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Response of a Channel With Alternate Bars to a Decrease in Supply of Mixed-Size Bed Load: A Flume Experiment

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The response of a channel with a topography and modeled bed material size typical of gravel bed rivers to reductions in sediment supply was investigated in a laboratory flume filled and fed with a sand-gravel mixture. After a series of quasi-stationary alternate bars were formed under equilibrium sediment transport, feed rate was reduced in two steps to one third and one tenth the initial rate as discharge was held constant. The primary response following both reductions was an increase in bed surface particle size as a corridor of intensive bed load transport contracted and local transport rates decreased. After the first feed rate reduction, the channel incised by twice the mean water depth, on average, and caused distal bar surfaces to emerge as terracelike features. Bar roughness decreased, and mean boundary shear stress exerted on bed surface particles increased. Little incision occurred after the second feed rate reduction.

INTRODUCTION

Gravel bed channels have a much greater capacity than sand bed channels to regulate the mobility of the bed surface through the formation of a surface layer of bed particles that is coarser than the particles supplied as load. The coarse surface layer affects bed mobility in two important ways. First, it reduces differences in mobility between coarser and finer particles on the bed surface by making the larger and less mobile particles more available for entrainment [*Parker and Klingeman,* 1982; *Andrews,* 1983]. Second, the coarseness of the surface of a streambed offers resistance to the entrainment of all bed particles [*Dietrich et al.,* 1989]. If transport capacity exceeds the sediment load supplied from upstream, for example, the bed surface can coarsen, thereby increasing overall resistance to transport. These interpretations of the role of the surface layer do not conflict, because in the example above, a coarsening of the bed surface would not necessarily lead to a change in bed load particle size.

Dietrich et al. [1989] fed mixed-size sediment at a high rate into a flume that contained sediment of the same size mixture as the feed and carried a flow with a low width: depth ratio. At a value of $\tau_* = \tau/[g(\rho_s - \rho)(D_{50})_{\text{load}}]$ equal to only 0.087 (τ is the mean boundary shear stress; $g(\rho_s - \rho)$ is the submerged specific gravity of sediment; and $(D_{50})_{\text{load}}$ is the median particle size of the sediment load), which is exceeded at bank-full stage in many gravel bed rivers, a coarse surface layer was not evident. But as feed rate was reduced in two steps to one tenth the original while boundary shear stress was held approximately constant, the surface coarsened across most of the bed. Despite the bed's being nearly flat and uniform, most of the bed load transport was restricted to the remaining fine-grained zone of the bed surface.

We extend their examination of bed surface response to changes in load into transverse as well as longitudinal dimensions by employing a width:depth ratio (~25) and bed topography (alternate bar/pool) that are typical of many gravel bed rivers. In previous papers [*Iseya et al.,* 1989; *Lisle et al.,* 1991] we focused on earlier phases of the experiment. Water and a sand-gravel mixture were fed into a flume with a screeded bed until equilibrium between sediment input and output was achieved. A series of alternate bars formed that were essentially stationary as a result of accumulations of coarse particles at bar heads which resisted erosion and deflected flow and sediment transport away from interior surfaces of bars. The flow structure created by the bar-pool topography induced pronounced sorting of particles transported and deposited over the bed surface. Particle sorting across the channel was responsible for the stability of the bars.

In this paper we report the response of the channel to reduced feed rates of sediment. As observed by *Dietrich et al.* [1989], the most important response was a coarsening of the bed surface as a zone of bed load transport narrowed and unit transport rates decreased. The coarsened surface rendered the bed less mobile. Hydraulic variables also responded as the channel incised somewhat, but in some cases these changes would seem to increase transport rates, not decrease them, as the imposed load was reduced.

EXPERIMENTAL PROCEDURE

We have described the flume and experimental procedures previously [*Iseya et al.,* 1989; *Lisle et al.,* 1991]. In summary, water discharge and feed rate of a mixture of sand and gravel (used also for bed material) were held constant until equilibrium between feed and bed load output was achieved. Bed load exiting the flume was collected at 5-min intervals and later dried, weighed, and sieved. At stages in evolution of the bed up to and including equilibrium, flow and feed were interrupted in order to measure bed topography and texture. Water surface elevations were measured immediately before stopping. The procedure was repeated for two reductions in feed rate.

