Laboratory Experiments on Downstream Fining of Gravel

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LABORATORY EXPERIMENTS ON DOWNSTREAM FINING OF GRAVEL

by The Feinstein Group *

1. INTRODUCTION

The problem of downstream fining in gravel rivers is reviewed in some detail in another paper presented at this Workshop, Parker [1991]. Most gravel–bed streams, and many sand–bed streams as well, display an overall tendency for characteristic bed grain size (e.g. D$_{50}$) to become progressively finer downstream. The pattern may manifest itself significantly over reaches as short as a few kilometers [Ferguson and Ashworth, 1991], or as long as several hundreds of kilometers [Shaw and Kellerhals, 1982]. Where manifested, it is usually associated with an upward concave bed profile, i.e. one for which bed slope declines in the streamwise direction as well. Downstream fining has often been associated with some combination of selective transport of finer grains and abrasion of grains.

Figures 1 and 2 show the long profile and pattern of downstream fining over a three-kilometer reach of a Scottish river, the Allt Dubhaig [Ferguson and Ashworth, 1991]. Surface (subsurface) D$_{50}$ is seen to decline from about 100 mm (35 mm) to about 20 mm (7 mm) over a downstream distance of 2.25 km, thence dropping rather abruptly into the sand range. This same decline is mirrored in bed slope, including the abrupt drop, where the gravel bed gives way to a bed containing almost one hundred percent sand. The lithology of the bed material is such that abrasion can be precluded as the cause of downstream fining. One may conclude that the variation in grain size is due to selective transport of finer grains. The stream displays a complicated morphology, including braided and meandering subreaches. It is likely that this morphology enhances selective transport relative to a straight configuration [Paola, 1989].

This paper is devoted to a report of the results of the first run of a series of laboratory experiments on downstream fining. The desirability of an experimental study of the phenomenon should be clear. As opposed to the field, in the laboratory the operator has control over the grain size distribution, discharge, and channel width. This allows for a systematic study of the relative importance of the various contributing factors.

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At the time this study was commenced, the authors were aware of only one other attempt to reproduce downstream fining in the laboratory, that of H. Ikeda and co-workers, Environmental Research Center, Tsukuba University, Japan [personal communication]. The attempt did not succeed. Extensive helpful discussions with H. Ikeda suggested that the standard deviation of the grain size distribution used in those experiments may not have been sufficient to allow for clear evidence of fining over a relatively short distance. This served as a guide for the grain size distribution used in the present experiment.

2. EXPERIMENTAL SETUP AND PROCEDURE

50 tons of poorly-sorted sediment were prepared by mixing gravel and sand obtained from a wide variety of pits. Grain sizes contained in the mix range from in excess of 64 mm to less than 0.125 mm. A histogram showing content fraction in each half-\( \phi \) grain size range is shown in Figure 3; note that

\[
D = 2^{-\phi}; \quad \phi = -\log_2(D)
\]

where \( D \) denotes grain size in equivalent diameter, and \( \phi \) denotes the logarithmic grain scale commonly used by sedimentologists. Content fractions are shown for two independent samples, indicating the consistency to which the grain size distribution could be reproduced on a batch–by–batch basis. The distribution is seen to be weakly bimodal, with a gravel content peak at 22.4 mm, a sand content peak at 0.35 mm, and an intervening minimum at 2 mm.

The experimental facility was built into a towing tank at St. Anthony Falls Hydraulic Laboratory, University of Minnesota. The towing tank is 2.74 m wide, 1.82 m deep, and over 60 m long. A false wall was built into the tank so as to form a narrow channel 0.30 m (1 ft) wide, 1.2 m deep, and 45 m long. The bottom of the channel was composed of concrete. Water was supplied to the upstream end of the channel from the Mississippi River; water discharge was regulated with an orifice meter.

The first run was conducted in the winter of 1991. Water discharge was set at 80 liters/second. The run was commenced with no sediment on the flat, concrete bed. Sediment was mixed at the upstream end and fed manually at the rate of 11.3 kg/minute. A gravel aggradational front developed in the channel and propagated downstream. Upstream of the aggradational front, bed elevation increased over time. The narrow channel width suppressed the formation of bars or meandering or braiding tendencies. The run was continued for 16 hours and 50 minutes, by which time the gravel front had propagated about 41 m downstream of the feed point. Long bed profiles were measured with a point gauge at regular intervals during the run.

