion. *Proc. R. Soc. London* A, Vol. 352: 523-537.
Grams, P.E., & Wilcock, P.R. 2007. Equilibrium entrainment of fine sediment over a coarse immobile bed. *Water Resour. Res.*, 43, doi:10.1029/2006WR005129.
Lisle, T.E. 1989. Sediment transport and resulting deposition in spawning gravels, North Coastal California. *Water Resources Research,* 25 (6): 1303 - 1319.
Morris, H.M. 1955. Flow in rough conditions. *Trans. Am. Soc. Civ. Eng.,* 120: 373 - 398.
Papanicolaou, A.N., Diplas, P., Bala, M., & Dancey, C.L. 1999. Computer Vision Technique for Tracking Bed Load Movement. *J. Comput. Civil Eng.*, 13: 71 - 79.
Papanicolaou, A.N., & Kramer, C. 2005. The Role of Relative Submergence On Cluster Microtopography And Bedload Predictions In Mountain Streams. *Published at the International Symposium, IAHR, River, Coastal, and Estuarine Morphodynamics*, October, 2005, Illinois.
Reid, I., Frostick, L. E., & Brayshaw, A. C. 1992. Microform roughness elements and selective entrainment and entrapment of particles in gravel-bed rivers. *Dynamics of gravel-bed rivers*, P. Billi, R. D. Hey, C. R. Thorne, and P. Tacconi, eds., Wiley, New York, 253–275.
Sakthivadivel, R., & Einstein, H.A. 1970. Clogging of porous column of spheres by sediment. *Journal of Hydraulic Division*, ASCE, 96 (2): 461 - 472.
Saldi-Caromile, K., Bates, K., Skidmore, P., Barenti, J., & Pineo, D. 2004. *Stream Habitat Restoration Guidelines: Final Draft.* Co-published by the Washington Departments of Fish and Wildlife and Ecology and the U.S. Fish and Wildlife Service. Olympia, Washington.
Shamloo, H., Rajaratnam, N., & Katopodis, C. 2001. Hydraulics of simple habitat structures. *J. of Hydraulic Research*, Vol. 39(4): 351-366.
Smith, G., & Ferguson, R. 1996. The gravel-sand transition: Flume study of channel response to reduced slope. *Geomorphology*, 16: 147 - 159.
Strom, K., Papanicolaou, A.N., Evangelopoulos, N., & Odeh, M. (2004). “Microforms in Gravel Bed Rivers, formation, disintegration and effects on bedload transport.” *J. Hydraul. Eng.*, 130 (6): 554 - 567.
Wohl, E. E. 2000. *Mountain rivers*. Water Resources Monograph 14. American Geophysical Union, Washington, District of Columbia, USA.