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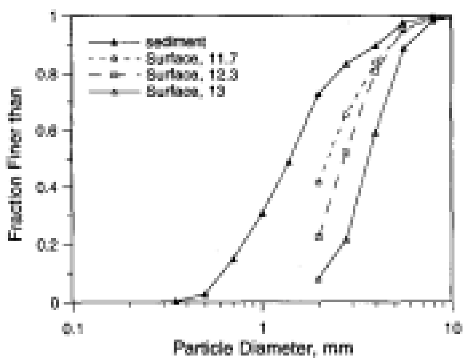

Fig. 1. Particle size distributions of sediment that was filled and fed into the flume and of the bed surface at the ends of runs 11.7, 12.3, and 13.

The flume was 0.3 m wide by 7.5 m long and inclined at a slope of 0.030. The channel bed and feed were composed of a moderately to poorly sorted, lognormally distributed mixture of sand and gravel (range, 0.35-8 mm; media size, 1.4 mm) (Figure 1). The feed rate was 488 g/min for the initial experimental runs, 11.1-11.7. (Digits to the right of the decimal refer to irregular intervals (80-315 min) during the same feed rate between times when the experiment was temporarily halted and measurements of the bed were made.) Successive feed rates were 157 g/min (runs 12.1-12.3) and 49 g/min (run 13). Water discharge was held constant at 582 cm^3/s. Conditions were set with attention to Froude and Reynolds numbers to avoid distortions that tend to occur in small-scale experiments.

After equilibrium had been reached (runs 11.7, 12.3, and 13), surface particle sizes were measured by draining the flume, photographing the bed, and measuring the small axis of projected particle images [*Adams*, 1979; *Ibbeken and Schleyer*, 1986]. This axis is assumed to approximate the sieve diameter of the particles. The bed surface was first mapped according to three surface facies types which were classified on the basis of percent gravel (D > 2 mm) exposed: <5%, 5-50%, and >50%. (*Iseya et al.* [1989] mapped the active portion of the bed according to five "bed load zones" that are related to both particle size and bed load transport characteristics). The area of each conterminous area (facies) was then measured, and facies representing each type were randomly selected for pebble counts. A full-scale image of each selected facies was projected onto a grid, and the diameter of each particle falling on a grid point was measured with a scale. At least 100 particles from each selected facies were measured. The median particle size of the bed surface, $(D_{50})_{sur}$, as well as the 84th percentile, $(D_{84})_{sur}$, was computed from the area-weighted means of each facies type.

Results

Bed Load Transport

Each reduction in feed rate was followed by a decline in bed load transport rate at the flume outlet until new equilibrium rates were attained (Figure 2*a*). Median grain size of bed load output decreased immediately following each feed rate reduction, as fine particles were winnowed from the bed surface, but later increased to that of the feed (Figure 2*b*).

Decreases in feed rate were accommodated by a decrease in both the width of a zone of significant bed load transport and unit transport rates within this zone. Significant bed load transport was restricted to a single continuous corridor running down the length of the channel (Figure 3). The corridor appeared generally finer than adjacent areas of the bed because of the abundance of bed load particles which were generally finer than winnowed material that surfaced inactive areas of the bed. The width of the corridor, which was monitored at crossovers between pools, decreased after each feed rate reduction in a pattern similar to that of bed load output (Figure 2*c*). Mean bed load corridor widths for equilibrium runs were 14.6 cm (run 11.7), 9.6 cm (run 12.3), and 5.6 cm (run 13), or 61%, 42%, and 24%, respectively, of mean water surface width. The ratio of percent decrease in corridor width to percent decrease in feed rate was 2.0 during the first feed rate reduction and 6.1 during the second. Because these ratios exceed unity, the primary adjustment

