MOVEMENT OF BED MATERIAL CLASTS IN MOUNTAIN STREAMS

BY
Luna B. Leopold, Professor Emeritus
University of California, Berkeley, CA
David C. Rosgen, Consulting Hydrologist
Pagosa Springs, CO

ABSTRACT

The growth in observational data shows that it generally is true in gravel streams that the material on the immediate surface is coarser than that which lies below. Unfortunately, this has led to the use of the word armored or paved. The use of those words has given the impression to those who do not work directly with gravel bed streams that the bed material of the stream does not move with ordinary discharges.

In nine mountain streams in Colorado rocks chosen from the bed surface to represent sizes D_{35}, D_{50}, and D_{84} were collected, painted, and placed in straight lines across the channel. A total of 30 such lines comprising 769 rocks ranging in size from 39 mm to 250 mm were observed during the snowmelt runoff season of 1989. Stream discharge, depth, velocity, and water surface slope data were collected on a daily basis throughout the runoff period.

Of the total rocks placed, about 65% of all the rocks moved during the season, even though discharges in none of the streams reached the bankfull stage. The distance the rocks moved was relatively small during any one movement, generally less than a few meters. Some individual rocks moved more than once, and a few moved as many as four times during the season.

These observations represent one type of evidence that material of the bed surface moves at discharges equal to or less than bankfull, even though the movement is for a short distance and the resultant transport rate is small.

GENERAL STATEMENT

Field data show that the surface material comprising the bed of gravel rivers is coarser than the layer immediately below the surface. An early presentation of such data was in Leopold, Wolman, and Miller (1964) that also included a discussion of possible explanations. They have developed in the literature two terms to describe the phenomenon, "armoring" and "paving," both of which unfortunately leave the impression that this surface layer is immobile except in extreme flood events.

Bray and Church (1980) suggested definitions for these words. They used "armour" to describe surface layers coarser than the rest of the bed resulting from winnowing of the fines. The word "pavement" was used to describe the surface layer coarser than the material below that layer, and the movement of this pavement occurred only during extreme floods. We prefer the words "cover layer" suggested by Carson and Griffiths (1987) to describe the physical relation without inference as to origin or frequency of movement. Also in agreement with a recommendation by Carson and Griffiths (p. 60), the present paper is devoted to a description of how bed material moves and under what circumstances.

ORIGIN AND PURPOSE OF THE EXPERIMENT

Our field measurements have demonstrated that in gravel streams in the Rocky Mountains the bulk or greatest volume of the bedload is of sand size or very fine gravel, far smaller than the D_{50} of the bed material. The gravel to cobble size makes up the point bars, central bars, and the riffle reaches, yet constitutes only a minute fraction of the total bedload. In fact, this minute portion of total load forms the main morphologic features of gravel streams (Leopold, 1990).

The gravel clasts 32 to 90 mm or larger are seldom caught in a Helley-Smith sampler, partly because of the size of the sampler mouth but partly because they move infrequently. To obtain more information on the discharge needed for motion and to measure the distance moved in a single excursion, the following procedure was used. Nine gravel streams of various stream types were chosen in Colorado for detailed study during the snowmelt seasons of 1988 and 1989. At each stream measuring section, size distribution of the surface material of the bed was determined by pebble counting. Then from the streambed downstream of the study reaches, many rocks were collected of each of the sizes D_{84}, D_{50}, and D_{35}. These rocks were painted bright orange. At each stream two lines of painted rocks were placed by hand in the channel, a line of rocks D_{84} size and a line of D_{50} size. In four of the nine streams there was also a line of D_{35} size. The rocks on a line were placed at about 4 diameters apart, so there were more rocks in a D_{50} line than in a D_{84} line. The location in distance across the channel was recorded for each rock placed.

Every day during the runoff season, about May 20-July 30, each line was inspected. The downstream and/or lateral movement of any rock was measured daily. At each position where a rock moved, a measurement by current meter of the vertical distribution of velocity was obtained. Discharge of the river was recorded.