Water was drained from the channel at the end of the run. The surface deposits were somewhat disturbed by an unexpected accidental rapid draining, but the subsurface deposits remained unaffected. The surface material was sampled using Wolman counts and magnetic paint sampling. The entire deposit was then excavated and sieved over several months, using time lines of bed profiles as guides.

3. RESULTS

In Figure 4, bed profiles are shown at \( t = 2 \) hours, 5 hours, 6 hours 30 minutes, and 10 hours from run commencement. A downstream–propagating
aggradational front is apparent, such that the bed profile is mildly upward concave upstream of the front. In the case of the profile at \( t = 10 \) hours, some convexity is displayed near the front.

Figure 5 documents the downstream variation in the following grain sizes in the substrate between the time lines defined by \( t = 6 \) hours 30 minutes and \( t = 10 \) hours: \( \phi_{10}, \phi_{20}, \phi_{50}, \phi_{70}, \) and \( \phi_{90} \). The trends are generally upward in \( \phi \), corresponding to a decrease in grain size \( D \). The values of \( \phi_{10}, \phi_{50}, \phi_{70}, \) and \( \phi_{90} \) are all seen to increase by about one \( \phi \) interval over 25 m, corresponding to a halving in grain size. For example, \( D_{90} \) declines from 46.2 to 21.9 mm; \( D_{50} \) declines from 6.8 to 3.3 mm. The size \( D_{30} \) shows an even stronger tendency to decline over the 25–m interval.

In Figure 6, substrate grain size distributions for material between the same time lines as those of Figure 5 are shown at sections H (\( x = 2.5 \) m), E (\( x = 20 \) m), and G (\( x = 27 \) m), where \( x \) denotes distance downstream of the inlet. The tendency for downstream fining is manifested over the entire range of grain sizes.

Figure 7 shows the percent sand (\( D < 2 \) mm) in the substrate as a function of downstream distance. While fluctuations are manifest, the overall tendency is for the sand content to increase in the streamwise direction. The strong jump near the downstream end likely indicates an incipient transition to a pure sand bed somewhat farther downstream.

During much of the run, a deposit of pure sand finer than 1 mm could be found downstream of the gravel aggradational front. The point of transition, which propagated downstream as the gravel front buried the sand, was quite sharp, with essentially no pea gravel or coarser material passing the front. It should be pointed out that the sharp transition cannot be associated with the absence or paucity of gravel in the 1–8 range, because the size distribution of the parent material was only weakly bimodal (Figure 3). Based on observations during the experiments, it appeared that particles moving as bedload could not easily propagate past the aggradational gravel front, whereas particles moving in suspension could overpass it and propagate downstream. The maximum size of particles depositing downstream of the front was thus likely controlled by the maximum grain size that could be suspended in appreciable quantity. Experimental results indicate that this maximum size was less than 1 mm.

4. CONCLUSIONS

The results of the experimental run reported here provide unambiguous evidence that significant downstream fining associated with channel aggradation can be reproduced in the laboratory over relatively short distances. The shortness (45 m) of the channel precludes abrasion as a possible mechanism for fining. As a result, it is concluded that the change in grain size is due to
selective transport of finer grains. The channel configuration was straight, with the absence of bars or meandering or braiding tendencies.

Toward the downstream end of the aggradational front, a sharp transition from a gravel-sand mix to a bed of pure sand was observed. This sharp transition occurs in spite of the fact the parent size distribution is only weakly bimodal. It appears to form in response to the settling out of sand from suspension as water flows past the front of bedload aggradation.

Additional experiments are planned for the future, including runs with a width sufficient to allow for weak braiding.

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REFERENCES


FIGURE 1. LONG PROFILE OF BED ELEVATION OF THE ALLT DUBHAIG [FERGUSON AND ASHWORTH, 1991].

