A Comparison of Time-Induced Stability Differences Between a Framework-Supported and a Matrix-Supported Gravel:Sand Mixture

H. Haynes & A. Ockelford
Department of Civil Engineering, University of Glasgow, Glasgow, United Kingdom, G12 8LT

ABSTRACT

It is well established that the critical threshold of entrainment decreases rapidly with sand content over the transition from a framework-supported bed to a matrix-supported bed in gravel-sand bed rivers. Also, it is recognized that the proportion of fines in the bed surface may be related to flood history. Seeking to combine this knowledge, recent ‘stress history’ experiments have shown that graded beds increase in stability when subjected to prolonged periods of sub-threshold flow durations.

Flume experiments are presented that compare fine and coarse grain size distributions response to exposure to two flow phases: (i) an *antecedent period* of 0, 10, 20, 40 and 60 minutes duration using an applied sub-threshold bed shear stress of magnitude 50% that of the critical entrainment of the D_{50}; (ii) a *stability test* in which flow was increased to establish the new critical entrainment threshold of the bed. As expected, results indicate that the critical shear stress for the fine distribution was up to 39.8% lower than that of the coarse. However, the fine bed was up to 3.5 times more responsive to stability induced during the flow history period. Discussion focuses on explaining these stress history effects with reference to recent literature.

Keywords: Graded, Sediment, Entrainment, Bedload, Stability, Stress History

1. INTRODUCTION

One of the most pervasive forms of habitat degradation in graded rivers is the modification of natural flow regimes. Climate change, reservoir management, catchment land-use and hydropower are just a few of the reasons for river regulation and each leads to changes in the frequency and magnitude of flood events (Acreman 2000; Hamill 2002; Sear *et al.*, 2000). Yet, analysis of the flood-flood temporality in terms of antecedent flow duration has typically received little attention in sediment entrainment studies. Traditionally it was accepted that the stability of a river bed could only be affected by sediment transporting flows (Gomez,1983); however, recent evidence now suggests a progressive stabilisation of the bed surface even during below-threshold applied shear stresses (Paphitis and Collins, 2005; Monteith and Pender, 2005; Haynes and Pender, 2007; Ockelford and Haynes, 2008). Primarily, this is thought to occur through local reorganisation of the bed surface into a configuration more able to resistant to entrainment by fluid flow. If this theory is correct, then the magnitude of these changes would be expected to be strongly dependent on the bed's grain size distribution.

Given that unconsolidated river gravels typically exhibit two distinct modal classes (coarse and fine), this paper focuses on the effects stress history on two sediment beds of different grain size distribution. The first data set employs a coarse distribution; this is defined as having a self-supporting gravel framework with finer material forming a significant secondary mode and occupying some or all of the interstitial spaces in the framework gravel (Carling and Reader, 1982). Conversely, the second data set uses a fine distribution dominated by a fine matrix containing more dispersed gravel clasts. Finally, the relative importance of grain size distribution is compared and contrasted to the wider literature.

2 METHODOLOGY

Experiments were performed within an *Armfield* flow-recirculating tilting flume (15m long × 0.3m wide × 0.45m deep). The glass-sided flume is of rectangular cross-section and the bed comprised the mobile test sediments for an effective working length of 13m. Two grades of sediment were employed using natural sand and gravel ranging from 1 to 16mm in diameter and approximating to sub-rounded shape. Full details of the initial bed compositions for each grade are provided in Table 1.

	Grain size distribution (% by weight)							
	1-1.4 mm	1.4–2 mm	2–2.8 mm	2.8–4 mm	4–5.6 mm	5.6–8 mm	8-11.2 mm	11.2-16 mm
Fine	12	16	17	20	15	10	6	4
Coarse	2	1	2	4	16	47	19	9

Table 1: Grain Size Distributions

The critical shear stress of entrainment threshold was established using a quantitative visual technique (Neill and Yalin, 1972; Eq. 1) corrected for use of a graded bed (Wilcock, 1988; Eq. 2)

$$\varepsilon = \frac{m}{At}\left(\frac{\rho D^5}{(\rho_s - \rho)g}\right)^{\frac{1}{2}} \quad \text{(Eq. 1)} \qquad\qquad \frac{m_i D_i^{\,2}}{f_i} = C \quad \text{(Eq. 2)}$$

The Yalin Criterion counts the number of grain detachments (m) from a given area of observation (A = 0.04m^2) over a specified time (t = 180s) such that the particle (of size D) entrainment threshold is determined where a lower limit of ε = 10^{-6}. The fluid density (ρ), sediment density (ρ_s), and gravity (g = 9.81m/s^{-2}) were constants in the present set of experiments. The refinement of Equation 1 for use in graded sediment beds is required as sampling duration is scaled with the particle diameter whilst, the area of the bed observed is scaled with the proportion of the bed surface comprising an individual grain size fraction (f_i); this means that the initial displacement of only one individual fraction of the mix (i) can be studied at any one time. C is therefore a constant determined by using the D_{65} (Wilcock, 1988).