The design has the possible disadvantage that placement of a rock in the water by hand might result in the rock being on a spot somewhat above the general level of the adjoining rocks of the bed materials. However, because the number of rocks placed was large, 769 rocks, we felt that there was also the possibility that our hand-placed rocks were put in hollows or depressions. Therefore, on the average, the placed rocks were only slightly more exposed or more likely to move than those deposited by flowing water.

ROCK SIZES AND NUMBER MOVED

The D_{84} size ranged from 77 mm at Goose Creek #4 to 250 mm at Goose Creek #1. At the other sites the size was between 100 and 200 mm. The D_{50} sizes varied from 43 mm to 110 mm. Table 1 shows the number of rocks, their sizes, and the number that moved. The table includes some of the characteristics of each site, including bankfull discharge and channel slope.

There were 769 rocks placed, and of these, there were 500 movements. The percentage of placed rocks that moved varied from 57% to 69%, and interestingly, the D_{84} size had about the same percentage moved as did the smaller D_{35} size.

Bedload transport rate was measured nearly every day at each site. Every time a Helley-Smith sample was taken, the largest clast caught was recorded as well as the usual size distribution analyzed in the laboratory. Note that during the runoff season the sampler caught one rock of size either near the D_{50} but in some cases nearly as large as D_{84}. In some streams an HS sampler with a large mouth was used.

RELATION OF ROCK MOVEMENT TO DISCHARGE

The most significant result of the study was that the D_{84} size on the streambed was consistently moved by discharges far less than bankfull. Because bankfull in the streams has a recurrence interval of one to two years, as is usual for most streams, the coarse fraction of the bed material is moved by frequently occurring discharges. This confirms the results found by Andrews (1983) for other gravel bed rivers in the mountains.

Table 2 shows the number of rocks in the D_{84} rock lines moved by various discharges, the latter expressed as percentage of bankfull discharge. The table includes all D_{84} rock movements at five stream sites. At these sites the total number of rocks placed in D_{84} lines was 168, and the number of recorded movements was 137 in the 1989 runoff season. Note that 114 out of 137 movements were caused by discharges less than 80% bankfull. Twenty-three movements occurred in two days when the discharge of S. Fork Cache la Poudre was 84% of bankfull.

ROCKS THAT MOVED MORE THAN ONCE

There is concern that placement of rocks by hand might favor movement as compared with rocks coming to rest having been moved by water. Many rocks moved more than once. Table 3 presents data for three streams in which individual rocks were observed to move once or more than once.

The stream, S. Fork Cache la Poudre, had more D_{84} rocks moved more than once than the other sites for reasons unknown. The rock movement data appear to confirm the concept that rocks placed on the streambed by hand are, on the average, a reasonable sample of the rocks moved by flowing water from locations determined only by stream processes.

It should be obvious that the data in Tables 2, 3, and 4 deal with the D_{84} size because these rocks are among the largest clasts on the streambed. Rocks of smaller size are more likely to move.

DISTANCE MOVED BY INDIVIDUAL ROCKS

Though a large percentage of painted rocks placed on the streambed moved during the runoff season as indicated in Tables 1-3, the distance a rock moved in an individual excursion was surprisingly short. Table 4 records the average distance moved in a single hop or single excursion. These distances averaged less than two feet, regardless of the magnitude of the discharge that caused movement.

SUMMARY

Painted rocks placed in lines on the bed of gravel streams in the mountains of Colorado included three sizes, the sizes D_{84}, D_{50}, and D_{35} of the bed materials of the individual stream. Sixty-five percent of the largest rocks placed, the D_{84} size, moved during the runoff season of 1989. None of the nine streams reached bankfull discharge during that year. Therefore, the larger fraction of bed material on these streams moved at discharges less than bankfull. The distance moved was very small, only a few feet. Thus the transport rate of the larger clasts is very small.