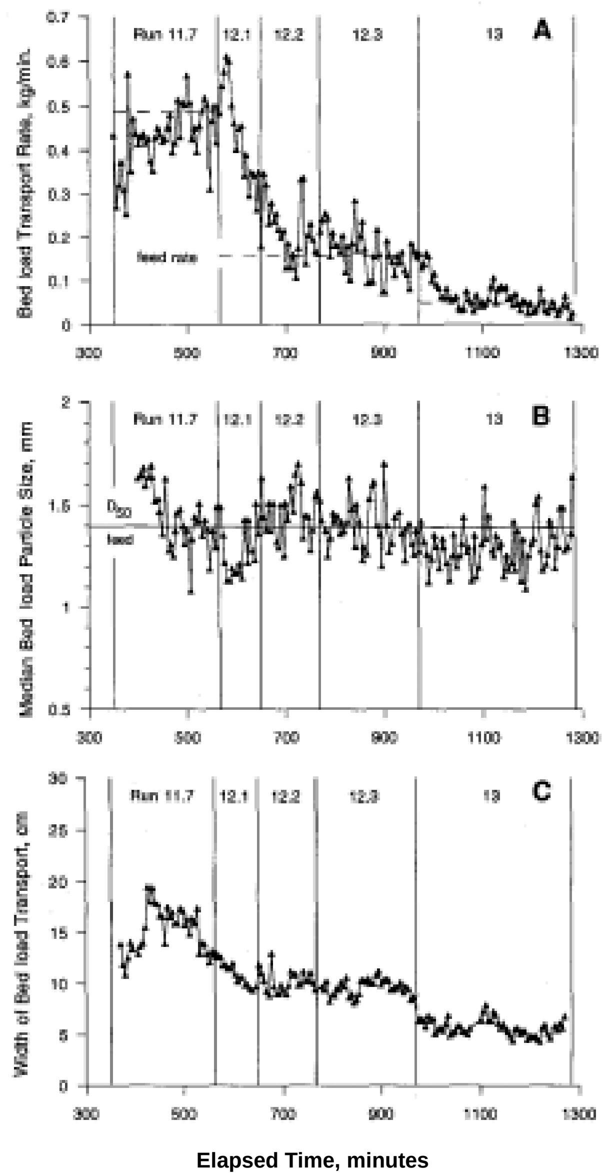

Fig. 2. Variations with elapsed time of (*a*) bed load transport rate at the flume outlet; (*b*) median particle diameter of bed load; and (*c*) width of the corridor of intense bed load transport. Figures 2*a* and 2*b* are reproduced from *Iseya et al.* [1989].