FIGURE 2. LONG PROFILES OF SURFACE D_{50}, SUBSURFACE D_{50}, AND CHANNEL SLOPE IN THE ALLT DUBHAIG [FERGUSON AND ASHWORTH, 1991].
Percentage of Total Mass at 1/2 $\phi$ Int.
Comparing SUM Batch 2 & 3 & 50

![Graph showing percentage of total mass at 1/2 $\phi$ intervals for different grain sizes.](image)

**Figure 3.** Content histogram at half-$\phi$ intervals of the sediment used in the fining experiment.

**Figure 4.** Long bed profiles at $t = 2$ hours, 5 hours, 6 hours 30 minutes, and 10 hours.
**Figure 5.** Downstream variation in the following substrate sizes: $\phi_{10}$, $\phi_{30}$, $\phi_{50}$, $\phi_{70}$, and $\phi_{90}$.

**Figure 6.** Substrate grain size distributions at stations H ($x = 2.5$ m), E ($x = 20$ m), and G ($x = 27$ m).
FIGURE 7. Downstream fining run #1. Downstream variation in the percent sand (<2 mm) in the substrate.
Conclusions

During the closing session, the participants were invited to submit their personal comments and conclusions. Since obviously it was not possible to obtain consensus on a number of points, it was decided to publish the comments received as conclusions, rather than to impose one personal view to describe the progress obtained during the Seminar.

Comments by A.J. Sutherland, University of Canterbury, New Zealand

The lack of consensus on so many issues during the seminar served to emphasise our limited understanding of non-uniform grain interactions. This was particularly evident when seminar participants were unable to satisfactorily answer Dr. Belleudy's question as to whether he should use hiding functions or active layers to control the mobility of size fractions in his numerical model.

Hiding functions and active layers can each represent grain interaction effects as evidenced by numerical models that successfully use one or the other. There are also successful models which use the two approaches together. While this may be satisfactory for obtaining results in controlled situations it does not give confidence when one extends the use of a model to a new situation nor does it aid our understanding of the underlying processes.

It is likely that certain situations are better represented by one or other of the two approaches. If so one must accept that if a model is to have some generality it will require both a hiding function and an active layer. The problem then becomes one of deciding how much of each should be used in any given circumstance. In support of this dual approach one could develop a theory based on hiding functions accounting for "horizontal effects" (eg sheltering, exposure, pivot angles) and active layers treating "vertical effects" which control the availability of size fractions through the composition of the surface layer. Such an approach would recognise the degree of independence that exists between surface grain size distribution and grain arrangement on the surface. The same grain size distribution can have quite different surface geometries and thus hiding effects eg the rearrangements of grains that takes place in static armouring experiments at nearly constant surface grain size distribution after the initial period of high transport rate has passed.

To help resolve this issue it would be valuable to have the results of tests using existing models on a series of standardised situations. One would seek to determine the conditions in which hiding functions (or active layers) strongly influence results and those conditions in which the results are not so influenced eg are hiding functions important when bed features are predominant or does the active layer approach serve better; is one or the other to be preferred with a bimodal sediment? The outcome of such tests should then guide experimentalists in
designing laboratory tests from which an improved understanding of grain interactions may emerge.

In such an exercise the distinction between the two types of hiding function drawn by Sutherland (this volume) will be important. Threshold hiding functions result essentially from the projection/exposure mechanism inherent in a stationary bed of non-uniform grains. Hiding functions for use in transport relations reflect interactions between moving grains and sediment bed on which there are both stationary grains and moving grains. The interaction effects in this case will be dominated by dynamic effects whereby different sized grains travel at different speeds, have different step lengths and rest period durations. To emphasise the care that needs to be taken in using and evaluating different hiding functions in a range of situations attention is drawn to the obligations that lie with researchers and the cautions for users outlined in section 7 of Sutherland (this volume).

Active layer procedures have reached a high degree of sophistication with de Silvio's four layer model (this volume) being a good example. A review of these developments and of the use of active layers in numerical models similar to that of Sutherland for hiding functions would be most useful. I would encourage a proponent of active layers to undertake such a review perhaps for a future seminar on non-uniform grain motion.