Employing a bed slope of S = 1/200, each bed was screeded to a depth of 60mm and slowly flooded. An initial *bedding-in period* employed a flow depth of 10mm for 10 minutes duration; this was designed to remove any air pockets or unstable grains generated within the bed screeding process. Flow was then increased to apply a shear stress of magnitude 50% that of the critical threshold for entrainment of the D_{50}; this constituted the *antecedent period* where beds were exposed to stress histories of 0, 10, 20, 40 and 60 minutes duration. The average bed shear stress for the channel cross-section was derived using the depth-slope method provided in Equation 3 (Powell and Ashworth, 1995; Hassan and Church, 2000, Measures and Tait, 2008) where R_b is the hydraulic radius corrected for the roughness effects of both the side walls and the bed according to Manning’s.

$$\tau_c = \rho g R_b S \qquad\qquad \text{(Eq. 3)}$$

In order to ascertain the effect of the antecedent period on entrainment threshold, the subsequent *stability test* incrementally increased flow depths in a stepwise manner. Each step of the stability test was 300 seconds in duration to allow flow stabilisation and visual assessment of whether or not the new threshold had been reached. In order to reduce the error and increase the reliability of the dataset, experiments were repeated three times for runs without an antecedent period and twice for all runs including an antecedent period. Total bedload transported during the stability test was also recorded by the bedload trap located 14m downstream of the inlet; this provided an indication of fractional mobility.

3 STRESS HISTORY RESULTS

A total of 32 experiments were undertaken. Stress history relationships with respect to measures of bed stability are presented in Figures 1a and 1b below.

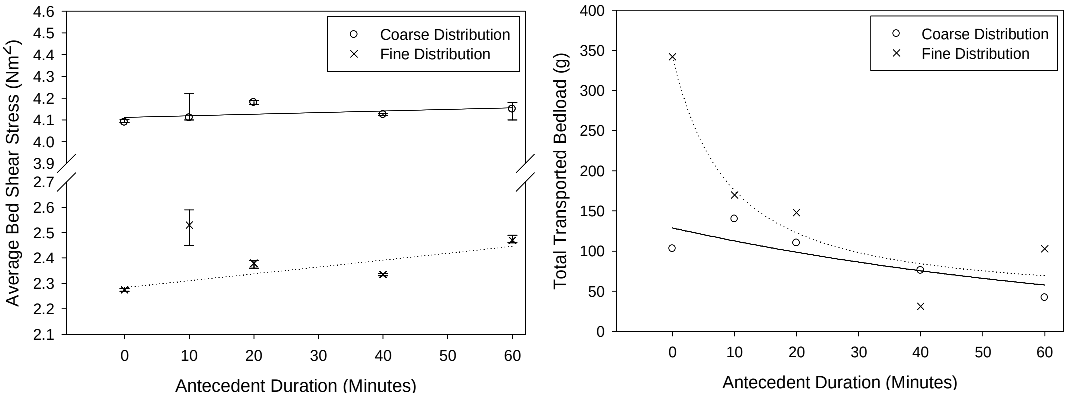


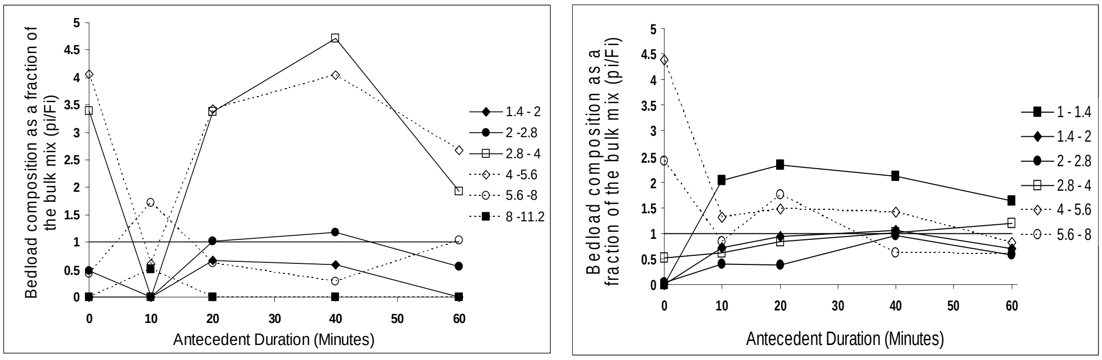
Figure 1a and 1b: Stress history relationships with average bed shear stress and total bedload respectively.