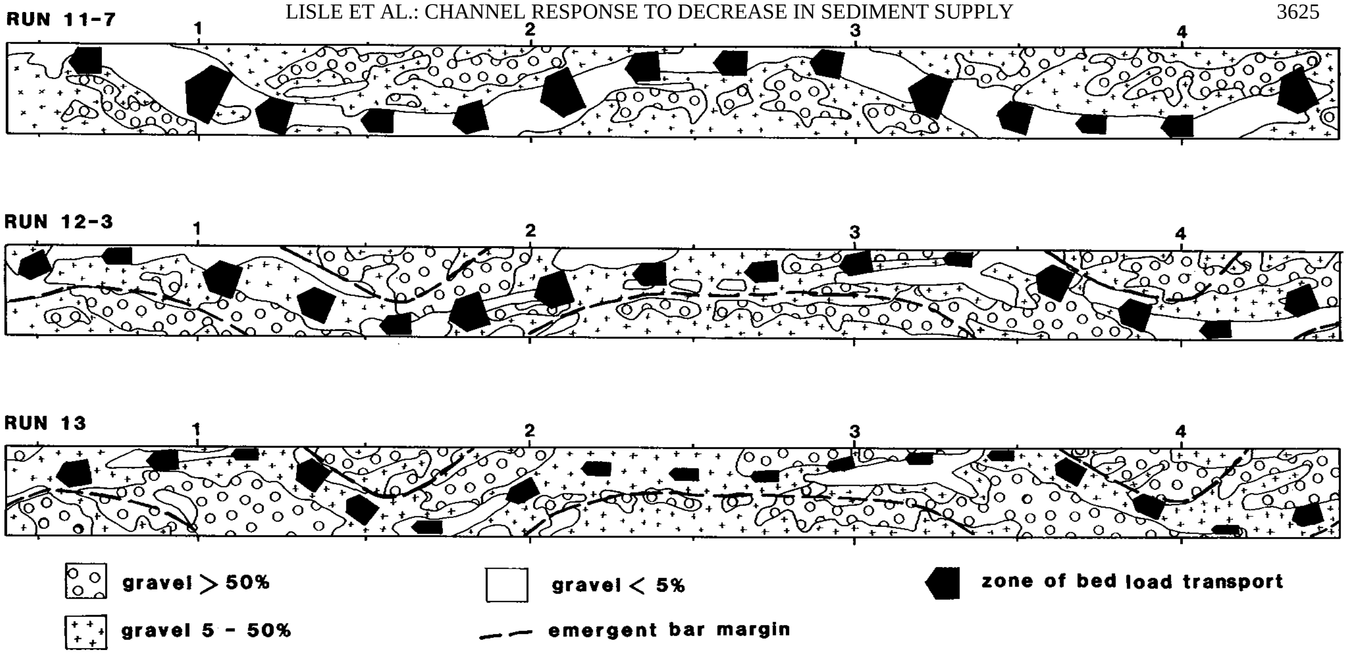

Fig. 3. Bed load corridor and bed surface facies, runs 11.7, 12.3, and 13.

to the decrease in sediment supply was a decrease in the width of the bed load transport zone, and the secondary adjustment was a decrease in unit transport rates. The adjustment in transport width became more dominant as supply was further reduced.

Channel Topography

The first reduction in feed rate caused incision of a narrower, deeper channel (Figure 4). During runs 12.1 to 12.3 the channel incised by an average of 1.6 cm or approximately 1.4 times mean depth and 7.1 times $(D_{50})_{sur}$ for run 11.7. This resulted in a decrease in channel gradient from 0.031 to 0.027, a 13% reduction (Table 1).The channel narrowed initially by 25% (run 12.1) and then widened to nearly the width that was achieved in run 11.7. Channel erosion and subsequent equilibrium progressed from upper to lower sections of the flume and are manifested by the pattern of declining bed load output rates in excess of the feed rate. Incision was concentrated in crossovers between pools, which in natural channels would correspond to riffles. As a result of incision, higher, inactive bar surfaces that can be analogous to floodplains along natural channels emerged as terracelike features [*Iseya et al.*, 1989].

The second reduction in feed rate resulted in little change in channel topography. Incision was negligible, and width increased by only 4%. Episodic lateral erosion of terraces occasionally created minor increases in bed load output.

Surface Particle Size

Winnowing of the bed following feed rate reductions caused nonuniform increases in surface particle size (Figure 3). A fine-grained area of the bed corresponding to the zone of bed load transport in run 11.7 became patchy in runs 12.3 and 13 as zones of relatively high velocity and shear stress were winnowed and coarser material was exposed. Fine sediment continued to collect along the inside banks of pools. Coarse zones at the heads of bars expanded. In response to the first feed rate reduction, facies of intermediate coarseness (surface gravel 5-50%) grew at the expense of fine facies (gravel <5%), while coarse facies (gravel >50%) changed little (Figure 5). Consequently, the mean value of $(D_{84})_{sur}$ computed from facies area-weighted averages increased by only 8% while $(D_{50})_{sur}$ increased by 22% (see also Figure 1). The degree of channel bed armoring,

