FLUME STUDIES OF THE TRANSPORT OF PEBBLES AND COBBLES ON A SAND BED

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ABSTRACT

During experiments on sediment transport and resistance to flow with a uniform 0.33 mm sand, data were taken on the movement of individual rocks having intermediate diameters from about 0.1 to 0.5 foot. The experiments were conducted in a flume 2-foot wide by 60-feet long and for most runs, depth was held constant at 0.5 feet.

The experiments showed that rocks on the sand bed moved downstream consistently only if the flow was in the upper regime; that is, only if the bed forms were plane bed, standing waves, or antidunes. The rocks moved at velocities that were approximately one-half of the average velocity of the water. With all bed forms in the lower flow regime (ripples, ripples superimposed upon dunes, and dunes), the rocks always moved upstream and down into the bed. That is, the rocks moved into a scour pocket that formed at the upstream side of the rock. The movement upstream and down into the bed is limited by and approximately equal to the distance below the original rock position of the minumum bed elevation plus approximately one-half the rock diameter.

The data indicate that cross-bedded sand deposits formed by the ripple or dune phases of transport would contain few, if any, pebbles or cobbles. Because the flow, in at least the downstream reaches, of most

rivers is in the lower regime, the upstream movement and scour into the bed demonstrated in these experiments is an important factor in the sorting process.

INTRODUCTION

During periods of low flow or no flow, pebbles, cobbles, and boulders are found scattered on and in the bed of sand channel streams, especially, on the beds of the dry washes and arroyos of the Western United States. (Leopold and Miller, 1956). Because the movement of these large particles has long intrigued investigators of sediment transport, the transport of individual rocks was studied coincidentally with a flume experiment on the mechanics of flow in alluvial channels [1/].

In the early phases of the experiment, it became apparent that the type and direction of rock movement was directly related to the form of bed roughness. As a result, rock movement with all flow regimes and forms of bed roughness from beginning of sand motion to antidunes were investigated. The regimes of flow and the forms of bed roughness are shown in Figure 1, which was presented first by Simons and Richardson

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Figure 1. Forms of Bed Roughness in Sand Channels

(1961) who systematically outlined the regimes of flow and the forms of bed roughness that occur in natural channels. Other detailed illustrations and discussions of sediment transport, flow resistance, and associated phenomena for water-sand flow are given in Simons, Richardson, and Albertson (1961) and Simons and Richardson (1961).

1/ Daranandana, Niwat, 1962. The effect of gradation of bed material on flow phenomena in alluvial channels. Colorado State University Ph.D. Thesis (in preparation).

APPARATUS AND PROCEDURE

The flume, which is 2-feet wide, 2.5-feet deep and 60-feet long, has a discharge capacity of from 0 to 7.5 cfs and can be adjusted to slopes of from 0 to 0.025 foot per foot. For more information on the flume see Simons, Richardson, and Haushild (in preparation).

Sufficient sand was placed in the system to maintain an average depth of sand in the flume of 0.5 foot. The source of the sand is a sandstone in the Deadwood formation near Hill City, South Dakota. The sandstone was crushed to discrete particles, dried to a moisture content of about one per cent, and then screened into the desired size fractions. The sand was coarser than the U. S. standard No. 60 screen (.246 mm), and finer than the No. 40 screen (.417 mm). The median fall diameter, d, was 0.33 mm and the gradation coefficient, σ_r, was 1.27. The gradation coefficient was computed using:

$$\sigma_r = \frac{1}{2} \left(\frac{d}{d_{16}} + \frac{d_{84}}{d} \right)$$

where d_{16} is the fall diameter for which 16 per cent by weight of the material is finer, and d_{84} is the fall diameter for which 84 per cent is finer.

The rocks used in this experiment were well rounded and nearly equidimensional. They ranged in intermediate diameter from 0.1 to 0.5 foot. The sizes and characteristics of these rocks are given in Table 1.

