

Study Of The Influence Of Time Varying Flows On Sediment Entrainment In Gravel Bed Rivers Using Flume Experimentation

Miguel M. Piedra¹ and Heather Haynes¹ and Trevor B. Hoey²

¹ Dept. of Civil Engineering, University of Glasgow, Glasgow, UK. G12 8LT.

² Dept. of Geographical and Earth Sciences, University of Glasgow, Glasgow, UK. G12 8QQ.

Introduction

One of the main aspects of the study of sediment transport in rivers is defining what is the minimum flow or fluid forces required to initiate particle motion. This minimum value is called *threshold* and is a key concept in sediment transport and fluvial engineering. The large majority of past sediment transport research has been carried out in laboratory flumes under steady flow conditions with little account for the duration of flow exposure of sediment beds (Paphitis and Collins, 2005; Parker *et al.*, 1982; Wilcock, 1993; Buffington and Montgomery, 1997). However, flow rates in natural channels vary across a wide range of values and time scales. Recent research has shown that the flows to which sediment beds are exposed before grain movement occurs (stress history) influence the resistance of the bed and thus, modify entrainment thresholds and sediment load rates (Saadi, 2002; Paphitis and Collins, 2005; Monteith and Pender, 2005; Haynes and Pender, 2007). This has been pointed out as one of the possible causes of the widely reported uncertainty in the determination of consistent values of flow thresholds. As flows in natural rivers are essentially variable, this is likely to affect existing methods for estimating entrainment and bed load sediment transport. Furthermore, when time-varying flows are applied, the gradient of the hydrograph also affects the sediment load (Saadi, 2002).

Whilst some research has been conducted on the effect that hydrographs have on bed-load and bed surface compositions (Reid *et al.*, 1985; Powell *et al.*, 2001; Parker, 2004; Parker *et al.*, 2006), very little research is available on how the rate of accelerating flows affects bed stabilisation and entrainment threshold. Therefore the research reported here, based on flume experimentation, aims to: advance the knowledge of sediment transport processes in gravel-bed rivers; obtain a deeper understanding of the effect of time and value of antecedent flow conditions -represented by varying flows; assess the performance of existing sediment transport equations; and propose a time component correction. The study of the effect of flow acceleration on the threshold of particle entrainment was carried out using a very well sorted gravel bed subjected to five accelerating flow rates. As current predictions of climate change in the UK suggest a marked change in hydrological conditions, this research is timely and relevant to assess also possible effects of climate change on river bed stability in the UK.

Methodology

The experimental work was carried out using a glass wall Armfield tilting flume, 7m long (effective length) 0.9m wide. The test bed was formed by a single-size gravel (4-5.6mm, $D_{50}=4.8\text{mm}$). The bed slope was set at 1/200.

The entrainment threshold of the test material was assessed using Yalin's criterion (Neill and Yalin, 1969). This technique consists of counting the number of particle movements occurring over a prescribed area for a fixed period of time. The threshold was defined when the minimum number of movements was 10. The experimental variables are shown in Table 1. A baseline value, or reference, threshold flow (Q_{ref}) for a bed with no antecedent conditions was determined. An exponential trend line was fitted to the average values of movements of the four repetitions undertaken, resulting in a $Q_{ref} = 35.6 \text{ l/s}$.

Table 1. Summary of experiment runs.

Name	Duration of Accelerating Flows (h, s) ⁽¹⁾	Acceleration Rate (l/s/s)	Range of flows (l/s)	Flow at threshold condition (l/s)	u_* at threshold condition (cm/s)	τ_0 at threshold condition (Pa)
Reference ⁽²⁾	0 (0)	---	11-56	35.6	6.39	4.07
AccRate1	0.5 (1800)	0.0129	9-56	40.8	7.41	5.48
AccRate2	1 (3600)	0.0064	10-57	38.8	7.21	5.18
AccRate3	2 (7200)	0.0032	10-57	42.5	8.15	6.63
AccRate4	4 (14400)	0.0016	9-56	45.1	8.35	6.96
AccRate5	6 (21600)	0.0011	9-56	44.9	8.19	6.70

⁽¹⁾ After a common bedding-in period of 30min. (values in brackets are duration in seconds).

⁽²⁾ Experiments included incremental flows in order to find the reference threshold flow.

Five acceleration rates were applied to the bed, ranging from 0.0011 l/s/s to 0.0129 l/s/s, corresponding to antecedent durations of 6h to 0.5h. The effect of acceleration rates was assessed by analysing the new flow at threshold obtained for each acceleration rate (repeated three times). Test hydrographs were formed by a series of increasing flow steps (Figure 1). Only periods of increasing flows, i.e. rising limb, were considered at this stage. Shear velocity (u_*) was calculated from the velocity profiles and shear stress (t_0) values were obtained from: $t_0 = \rho \cdot u_*^2$; where, ρ = density of water.