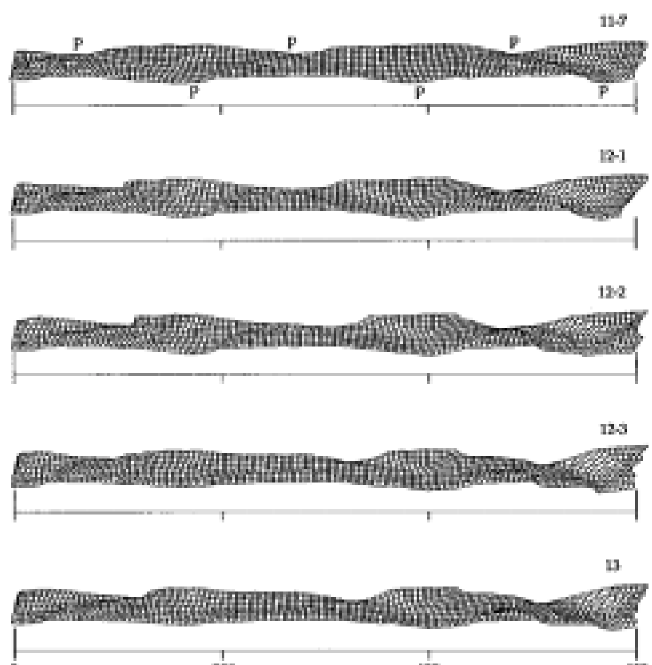

Fig. 4. Oblique view of the lower 6 m of channel at the end of runs 11.7, 12.1, 12.2, 12.3, and 13. Flow is from right to left. There is no vertical exaggeration. The locations of pool deeps are denoted by *p* in run 11.7; they shift upstream in subsequent runs.

TABLE 1. Mean Hydraulic Variables for Runs 11.7, 12.1, 12.2, 12.3, and 13

	Run 11.7	Run 12.1	Run 12.2	Run 12.3	Run 13
Mean depth, cm	1.1	1.3	1.1	1.0	1.1
Mean width, cm	24.1	18.1	20.8	22.9	23.7
Mean velocity, cm/s	21.2	24.7	24.7	24.9	21.7
Water surface slope	0.031	0.030	0.028	0.027	0.028
Friction factor (C)	0.077	0.062	0.051	0.044	0.064
Mean boundary shear stress, (τ), dyn cm^{-2}	35	38	31	27	30
Unit stream power,* dyn cm^{-1} s	730	940	770	670	650
Shear stress on grains, (τ_G), dyn cm^{-2}	24	…	…	24	26
Bar roughness (A_x/A_B)	0.023	…	…	0.0087	0.013
Shear stress on bars, (τ_B), dyn cm^{-2}	10	…	…	3.3	4.6

*Equal to τ_U.

measured as the ratio of $(D_{50})_{sur}$ to median grain size of the load, $(D_{50})_{load}$, increased from a value of 1.6 in run 11.7 to 2.0 in run 12.3.

In response to the second feed rate reduction the fine facies continued to shrink, the intermediate facies changed little, and the coarse facies grew. As a result, both $(D_{84})_{sur}$ and $(D_{50})_{sur}$ increased substantially. The ratio of $(D_{50})_{sur}$ to $(D_{50})_{load}$ increased to a value of 2.6.

Mean Hydraulic Conditions

After the first feed rate reduction, mean depth and mean velocity initially increased, and mean width and water-surface slope decreased (run 12.1, Table 1). As transport rates declined to the new equilibrium (run 12.3), depth decreased to its former value, velocity remained unchanged, width increased, and slope decreased further.

Hydraulic friction was evaluated by a resistance coefficient, C, equal to one eighth the Darcy-Weisbach resistance coefficient [*Parker and Peterson,* 1980] with the approximation that in wide channels mean depth equals hydraulic radius:

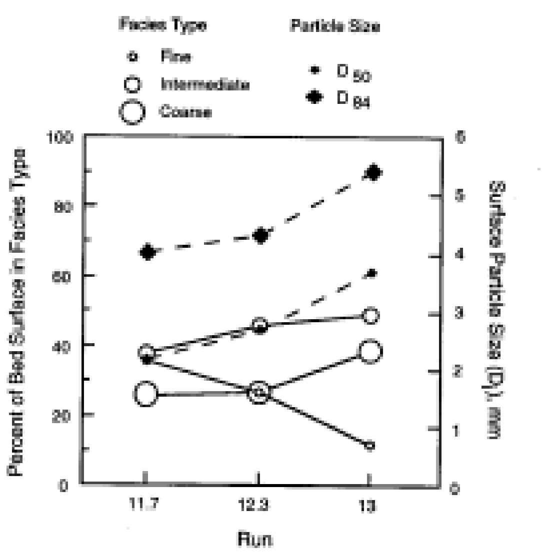

Fig. 5. Facies areas, $(D_{50})_{sur}$, and $(D_{84})_{sur}$ for runs 11.7, 12.3, and 13.

$$C = gdS/U^2 \quad (1)$$

where d is mean depth, S is energy slope, and U is mean velocity. Water surface and mean bed slopes were equal to within 4%, and so water surface slope is used to approximate energy slope. After the first feed rate reduction, C decreased continually from runs 12.1 to 12.3, when equilibrium was reestablished.