Figure 1a shows both grades to indicate a positive correlation between entrainment threshold and stress history duration. Increasing the antecedent duration from 0 to 60 minutes increases the average threshold shear stress by 8.37%, and 2.23% for the fine and coarse beds respectively. This shows that the fine bed was slightly more (up to 3.5 times) responsive to stability induced during the antecedent period. Error bars on Figure 1a show acceptable variability of up to ±8% for the fine distribution and ±11% for the coarse distribution; this is in line with the experimental data errors of other studies (Paphitis and Collins, 2005; Ockelford and Haynes, 2008). Data variability is greatest for runs employing a 10 minute antecedent period, independent of grade; specifically the 10 minute data set for the fine bed appears a possible outlier to the trend (Figure 1a). If the outlier is excluded from analysis, a linear regression appears to approximate to the trend well for the fine distribution ($R^2 = 0.72$); poor performance is noted for the coarse distribution ($R^2 \sim 0.20$). As expected, the critical shear stress for the fine distribution was up to 39.8% lower than that of the coarse (Figure 1a) due to the reduced weight of smaller particles permitting entrainment at lower flows.

Total bedload data (Figure 1b) illustrates an inverse relationship between bedload and stress history. Extending the antecedent period from 0 to 60 minutes resulted in bedload reducing by 70% for the fine-skewed bed and 59% for the coarse-skewed bed. Given that a more stable bed will exhibit less sediment entrainment or bedload transport, this data supports the argument for increased bed stability with increased antecedent flow duration. Bedload transport rates were up to 2.3 times higher in the fine-skewed bed than those recorded for the coarse-skewed grain size distribution; this is most likely a function of the greater availability of finer material in the tail of this grain size distribution tail which, in turn, increases winnowing.

4 FRACTIONAL BEDLOAD RESULTS

Analysis of the relationship between transported fractions and their availability in the bed provides a more detailed understanding of the mechanistic processes that appear to underpin the antecedent changes to bed stability. As graded beds demonstrate a surface comprising of a mixture of different size fractions in unequal proportions it is necessary to represent the changing bedload composition (p_i) as a fraction of the original bulk mix (F_i). Results where $p_i/F_i = 1$ indicate that the percentage of that particular gain size in transport is equal to that of the initial mix of the sediment, where $p_i/F_i < 1$ fraction i is less mobile than that expected from equal mobility with the converse true if $p_i/F_i > 1$. Figures 2a and 2b therefore present p_i/F_i data from the current experimental program. This indicates significantly different patterns of fractional bedload data for fine and coarse grain size distributions.



Figures 2a and 2b: p_i/F_i ratios for the fine and coarse beds respectively (data for fractions which remain immobile throughout are not shown).

Data for the fine bed (Figure 2a) indicates a general trend for grain sizes 1.4-4mm and >8mm to be under-represented in the bedload; this implies a higher fractional stability than that exhibited by other fractions of the bed. Whilst the coarsest fractions remain immobile due to their greater submerged weight, stability of the fine gravels is more likely to be due to hiding effects from coarser grains. These more stable fractions comprise the median grain size and modal class of the fine grain size distribution (2.8-4mm). Conversely, the 1-1.4mm and 4-5.6mm fractions are over-represented in the bedload. The finest fraction is likely to be more susceptible to turbulent entrainment due to the low submerged weight of individual particles; however, 4-5.6mm fractional mobility is more difficult to explain. One possibility is increased exposure of this fraction as the surrounding finer fractions vertically settle during the antecedent period.

Figure 2a also suggests evidence that may explain the mechanics of stress history. The most noticeable trend is the overall decrease in the mobility of the coarser fractions (>4mm) with increasing duration of the antecedent period from 0 to 60 minutes. This is most dramatically observed by extending the antecedent period from 0 to 10 minutes (Figure 2a) and may explain the large increase in threshold shear stress observed in Figure 1a. Due to the employment of p_i/F_i ratio technique, this consequentially causes a slight rise in the 1.4-4mm fractions (Figure 2a). As such, it appears logical that increased stability of the fine-skewed bed is primarily attributed to the degree of stability of fractions > 4mm (i.e. D_{84} and above) that is attained during the antecedent period.