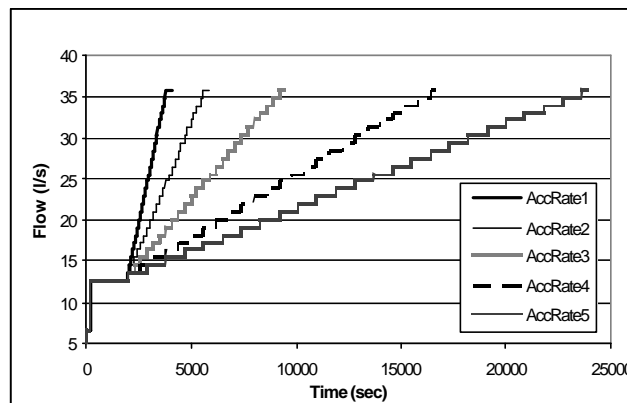


Figure 1. Test hydrographs.

Results and Discussion

Figure 2 shows the plots of average particle movement count (N), range of values and the regression curve used to obtain the threshold flow at $N = 10$. It shows a positive correlation of particle displacements with flow rate and a general reduction of particle movements with antecedent flow durations (smaller acceleration rates), reflecting a bed strengthening.

Figure 3 presents the ratio of the new threshold flow (Q_{cr}) obtained for each rate and $Q_{cr \text{ ref}}$. Compared to the reference flow, all test runs lead to an increase in flow at entrainment threshold. The slight reduction of average flow at entrainment shown by AccRate5 is likely to be related to small variations of flow in a region where flow resistance is very similar. The more noticeable negative departure of AccRate2 appears related to the presence of a large range of flows (37-44 l/s) with the same average particle count (Figure 2), which may displace the flow threshold, altering the trend.

Figure 3 demonstrates that the positive correlation between Q_{cr}/Q_{ref} and acceleration rates progressively weakens at higher acceleration rates. This suggests convergence to an upper limit of

antecedent-generated stabilisation. This supports the argument of a general threshold for the bed under the tested conditions, for which flows above it will mobilise the bed, independently of the flow history undergone by the bed. Paphitis and Collins (2005) undertook similar investigations using sand material. When compared to their work, the results shown in this paper show a similar trend: An increase of the critical threshold with antecedent flow duration and a possible slight decrease for the longest durations (Figure 4).