We pay particular attention to quantities that are commonly used to predict sediment transport. Mean boundary shear stress and unit stream power initially increased (run 12.1) but then decreased (run 12.3) to a value below that established for the former equilibrium (run 11.7). To correctly evaluate these changes, however, it is necessary to separate the portion of boundary shear stress exerted on surface particles, and thus responsible for their motion, from that exerted on the form roughness of bars. We assume that the sum of these two sources of resistance equals the total, and under the moderate transport rates in our experiment the flow resistance offered by static and moving particles is equal to that of static particles alone. A friction equation for channels with low relative submergence [*Bathurst,* 1985] was used to calculate a coefficient for resistance attributed to surface particles, C_G:

$$\frac{1}{(C_G)^{1/2}} = 5.62 \log\left[\frac{d}{(D_{84})_{sur}}\right] + 4 \quad (2)$$

Such an equation based on mean variables does not account for areal variations in surface particle size and local depth. Nevertheless, mean boundary shear stress exerted on surface particles, τ_G, and therefore responsible for their entrainment can be evaluated by

$$\tau_G = pC_G U_r^2 \quad (3)$$

where U_r is a reference velocity with bars removed and is computed by substituting $U = q/d$ in (1) (q is unit discharge), solving for d in (2); and then solving for U_r using the above equation. This value of τ_G probably underestimates the local boundary shear stress exerted on bed particles in the observed zones of bed load transport, which corresponded roughly to the thalweg where stresses are commonly high.

An estimate of bar resistance is provided by *Nelson and Smith* [1989]:

$$\tau_B = \frac{1}{2} p C_D U_r^2 \frac{A_x}{A_B} \quad (4)$$

where C_D is a drag coefficient for form roughness in the absence of flow separation and is equal to 0.84; A_x is the cross-sectional area of a bar at its apex; and A_B is the area of the channel occupied by the bar. Substituting (3) into (4) and using $\tau = \tau_G + \tau_B$, τ_G can be computed by

$$\tau_G = \frac{\tau}{\left(1 + \frac{1}{2}\frac{C_D}{C_G}\frac{A_x}{A_B}\right)}$$

Mean values of τ_G and τ_B were computed for runs 11.7, 12.3, and 13 from mean values of A_x/A_B, $(D_{84})_{sur}$, and hydraulic variables (Table 1).

Despite an increase in grain friction (C_G) from runs 11.7 to 12.3, τ_G remained approximately constant as slope and mean depth decreased. Most of the decrease in τ resulted from a decrease in r_B. Bar roughness, A_x/A_B, decreased as pools widened and shoaling bar heads flattened (Figure 4). The reduced transport capacity was apparently caused by the increase in $(D_{50})_{sur}$ and the associated decrease in bed surface mobility.

The second feed rate reduction resulted in smaller changes in hydraulic variables than the first. Mean velocity decreased by 13%, but mean depth remained equal as the incised channel was widened to approximately the width in run 11.7. Water surface slope also showed little change as incision ceased. Hydraulic friction increased. Mean boundary shear stress increased by 11%, and unit stream power was essentially unchanged. The value of τ_G increased to become higher than in run 12.3, as well as 11.7, but the effect on bed mobility was offset by the increase in surface particle size. Values of A_x/A_B and τ_B increased, apparently in response to construction of bars mantled with coarse material within the incised channel margins.

In summary, reductions in sediment load led to incision and narrowing (followed by widening), a reduction in bar roughness, and progressive coarsening of the bed surface. Boundary shear stress acting on surface particles remained nearly constant or increased slightly; thus bed coarsening was responsible for the decrease in sediment transport that was imposed by the decrease in supply.

Discussion

The results of our experiment help to verify those of *Dietrich et al.* [1989] that bed surface texture in gravel bed channels can respond to changes in sediment load. The significance of our experiment is to show that textural changes remain an important adjustment when the channel is also free to adjust its width (although ours was initially constrained) and its bed topography.