Comments by B. Willetts University of Aberdeen and R. Bettess Hydraulic Research, Wallingford

A note made following the general discussion of Wednesday 23 October 1991.

a) Description of sediment grading curves.

If grain sorting effects are to be described fully then it is not sufficient to characterise the sediment grading by statistics such as $D_{50}$ or $D_{84}/D_{16}$. It is necessary to use better statistical descriptions to characterise the full distribution. Professor Parker suggested that this should be done using the first three moments of the distribution expressed in log units. It is not yet clear whether this is the most effective description for all applications but it certainly has a number of advantages. There would be benefits in having more or less standard ways of describing size distributions but until these emerge it is important that workers give as full a description as possible of size grading.

b) Extremes of sediment size distributions

Evidence seems to be mounting to suggest that the extremes of the size distribution have a disproportionately large effect on both armour development and alluvial friction. The challenge would appear to be to quantify the impact of the extremes to determine their relative importance. This bears on the form of statistical description which might be adopted to define sorting.
c) Hiding functions

It seems to be universally agreed that to extend a theory of sediment transport from a uniform sediment to a widely graded sediment hiding functions are required. The precise formulation of these functions is not clear. Presumably the hiding functions will be dependent upon the sediment transport theory used and the correct formulation may depend upon the nature of the theory to which it is being applied. The scarcity of reliable transport data on the movement of size fractions means that at present hiding factors can only be derived for a restricted range of circumstances. There is a clear need for further laboratory and field data.

The interaction between fractions might be expected to be quite different at threshold compared with that during active transport. The latter involves more interaction processes than the sheltering/exposure of small and large grains respectively which are the dominant 'hiding' effects at threshold. At low transport stages, however, grains move intermittently and the intervals between motion have an important influence on transport rate. In such circumstances the transport hiding function will share to some extent the characteristics of the threshold hiding function. This is unlikely to remain true at high transport stages.

Approaches in the past to hiding functions using the grading of the parent material have sometimes included variables such as $\tau_*$. These may represent surrogate variables for the surface distribution.

d) Alluvial roughness

While the composition of the bed has long been recognised as being important in determining alluvial roughness it appears that the influence of the spatial structure of the bed should be investigated. Experimental work has suggested that distinct spatial structures can be identified in the laboratory. It is important to establish their existence in the field and their significance in influencing the hydraulic roughness of the bed.

e) Active layer

All modellers seem to have to make an assumption of some form of active layer. As yet there seems to be little idea about the vertical structure or physical processes within such a layer. This ignorance is the central obstacle to improved prediction methods.

f) A general challenge for the practitioners in the future would seem to be how to make river engineering less interventionist. To design prudently in limitation of natural channel conditions is a much more demanding exercise than to design artificial channels, and makes much more demanding calls on our knowledge of the channel processes.

g) Numerical modellers made a plea for simplified conceptualisation. It was pointed out that calibration involving a hiding function only was as effective and much simpler than one using both a hiding function and an adjustment of active layer depth.
Comments by Martin N.R. Jaeggi, Laboratory of Hydraulics, Hydrology and Glaciology, Zurich

The following comments have been made on the basis of personal notes taken during the presentations and the general discussion. It is attempted to answer the questions raised in the introduction.

Generalities

Definition of mean grain size: According to Parker, the mean grain size of a mixture should not be defined on a linear, but on a logarithmic basis. This can have a substantial impact on single grain concepts. In a fractionwise calculation too, a mean grain size must be defined as a scaling size for the hiding function.

The introduction of mixing layer concepts induces that the grain size distribution of the bed surface and its mean grain size are considered for computing transport rates. Current transport theories rely on bed material distribution. This may lead to other inconsistencies in applying numerical models.

Sampling techniques: Although treated extensively in the recent literature, sampling technique is still an element of uncertainty. The experiments of Wilcock (grid by number sampling), Diplas (clay technique), and BenSlama/Chee (sieve analysis) differ concerning the sampling technique of the surface sample. When calibrating numerical models to such experiments, the problem of the sampling technique must be considered somehow.