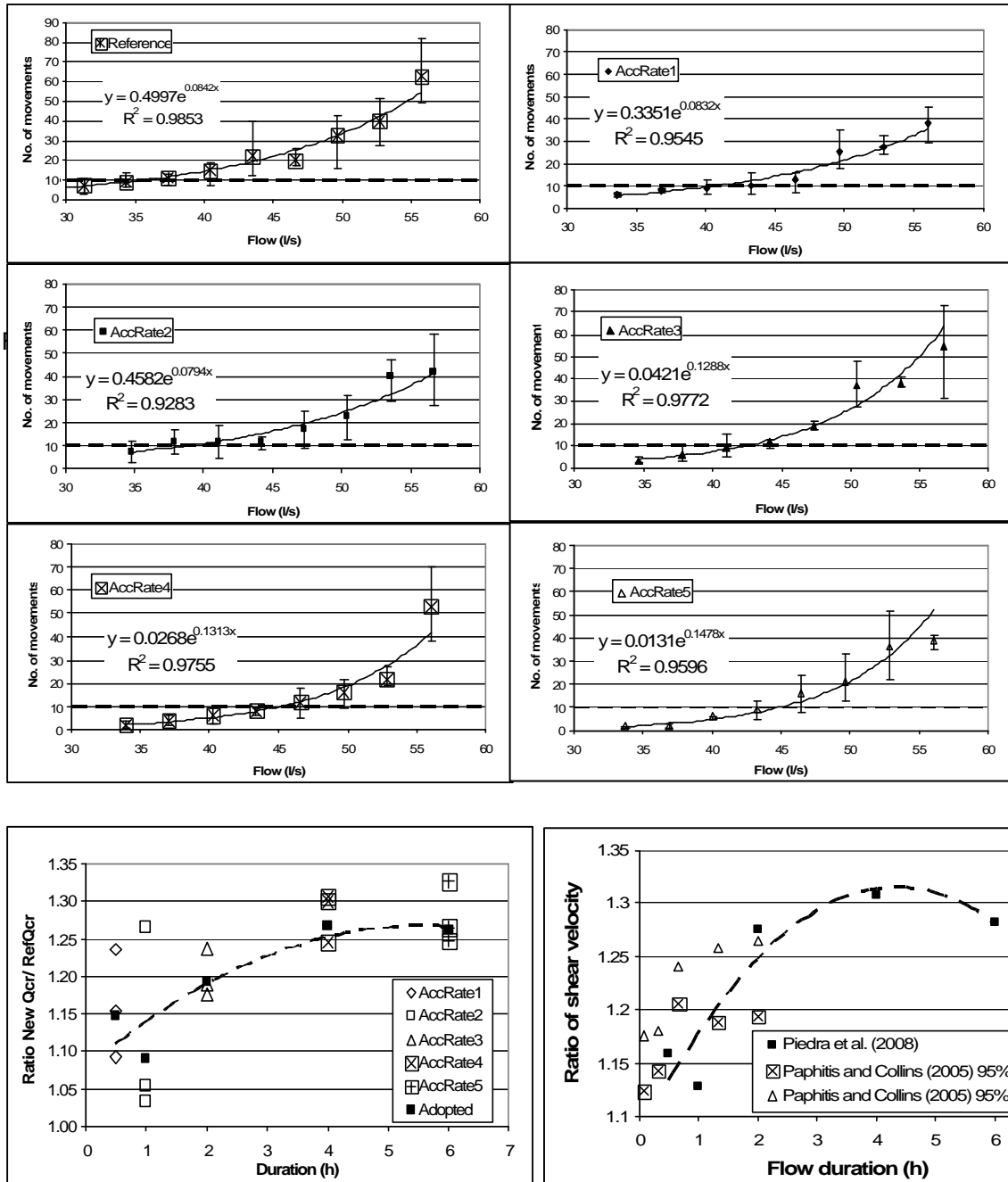


Figure 3. Ratio of new critical flow (Qcr) and reference critical flow (Qref) with flow duration. Adopted value is shown in Table 1.

Figure 4. Ratio of critical shear velocity with flow duration. Paphitis and Collins (2005) data (maximum and minimum) for 95% pre-threshold velocity included.

Conclusion

The work presented here shows a clear influence of acceleration rates on gravel bed stability. This implies that more attenuated hydrograph rising limbs prolong antecedent conditions and increase bed stability. Yet, data obtained from the reported experiments indicate that there is a limit to bed stabilisation provided by antecedent flow conditions and a possible general bed threshold that is independent of the bed flow history. Given predictions for faster acceleration of rising limbs of fluvial hydrographs in the UK due to climatic change, the data presented in this paper implies reduced thresholds or entrainment, less stable river beds and the consequence of higher bed load transport rates and more dynamic fluvial morphology. Such findings are critical to understanding long-term fluvial geomorphology and engineering. However, it is noted that the work presented refers only to a limited data set and further investigation is required.

Acknowledgements

The first author's research is funded by the Dept. of Civil Engineering, supported by ESPRC. Thanks are conveyed to the technical staff of the Hydraulics Facility; in particular, Mr. Stuart McLean for his contribution on the discussion of methodologies and results. The author also gratefully acknowledges the support of Scottish Natural Heritage.

References

- Buffington, J. M. and Montgomery, D. R. (1997). A systematic analysis of eight decades of incipient motion studies, with special reference to gravel-bedded rivers. *Water resources research*, vol. 33, 8, 1993-2029.
- Haynes, H and Pender, G. (2007). Stress history effects on graded bed stability. *Journal of Hydraulic Engineering*, vol.133, 4, 343-349.
- Monteith H. and Pender G. (2005). Flume investigation into the influence of shear stress history. *Water Resources Research*, 41. DOI: 10.1029/2005WR00497.
- Neill, C. R. and Yalin, M. S. (1969). Quantitative definition of beginning of bed movement. *Journal of the Hydraulic Division*, HY1, 585-588.
- Paphitis, D. and Collins, M. B. (2005). Sand grain threshold, in relation to bed Stress history: an experimental study. *Sedimentology*, 52, 827-838.
- Parker, G., Klingeman, P. C. and McLean, D. (1982). Bedload and size distribution in paved gravel-bed streams. *Journal of the Hydraulic Division*, vol. 108, HY4, 544-571.
- Parker, G. 2004. Response of the gravel bed of a mountain river to a hydrograph. *Proceedings, 2002 International conference on slopeland disaster mitigation, Taiwan, 5-6 October 2004.*
- Parker, G., Hassan, M., and Wilcock, P. (2006). Adjustment of the bed surface size distribution of gravel-bed rivers in response to cycled hydrograph. *Gravel-Bed Rivers VI.*
- Powell, D. M., Reid, I., and Laronne, J. B. (2001). Evolution of bedload grain size distribution with increasing flow strength and the effect of flow duration on the caliber of bed load sediment yield in ephemeral gravel bed rivers. *Water Resources Research*, vol. 37, 5, 1463-1474.
- Reid, I. Frostick, L. E. and Layman, J. T. (1985). The incidence and nature of bedload transport during flood flows in coarse-grained alluvial channels. *Earth Surface processes and Landforms*, vol.10, 33-44.
- Saadi, Y. (2002). The impact of unsteady flows on erosion and transport of mixed size sediment. Unpublished PhD thesis, Dept. of civil and structural engineering, University of Sheffield.
- Wilcock, P. R. (1993). Critical shear stress of natural sediments. *Journal of Hydraulic Engineering*, vol. 119, 4, 491-505.