Dietrich et al. quantify the adjustment of surface particle size with a dimensionless ratio, q_*, of bed load transport rate based on the existing bed surface particle size to that based on bed load particle size. Their hypothesis is that as supply fulfills the bed load transport capacity of the channel (given its dimensions, particle size of supplied sediment, and flow), the bed surface becomes as fine-grained as bed load.

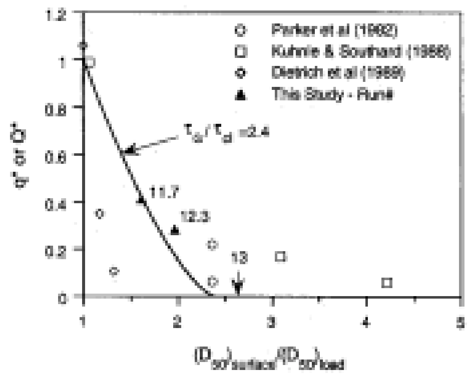

Fig. 6. Plot of q_* or Q_* versus degree of armoring, $(D_{50})_{sur}/(D_{50})_{load}$. The scatter of points about the decreasing trend of q^* with $(D_{50})_{sur}/(D_{50})_{load}$ is due to variations in τ_G/τ_{cl}. The plot of $\tau_G/\tau_{cl} = 2.4$ describes the mean trend of our experiment.

In this case, q_* approaches unity. Theoretical transport rates used to evaluate q_* are computed from functions of boundary shear stress in excess of that required to mobilize the median size of bed surface particles. The relationship between the measured degree of armoring (ratio of median size of surface material to that of the load) and q_* is borne out by data from experiments of theirs, ours, and others (Figure 6, derived from Figure 3 of *Dietrich et al.* [1989]). We computed Q_* (in place of q_* to denote a value that is computed from mean variables for the channel as a whole) from equation (2) of Dietrich et al.,

$$Q_* = \left(\frac{\tau_G - \tau_{cs}}{\tau_G - \tau_{cl}}\right)^{1.5} \quad (5)$$

where τ_{cs} and τ_{cl} the critical boundary shear stress to mobilize the surface and load, respectively, and are computed from a value of $\tau_* = 0.045$.

The plot of our data in Figure 6 reveals the importance of spatial variations in armoring and shear stress in determining the overall transport capacity of a channel. High values of Q_* could be expected for run 11.7, which has the highest feed rate, because bed load was transported across most of the width of the channel, and hydraulic conditions and bed topography initially came into equilibrium under the feed rate of this run. The value of Q_* (0.41) is lower than expected. This was apparently caused in part by the coarseness of bar heads, where large particles accumulated as bars were constructed [*Lisle et al.,* 1991]. Similarly, there is no solution for (5) for run 13, because τ_G is less than τ_{cs}, indicating a lack of particle motion (although very small rates of transport can occur at $\tau_* < 0.045$). Most of the channel was indeed inactive and highly armored, but bed load transport was maintained in a narrow zone, where armoring was weaker.

Results of sediment transport experiments in flumes must be interpreted with caution, and conclusions verified by observations in natural channels. Sediment systems in flumes impose either complete dependence (recirculating systems) or independence (feed systems) of sediment transport on flow, and this can strongly influence the outcome of experiments [*Wilcock and Southard*, 1989]. In experiments using sediment recirculation, armoring is high at low excess boundary shear and low at high stress [*Wilcock and Southard,* 1989]. It can be argued that transport capacity is always met in recirculating systems and the decrease in armoring observed during declining stresses can be due in part to the loss of fine particles to the subsurface, whose depth of transient scour and fill decreases as transport intensity decreases.

Bed load transport in natural channels can be either more nearly independent or dependent on sediment supply, depending on scales of time and space considered [*Wilcock and Southard*, 1989]. Over a period of decades or centuries a river conveys the sediment supplied by its basin, and its channel adjusts accordingly. Except in cases where a large volume of sediment is introduced immediately upstream, however, most bed load is stored in the bed itself, which constitutes the supply, and so sediment transport through a reach of river over a period of hours or days can depend more closely on hydraulic forces than on supply. At a still smaller scale, however, particle sorting and discontinuities in transport can cause local areas of the bed to be inundated or starved of sediment and lead to strong spatial variations in armoring [*Dietrich et al.*, 1989*; Lisle and Madej*, 1992].