Fractional analysis of the coarse bed (Figure 2b) suggests a higher and more persistent degree of size selective entrainment over the range of stress histories tested. Overall trend analysis clearly indicates that 2.8-5.6mm fractions are generally over-represented in the grain size distribution and show higher than expected mobility. These fractions are finer than the median or modal class (5.6-8mm) and comprise only a very small proportion of the of the coarse grain size distribution. Two possible explanations of this data are proposed in order of influence: firstly, the low proportion of these fractions in the bulk mix leads to the p_i/F_i ratio technique over-exaggerating slight changes to the bedload composition; and, secondly, the coarse grain bias of the bed composition increases bed roughness and the intensity of near-bed turbulence fluctuations so as to increase the likelihood of fine gravel entrainment. Figure 2b also shows that fractions either side of this range (i.e. < 2.8mm and > 5.6mm) show slight fluctuation around and below $p_i/F_i = 1$. In explanation, the finest grains are likely to be vertically winnowed into larger pore spaces within the coarse bed; this is corroborated by no 1-1.4mm grains within the bedload data set. Similarly, the greater submerged weight of the coarsest grains increases their resistance to entrainment and reduces their p_i/F_i value to less than 1. Of specific note is the mobility of the 8-11.2mm fraction in Figure 2b compared to Figure 2a; this is due to greater bed roughness of the coarser bed causing elevated instantaneous bed shear stresses capable of entrainment of heavier grains. Analysis of Figure 2b provides no conclusive relationship to stress history.

4 DISCUSSION

Evidence is provided to support the idea of stress history induced bed stability (Paphitis and Collins, 2005; Monteith and Pender, 2005; Haynes and Pender, 2007; Ockelford and Haynes, 2008). This has been demonstrated by interpreting two bed stability indicators; critical entrainment threshold and resultant bedload transport. Firstly, the magnitude of the increase in critical threshold found in the fine bed (8%) is comparable to previous graded bed research which suggested an 8-10% increase for bimodal and unimodal beds of similar grain size (Ockelford & Haynes, 2008). Given the significant departure of coarse bed data (2%), grain size distribution appears intrinsically related to a graded bed’s response to stress history. Secondly, bedload transport data indicates slightly higher stability gains (59-70%) than those found in past experiments employing bimodal beds (48%; Monteith and Pender, 2005). This latter finding is likely to be a function of the shorter bedding-in period employed in the present study, hence less time for sub-threshold bed rearrangement into a more stable configuration.

The lower entrainment thresholds of the fine bed are in agreement with the literature (e.g. Jackson and Beschta, 1984; Ikeda and Iseya, 1988; Wilcock, 1988); yet the response to flow antecedency requires explanation. During the antecedent period, observations noted particle vibration and vertical winnowing of fines into bed pore spaces and settlement of fines around neighboring large particles. As a consequence, coarser grains are more exposed and hiding effects develop in the fine bed. With increasing antecedent duration this progressive surface rearrangement increases the packing density of the bed surface, consolidating bed structure and enhancing bed stability. In particular, longer durations of sub-threshold flow enhance the stability of the coarser material (>4mm) due to particle "rooting"; this is where the increasing stability of surrounding fines more than offsets the instability caused by increased exposure of the coarse particle. This stabilization of coarser particles in turn permits greater hiding and enhanced stability of fines. However, bedload data highlights continued downstream winnowing of fines even after 60 minutes of antecedent flow; this suggests that the bed retains only the proportion of fines needed to stabilise itself. Overall, the theory that matrix fines increasingly consolidate and stabilise framework gravels via the lateral and vertical winnowing of fines is supported by wider evidence from the literature (e.g. Reid *et al*., 1985; Allan and Frostick, 1999).

Therefore, it appears logical to assume that the lack of response to flow antecedence within the coarse distribution is a facet of the low proportion of fines within the bed. Bedload shows limited transport of fines, suggesting their penetration deeper into the larger pore spaces of the framework-supported. Consequently, fines cannot offer any significant structural strength to the gravel framework and larger grains are effectively left isolated upon the bed surface. Logically, as bed roughness increases with flow antecedence it influences turbulent interactions (Nakagawa and Nezu, 1977; Paphitis and Collins 2005) acting to destabilise the bed. As such, the research presented in the present paper is being extended with the collection of detailed turbulence data and laser displacement data of the bed surface topography; this is being analysed over an extended range of grain size distributions and stress histories.