Throughout the steady discharge runs, the average depth of water was held constant at 0.50 $\pm$ .02 foot, the water temperature was maintained at $20^\circ \pm .02^\circ$ C, and the flume and water-surface slopes were maintained nearly parallel. For each run a given water-sand discharge was recirculated until the average slope of the water surface remained constant; the form of bed roughness was fully developed; and the imposed restrictions on temperature, slope, and depth were fulfilled. Then, configuration and movement of the bed forms, flow variables, and amount of sediment transport were measured. After these measurements, the cobbles and pebbles were placed one at a time upon the sand bed either by gently laying them in place or by dropping them from the water surface and the data on the movement of the rocks were obtained. The mean downstream velocity of the rocks (Table II) was based on the average of all trials where rock moved continuously, or only stopped momentarily, through the downstream 40 feet of the flume. The average time required for each rock to move the 40 feet was based on three measurements. The two fastest velocities for each rock were averaged to get the average v_{max}. (Table II). These were thought to be the velocities which could be reproduced most easily because they represented the most nearly continuous passes through the flume. These velocities were used with the mean velocity of the water to compute the relative velocity of the rocks (Table II). A screen was placed at the end of the flume to catch the rocks as they arrived.

To supplement the steady-discharge data shown in Table II, observations were made during a few runs in which discharge was varied with time. In these runs, the rate of change of discharge with time, the flume slope, the form of bed roughness, and depth of flow were varied over a large range to obtain qualitative evaluations of the effect of these variables on the rock movement.

ANALYSIS OF DATA

Steady Discharge

In the steady discharge runs, the movement of the rocks in the upper flow regime was almost always in the downstream direction but was continuous only with a plane bed. The data from these runs is summarized in Table II.

The rocks moved downstream by primarily rolling. When a rock landed on a particularly flat face or perhaps hit a soft spot in the bed, the rock might slide or both roll and slide at the same time. The rocks appeared to be in contact with the bed at all times.

The nature of the downstream motion was determined by the flow characteristics and the nature of the bed. For a given flow and bed situation, each rock moved downstream in a way and with a velocity similar to all other rocks; therefore, the downstream motion was independent of rock size. Sometimes, with plane bed, upper regime flow, the rocks rolled for short distances and stopped, but again they might move downstream through the complete flume length without stopping. As the slope or discharge or both increased the rocks rolled without stopping for longer distances. Once the rocks stopped on a plane bed they were not likely to again move downstream as upstream scour started immediately and the rock rolled upstream and down into the bed. The original motion of the rock was probably due to its exposed position on the bed surface and to the force acting on it at the moment of release.

With antidunes, in the upper flow regime, the forces of the water and the bed condition are both important because of their variability. In Figure 1 it is apparent that the downstream force component of the water acting on the rock is much less in the deeper flow of the breaking wave than in the shallower flow between the waves. The bed is also quite soft under the wave crest and quite firm under the wave trough. Therefore, the rocks rolled readily where the bed was firm and the forces were the greatest, in trough areas, and often, but not always, stopped under the wave crest where the bed was softest and forces least. Rocks having sufficient momentum were slowed but did not stop in the breaking waves. Almost always, rocks which stopped and were partly scoured into the sand bed in the breaking wave area were again set in motion downstream when exposed to the greater forces of the water in an antidune trough. The velocity with which the rocks traveled was approximately one-half that of the mean velocity of the water. The range in average maximum velocity indicates that the velocity was not a function of the size of the rock.

At a mean velocity of 2.6 fps the flow lacked sufficient force to roll the rocks downstream and upstream movement ensued. At a mean velocity of 4.0 fps all of the rocks were moved downstream. A comparison of this data with that from a gravel bedded glacial stream (Fahnestock, 1961) suggests that the rocks moved as easily on the plane sand bed as on the gravel.

In the upper regime when the force of the water did not move the rocks downstream, the major scour occurred upstream from the rocks and they moved upstream; however, minor scour also occurred on the downstream side.

In all instances with ripples and dunes, lower regime flow, the force of the water was insufficient to move the rocks downstream, the sand bed scoured at the upstream side of the rock and, within a few minutes, the rocks started to roll upstream and down into the scour pocket. Figures 2 and 3 are illustrations of rock motion. The rocks moved about one-half diameter upstream and one-fourth to one-half diameter down into the bed when the bed elevation was fixed. When the

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Figure 2. Excavation of the sand bed to show the upstream movement and burial of rocks. The bed form is dunes in the transition between the upper and lower flow regime. The stakes mark the before and after positions of the rocks.