It may be pointed out at this place that in field situations with very coarse components, for instance as shown during the field trip in the Reuss valley, other sampling techniques may have to be applied. Transect surface samples, transformed into fictitious sieve samples of the parent bed material through an appropriate conversion calculation, have been a useful tool in recent Swiss investigations.

Sorting at low shear stress with sediment transport (Case C of table in the introduction)

Wilcock's experiments indicate that a limiting grain size may be defined, below which all the grains have the same mobility, and above which the grains move with a mobility decreasing with size. The experiments of Ben Slama and Chee seem to confirm this statement, since they found that the grains size distribution during the armour layer development is identical to the original one below a limiting grain size, above which the curve deviates. Suzuki and Hano's experiments, where the sediment feed has the same grain size distribution as the bed material, show an important coarsening for lower shear stresses and then a fining of the surface layer with increasing shear stress, still with a sediment feed corresponding to equilibrium conditions. These results seem to be consistent with each other, although the sediment feed conditions were different.

Weak transport, considered here to be the transport of fines over a still armored bed, is not found in such situations, since all the fractions are then moving, although some of them in smaller proportions. In a one-dimensional optic, weak transport is then only possible at shear stresses which are below critical (with respect to the mean grain size of the bed material). However, Hey's field observations show that two dimensional effects favour a weak transport (and therefore supply limited transport) even above this threshold value. The sediment regime

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of a river with respect to these finer fractions is therefore reasonably complex. Tsujimoto attempts to model this particular aspect of sorting.

More generally speaking, sediment transport rates of all fractions are supply conditioned in the region of potential armour layer formation. Rakoczi's proposal of seasonally applicable transport functions in this region which, more generally speaking, have to be derived from supply conditions in the catchment, is interesting in this respect.

Hiding function

There seems to be quite a consensus on the fact that the behavior of the different fractions can be defined by a hiding function. It is defined as a function of the ratio of a certain grain size to the mean grain size or scaling size. The hiding function slightly deviates from an equal mobility function.

As Sutherland explains in detail, there is for the moment no universally acceptable function. Shear stress is recognized to be an important additional parameter in defining the hiding function, as protrusion into the flow will have different effects for different flow conditions. Bridge's distinction between pivoting angle (exposure-sheltering) and protrusion is consistent with this.

For one reference grain size there is no correction, since there must be a transition from sheltering to exposure. As a first approach, it is assumed that this is true for the mean grain size of the surface material. According to Sutherland, this scaling size may be basically variable. He refers to White and Day (1980) who attempted to give a function for this variable. Ranga Raju introduces a correction as function of grain size distribution, which may account for variable scaling size and protrusion.

Mixing layer

Di Silvio's four layer concept gives the most universal approach. The numerical models in use take into account only part of it and present one, two or three layers. There is some debate if the mixing layer represents a layer of equivalent bedform height or the size of a mobile or static armour layer. Klaassen overcomes this difficulty in introducing two corresponding layers. In mountain rivers with coarse bedload material one layer seems to be sufficient. Belleudy claims that the thickness of the mixing layer has a minor influence of the simulated riverbed behavior.

Dynamic armoring (Case D in the table of the introduction)

There seems to be a correspondence between Julien's and Suzuki and Hano's experiments. For high shear stress conditions, for which a static armour layer can not form, a reversal of the situation is noted where the movement of coarse particles is accelerated on a layer of fine components. This raises the question if Diplas' fine subsurface layer is not a remnant of the fine active layer formed during high shear stress conditions, rather than an intrusion of fines compensating the formation of a coarse armour layer.

Static armor prediction

The state of the art was given by Schöberl. Numerical models using an appropriate hiding function should be able to reproduce the results given by these procedures. According to Sutherland, a number of hiding functions have been calibrated on self armoring experiments.
Roughness of armour layer

Tait and Gessler point out that roughness of an armour layer depends not only on grain size, but on the formation of roughness elements (clusters?). This fact may cause a certain lag in the formation or reformation of an armour layer.

Relevance of sorting?

According to Klaassen it is always relevant in the case of graded sediment. According to Copeland it is always relevant when there is deposition and subsequent reerosion.