The larger rocks of the bed material are plucked individually off the streambed and moved short distances at ordinary or frequent discharges. Not all rocks of a given size are moved, even when some of that size are moved.

The material on the bed of a gravel stream constitutes only a small part of the annual bedload volume, but it is the part of the sediment load responsible for the major morphologic features of the channel, the riffles, the bars, and the point bars.

ACKNOWLEDGMENT

The authors gratefully recognize the fine observations and measurements obtained by the numerous field personnel of the USDA Forest Service of the Rocky Mountain Region who participated in this study.

REFERENCES

Andrews, E. D., 1983, Entrainment of gravel from naturally sorted riverbed material: Bull. Geol. Soc. Amer., vol. 94, pp. 1225-1231.

Bray, D. I., and Church, M., 1982, Armoured versus paved gravel-beds: Jour. Hydr. Div. Amer. Soc. Civil Engineers, vol. 108, pp. 7727-7728.

Carson, M. A., and Griffiths, G. A., 1987, Bedload transport in gravel channels: Jour. Hydrology (New Zealand), vol. 26, No. 1, 151 pp.

Leopold, Luna B., 1990, The sediment size that determines channel morphology: Gravel Streams Conference, Florence, Italy, September, in press.

Authors cited in text (in order):
- Leopold, Wolman, and Miller (1964)
- Bray and Church (1980)
- Carson and Griffiths (1987)
- Leopold (1990)
- Andrews (1983)

Table 1. Painted rocks of three sizes, in several streams, Colorado, 1989

Stream	Left Hand	S. Fork Cache la Poudre	Upper Trap	Little Beaver	Goose #1	Goose #2	Goose #3	Goose #4	Middle Boulder
Drainage area (mi^2)	52	88	--	12	81	81	81	81	36
Bankfull discharge (cfs)	175	325	156	46	240	240	240	240	340
Slope	.035	.007	.06	.026	.012	.007	.005	.005	.013
Largest clast caught in HS sampler (mm)	113	43	136	45	30	81	--	41	98
D_{35}									
Size (mm)	42			39	70				57
No. rocks	51			52	35				64
No. movements	45			8	13				49
D_{50}									
Size (mm)	58	60	60	56	110	92	70	43	83
No. rocks	44	74	13	49	28	30	53	No data	71
No. movements	38	99	No data	6	8	14	15	No data	54
D_{84}									
Size (mm)	122	111	144	128	250	150	100	77	174
No. rocks	24	64	8	19	8	10	32	41	20
No. movements	21	84	No data	10	2	2	10	13	9

Total all sites:		% of rocks moved
D_{35}		
No. rocks	202	
No. movements	115	57
D_{50}		
No. rocks	349	
No. movements	234	67
D_{84}		
No. rocks	218	
No. movements	151	69
Total rocks placed	769	
Total rock movements	500	65

Table 2. Number of rocks of D_{84} size moved at discharges of different percentages of bankfull; data are for five sites that had a total of 168 rocks in the D_{84} lines.

Discharge in % of bankfull	Number of rocks moved
10-20	11
20-40	26
40-60	42
60-80	35
80-100	23
	137

Table 3. Number of rocks that moved once or more during runoff season, D_{84} size.

Stream	S. Fork, Cache la Poudre	Little Beaver	Left Hand
Number of D_{84} rocks placed	64	19	24
Number that did not move	16	14	0
Moved once	22	2	24
Moved twice	17	2	0
Moved thrice	7	0	0
Moved four times	2	1	0

Table 4. Distance in feet rocks of D_{84} size moved by discharges of various percentages of bankfull; data from five sites; total number of movements was 137.

Discharge in % of bankfull	Average distance of movement (ft)	Number of rocks moved out of observed reach
10-20	0.6	--
20-40	1.2	--
40-60	1.7	13
60-80	1.1	--
80-100	0.6	3