Figure 3. Upstream displacement of boulder AA. The thermometer shows the original position of the center line of the boulder. The bed form is ripples in the lower flow regime.

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bed elevation varied as with dunes the maximum depth (which the rocks were scoured) was approximately one-fourth to one-half diameter below the deepest depth in the dune troughs.

When the height of the dunes or ripples was about the same as the rock diameter, the sand waves advanced over the rock as if it were not there. With rocks larger than the height of the bed roughness, a scour pocket was usually maintained as the dune passed the rock's position. The total distance moved apparently depended both on the size of the scour hole, which was a function of rock size, and on the height of the bed roughness. The upstream movement of the rocks was primarily by rolling with a minor amount of sliding as the underlying sand slumped into the scour hole; the rocks rotated one-fourth to three-fourths of a turn. At a constant depth, the rate at which the rocks moved upstream was a function of the sand transport within the flume; that is, the greater the transport and scour, the more rapidly the rocks moved. Also, the scour that occurred at the upstream face was accompanied by the deposition of a ridge of sand downstream from the rock.

In the experiments, observations were made only during equilibrium conditions when the bed elevation remained essentially constant. In a depositional environment, upstream movement probably would be similar, but, with degradation the upstream movement probably would be far greater. For example, with 5 feet of bed scour, rocks would move from 5 to 10 feet upstream. The result would be the same whether the total scour occurred as local scour during the passage of a single flood on a major stream or as degradation over a period of years, as long as the flow stayed in the lower regime.

Variable Discharge

When the discharge and depth of water were varied with time, differences in rock movement were observed as compared to the movement with the foregoing steady discharges and constant flow depth. Depths in excess of 0.5 foot were not used in these experiments. Even in the upper flow regime, the rocks did not move downstream unless the flow depth was greater than or equal to the diameter of the rock. At all flow depths less than the rock diameter, regardless of regime, upstream scour and movement of a rock occurred. Leopold and Miller (1956), p. 6 have reported downstream movement of boulders in flows shallower than the boulder diameter. In this case it is possible that the bed was composed of much coarser materials than the sand used in this study and consequently the slope might have been steeper. The relative ease with which the experimental sand was scoured also may have been a factor in the rock movement.

Slug flow imposed a water-wave front or fronts upon rocks placed on the sand bed in the flume but insufficient forces were exerted on the rocks by the fronts to cause rock movement. The rock would move upstream or downstream after the front passed depending upon the regime and the depth of the following flow.

SUMMARY AND CONCLUSIONS

Individual rocks on a sand bed moved downstream only when the bed form was plane, standing waves, or antidunes. Rock velocities were approximately one-half the average velocity of the flow. A pebble or cobble observed rolling on the bed in a sand channel stream, would be a clear indication that the flow was in the upper regime. The presence of such materials scattered over the bed surface of a dry sand channel would indicate that upper regime flows had occurred. Where the forces were insufficient to set the rock in motion downstream even though the flow was in the upper regime, upstream scour occurred and the rock movement was upstream.

When the bed form was ripples, ripples superposed upon dunes or dunes, the rocks moved upstream and down into the bed. The movement upstream and down into the bed is limited by and approximately equal to the distance below the original rock position of the minimum bed elevation plus approximately one-half the rock diameter.

Because the flow in, at least the downstream reaches, of most rivers is in the lower regime, the upstream movement and scour into the bed demonstrated in these experiments is an important factor in the sorting process. Materials coarser than sand would not be transported through a sand bedded reach in lower regime flow and therefore, downstream deposits of such a stream would contain little or no coarse materials.

In addition, the experiments indicate that pebbles and cobbles would be found in a sand deposit only if the bedding within that deposit were planar. In support of this observation, it has been the writers' experience that when scattered pebbles and cobbles are exposed in a cut bank of a sand deposit, they are found in the stringers characteristic of upper regime transport rather than in cross-beds which are characteristic of lower regime transport.

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