5 CONCLUSION

The structural strength of a graded bed is shown to be contingent upon both the antecedent period applied and the grain size distribution of the bed surface. Matrix-supported fines are more responsive to stress history than framework-supported fines, demonstrating an 8% increase in critical threshold. In explanation, where the inter-dependence of fine and coarse fractions is afforded, the temporal development of local hiding effects and enhanced consolidation of the bed surface leads to increased bed stability. Whilst more detailed analysis of the particle mechanics of stress history induced stability are ongoing, the importance of the antecedence of a flow regime imposed upon the bed surface is clearly relevant. This is of particular interest in applied science and engineering practices, ranging from stable channel design, river regulation and design, flushing flows and assessment of aquatic habitat.

6 REFERENCES

Acreman, M. 2000. Guidelines for the sustainable management of groundwater-fed catchments in Europe. GRAPES. Groundwater and River Resources Action Programme on a European Scale. Institute of Hydrology, Wallingford.

Acornley, R.M. and Sear, D.A. 1999. Sediment transport and sedimentation of Brown trout (*Salmo trutta* L.) spawning gravels in chalk steams. *Hydrological Process.* 13: 447–458

Allan AF, Frostick LE. 1999. Framework dilation, winnowing and matrix particle size: the behavior of some sand-gravel mixtures in a laboratory flume. *Journal of Sedimentary Research.* 69: 21-26.

Beschta R.L., Jackson, W.L. 1979. The intrusion of fine sediments into a stable gravel bed. *Journal of the Fisheries Research Board of Canada.* 36: 204-210.

Carling, P.A. Reader, N.A., 1982. Structure, composition and bulk properties of upland stream gravels. *Earth Surface Processes and Landforms.* **7**: 349–365.

Gomez, B., 1983. Temporal variations in the particle size distribution of the surficial bed material: the effect of progressive armouring. *Geografiska Annaler*. 65: 183-192.

Hassan, M.A. and Church, M., 2000. Experiments on surface structure and partial sediment transport on a gravel bed. *Water Resources Research*. 36: 1885-1895.

Haynes, H and Pender, G., 2007. Stress history effects on graded bed stability. *Journal of Hydraulic Engineering.* 33: 343-349.

Hey, R.D., 1990. Environmental river engineering. *Journal of the Institution of Water and Environment Management*. 4: 335-340.

Ikeda, H. and Iseya, F., 1988. Experimental study of heterogeneous sediment transport. Paper 12, Environmental Research Centre, University of Tsukuba, Japan.

Jackson, W.L. and Beschta, R.L., 1982. A Model of Two-Phase Bedload Transport in an Oregon Coast Range Stream. *Earth Surface Processes and Landforms.* **7**: 517–527.

Measures, R. and Tait, S., 2008. Quantifying the role of bed surface topography in controlling sediment stability in water worked gravel deposits. *Water Resource Research.* 44: doi: 10.1029/2006WR005794.

Monteith H. and Pender G. 2005. Flume investigation into the influence of shear stress history. *Water Resources Research*, 41: doi: 10.1029/2005WR00497.

Nakagawa, H. and Nezu, I., 1977. ‘Prediction of the contributions to the reynolds stress from bursting events in open-channel flows’, *Journal of Fluid Mechanics.* 80: 99–128.

Neill, C.R. and Hey, R.D., 1982. Gravel-bed rivers; engineering problems. *Gravel-bed Rivers*, Hey, R.D., Bathurst, J.C. and Thorne, C. (eds.), John Wiley and Sons, New York: 15-25.

Neill, C.R. and Yalin, M.S., 1969. Quantitative definition of bed movement. *Journal of the Hydraulics Division, American Society of Civil Engineers.* 95: 581-588.

Ockelford, A. and Haynes, H**.,** 2008. The Effect of Grain Size Distribution Modality on the Relationship Between Stress History and Entrainment Threshold. 6th International IAHR River Flow Conference, 3rd- 5th September 2008, Cesme-Izmir, Turkey, 935

Paphitis, D. and Collins, M.B., 2005. Sand grain threshold, in relation to bed Stress history: an experimental study. *Sedimentology*. 52: 827 - 838.

Powell, D.M. and Ashworth, P.J., 1995. Spatial pattern of flow competence and bedload transport in a divided gravel bed river. *Water Resources Research*. 31: 741-752.

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*. 10: 33-44.

Wilcock, P.R., 1988. Methods for estimating the critical shear stress of individual fractions in mixed-size sediment. *Water Resources Research*. 24: 1127-1135.