Erosion and sediment transport measurement
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Some observations on the movement of cobbles on a streambed

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GENERAL STATEMENT

Numerous experiments have been undertaken to measure the bed shear stress necessary to move particles of different sizes. The well known Shields curve for initial motion is supported by compilations of other data, for example, Leopold, Wolman, and Miller (1964), Fig. 6-11, p. 170. However, flume experiments have dealt primarily with debris of uniform size. In natural gravel bed rivers, size distribution makes the application of such curves problematical for the effect of hiding—small grains being protected from stress by larger grains—is poorly known. It has been shown that the closer one rock is to its neighbors, the larger is the shear stress needed to move either (Langbein and Leopold, 1968). Experiments in an ephemeral stream by Leopold, Emmett, and Myrick (1966) demonstrated that the effect of proximity becomes negligible when adjacent cobbles are separated by 8 diameters or more.
If the shear stress is sufficient to move a rock of a given size, it is not known whether all rocks of that size will move, whether all rocks of smaller size will move, or how far each moved rock will be carried. A preliminary and incomplete experiment to answer those questions is described here. Because of its simplicity, however, the procedure might be used for a more sophisticated experimental design.

EXPERIMENT

White Clay Creek at the Stroud Water Laboratory drains 7.25 km² in the West Grove Quadrangle, Pennsylvania. The stream at that place has a width of 5.2 m, and a gravel bed the median grain size, D₅₀, of which is 58 mm. Its pattern is sinuous or straight with well developed pools and riffles. The drainage area is agricultural, mostly in pasture with moderate amounts of forested woodlot interspersed with some tilled cropland. Mean annual precipitation is about 1200 mm.

Three riffles were selected from which cobbles of various sizes were collected. From the rocks collected 90 were selected, representing three size classes. The smallest class was typical of rocks on the riffles 35% finer and is designated D₃₅. In this class the dominant size was 47 mm on the B axis (intermediate axis). The middle size rocks represented D₅₀ (50% finer) and the dominant B axis dimension was 58 mm. The largest size represented D₈₄ (84% finer); the dominant B axis dimension was 91 mm.
These 90 rocks were painted yellow and were put in lines across the channel bed. On each of the three riffles three lines of rocks were placed, the lines oriented across the channel orthogonal to the flow direction. On each riffle the upstream line consisted of 10 $D_{35}$ rocks. Downstream a distance of 1.5 m was a line of 10 rocks of size $D_{50}$. Further downstream a distance of 1.5 m was a line of 10 rocks of size $D_{84}$.

Two staff gage plates were installed in each riffle, separated by downchannel distances of 10 to 17 m. Simultaneous water surface elevations observed at a pair of staff gages allowed water surface slope to be computed.

Across each riffle a representative cross section was surveyed. From it, relations of cross sectional area and mean depth to reading on a gage plate could be constructed. A few hundred meters downstream is a gaging station with water stage recorder. Simultaneous readings of water surface at the gage and at the riffle staff plates allowed construction of discharge rating curves for each of the three riffles. Thus for any discharge, values of mean depth and slope were available at each riffle allowing an estimate of mean bed shear stress as

$$\tau = \gamma ds$$

where $\tau$ is shear stress in kg m$^{-2}$, $\gamma$ is the specific weight of water, 1000 kg m$^{-3}$, and $d$ is depth in m.
After each significant peak discharge the rock lines were inspected. The distance downstream that any rock moved was recorded. After several storms individual rocks were removed from their downstream positions and replaced on the line where they had been originally. Only in unusually high discharges were some rocks moved so far that they could not be located.

ANALYSIS

In the winter of 1979-1980, 11 storms occurred, the discharges from which were sufficiently high to require measurements of rock movement. It was assumed that any rock movement could be attributed to the largest peak discharge occurring between dates of rock inspection. Thus the computation of the shear stress associated with each rock movement was based on the highest discharge observed between inspections. These discharge values varied from 0.23 m³ s⁻¹ to 3.42 m³ s⁻¹. The corresponding values of shear stress varied from 2.15 kg m⁻² to 14.6 kg m⁻².

The local slope and depth differed among the three riffles at the same discharge and therefore any given discharge produced a different value of bed stress at the cross sections. The Laboratory Riffle No. 1 maintained a constant slope for different discharges and the value of τ thus varied directly as depth.

At the White Rock Riffle No. 2, slope decreased slightly with discharge so the values of shear are smaller than those at No. 1. At the Willow Riffle No. 3, the computed slope decreased rapidly with discharge.
discharge but the scatter of data was large and no reliable average
relation of slope to discharge could be constructed. Therefore, for
that location no values of shear stress are presented.