That sediment supply affects bed surface texture in reaches of natural stream channels is suggested by several lines of evidence. *Kinerson* [1990] correlated bed surface armoring with supply in six streams in California, and *Lisle and Hilton* [1992] correlated pool filling by fine sediment, which can manifest the fining of the bed surface of natural gravel channels, with sediment supply in eight other channels. *Lisle and Madej* [1992] measured spatial variations in surface texture in Redwood Creek, California, a channel with alternate bars that was in a state of aggradation, and found a very low degree of armoring overall. In fact, reach-averaged values of degree of armoring for the two reaches examined, 1.2 and 1.6, are very close to the value, 1.6, for run 11.7. In both cases the channels were conveying bed load nearly at transport capacity. Most of the armoring in Redwood Creek occurred over riffles and bar heads, as was observed in our experiment. Degree-of-armoring values for the two runs with reduced feed rates (2.0 and 2.6) were within the range of values (2.0-5.6) for 24 gravel bed channels in Colorado, which have low supplies of sediment [*Andrews,* 1984].

It has been customary, particularly in the engineering literature, to assume that bed load transport rates respond to changes in mean variables that describe the impetus for transport, and vice versa. Our relatively simple channel behaved far more complexly, however. First, it was obvious from the existence of a zone of concentrated sediment transport that bed mobility was highly nonuniform. Even in the experiment of *Dietrich et al.* [1989] when nonuniformity was suppressed, active and inactive zones of sediment transport responded to supply. In both experiments, many areas of the channel, particularly under lowered rates of sediment supply, were inactive and affected sediment transport only insofar as they helped to maintain hydraulic conditions for transport in the bed load corridor. If the load had shifted to the inactive areas, they would have conveyed it without, most likely, a large change in local boundary shear stress. Local bed load transport rates, therefore, appeared to depend more on the supply along pathways extending upstream than on local transport capacity. *Ferguson et al.* [1989] observed a similar phenomenon in a natural channel. Bed load transport of sand and gravel was exceptionally high in a narrow zone where abundant sand provided a smooth transport surface. Boundary shear stress over this zone was lower than over adjacent gravel-dominated areas where transport was low

Much of the channel in our experiment was able to become inactive because of the availability of a wide range of particle sizes. Even areas with relatively high boundary shear stresses were rendered inactive by the accumulation of coarse particles and the winnowing of fine particles as the areas became starved of bed load from upstream. Partly as a result of winnowing and general coarsening of the surface, the mean value of boundary shear stress exerted on bed particles actually increased after the load was first decreased. Thus the increase in bed surface roughness offset a decrease in gradient, which would tend to decrease boundary shear stress, as the channel incised. Moreover, the increased resistance of the bed surface to transport more than offset an apparent increase in transport capacity measured by mean boundary shear stress.

One way to evaluate the relative importance of adjustments to sediment load among variables is to note if their change is consistent with the change in load. In our experiment, only surface particle size responded consistently with decreases in load, suggesting this to be the primary adjustment. *Dietrich et al.* [1989] proposed that degree of armoring may be the foremost adjustment of load for gravel bed channels transporting less than their capacity, and in others it may still be an important adjustment in local areas of the bed. This suggests that predictive transport equations must be based on the particle size of the bed surface, as well as that of the load or subsurface [*Parker;* 1990] and offers a challenging problem since surface size in local areas can be expected to vary with stage.

Conclusions

The surface of a gravel bed channel can respond to a reduction in sediment load by increasing resistance to bed load transport through coarsening of the bed surface. In our case of a wide channel with alternate bars, bed surface coarsening was accomplished by narrowing of the zone of bed load transport, accretion of coarse particles onto emerging bar heads, and winnowing of inactive areas of the bed. Under a greatly reduced supply of bed load sediment, surface coarsening stabilized the bed with only a small amount of incision.

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