It would be expected that the number of rocks of a given size
moved by various flows would increase with bed shear stress. The
observations are presented in Fig. 1 as plots of percentage of
rocks moved as a function of bed shear stress for each flow event,
and separate graphs are shown for the small rocks ($D_{33}$), medium size
rocks ($D_{50}$) and large ones ($D_{54}$). On each graph is an arrow indi­
cating the value of shear stress needed to initiate motion of the
rock sizes used; the values of stress were read from Fig. 6-11, in
Leopold, Wolman, and Miller (1964).

The figure shows that the shear stress on White Rock Riffle No. 2
exceeded that necessary for movement only on a few occasions and
as a result, the maximum number of rocks moved by any flow was only
10% of the total number, regardless of rock size. On the other
hand, Laboratory Riffle No. 1 experienced shear stress above the mini­
mum necessary in nearly every hydrograph rise. Consequently move­
ment of all three rock sizes occurred in about two thirds of all flow
events. However, the salient fact is that in only one instance did
as many as 60% of the rocks move, and in all other cases 40% or less
of the rocks experienced motion. This small percentage of rocks
moved was characteristic despite the fact that the shear stress
became as large as 5 times the value necessary for movement. In
the flow where 60% of the $D_{50}$ rocks moved, the experienced shear
stress was 2.9 times that needed for initial motion.
The total number of movements out of the 90 rocks placed occurring in the 11 flow events is summarized in Table 1. In each of the riffles the number of rocks moved decreased with increase of rock size as one might expect because there were fewer flows providing large values of shear stress than those providing small values.

Regarding distance that rocks moved, Fig. 2 shows for each storm at Laboratory Riffle No. 1 the total distance of all movements as a function of shear stress. The total distance means the sum of movement distances of each rock of a given size class that moved. The distance moved increased geometrically with increase of shear stress. In the single flow event where shear stress exceeded 14 kg m$^{-2}$, 7 of the 90 rocks were swept downstream so far that they disappeared and distance moved is unknown.

Fig. 2 shows no obvious relation of distance moved to rock size but when movement distances are summed for all 11 flow events, the relation becomes more clear as shown in Table 2. The table shows that the smaller rocks moved a somewhat longer distance than did the large rocks. Yet except for the largest flow that moved some rocks completely out of the riffle area, the distances moved were small, usually less than 2 m even in flows where the shear stress was several times the value needed for motion.
CONCLUDING COMMENT

Data on shear stress needed for initial motion of a rock of given size are usually compiled either for an isolated rock on a uniform bed or the first motion of any rock in a bed composed of rocks of the same size. The interaction of a rock with its neighbors, the tendency for a smaller one to be protected from shear stress by larger ones in the vicinity, makes the experimental values of required stress to be minimal.

The present modest experiment suggests that even when shear stress is several fold larger than the minimal value derived from initial motion data mentioned above, only a small proportion of available rocks will actually be set in motion. It therefore takes repeated flows of competent shear stress to move all of the rocks of a given size. If a gravel riffle is an expression of a kinematic wave as suggested by Langbein and Leopold (1968), complete replacement of rocks in a zone of concentration requires not one but a series of flow events sufficiently energetic to move those rocks.

This general conclusion has been confirmed by the authors in other marked rock experiments. On the East Fork River, Wyoming, marked rocks placed on a gravel bar gradually disappeared over a period of 4 to 5 yrs, despite annual flows sufficient to move rocks of that size.

The average distance moved in a flow event of the present experiment was about 2 m, the rocks being of the order of size of 0.06 m. This is a movement of 33 rock diameters, a general confirmation of the estimate of H. Einstein that a single bedload movement is usually of the order of 100 grain diameters.
ACKNOWLEDGEMENTS

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REFERENCES

Langbein, W.B., and Leopold, L.B., 1968, River channel bars and dunes—theory of kinematic waves: USGS Prof. Pap. 422-L.


Table 1. Total number of rock movements in 11 storm events.

<table>
<thead>
<tr>
<th>Riffle name</th>
<th>Size class</th>
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<tr>
<td></td>
<td>$D_{35}$</td>
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<td></td>
<td>(47 mm)</td>
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<tr>
<td>Laboratory Riffle 1</td>
<td>14</td>
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<td>White Rock Riffle 2</td>
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</tr>
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<td>Willow Riffle 3</td>
<td>19</td>
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</tbody>
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Table 2. Total distance (m) moved by all rocks in all 11 flow events.

<table>
<thead>
<tr>
<th>Riffle name</th>
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<tbody>
<tr>
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<td></td>
<td>(47 mm)</td>
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<tr>
<td>Laboratory Riffle 1</td>
<td>13</td>
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<td>White Rock Riffle 2</td>
<td>11</td>
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<tr>
<td>Willow Riffle 3</td>
<td>37</td>
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</table>
Figure 1. Percentage of rocks moved by flows having different values of bed shear stress. For each of three rock sizes a separate diagram is presented. Vertical arrow indicates shear stress value needed for initial motion of that rock size.
Figure 2. Total distance moved by all rocks of given size as function of shear stress, Laboratory Riffle No. 1.