An experimental study of the effect of bed grain roughness on sediment sorting by entrainment

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Abstract

A series of experiments were conducted to investigate the effect of bed grain roughness on the sorting of mixed-size sediments during entrainment. Loose sediments were entrained off stabilised beds with different roughnesses and the masses and size characteristics of the permanently trapped material analysed. The results show a strong dependence of entrainment on bed roughness and flow conditions which varies with sediment size. Entrainment is also significantly affected by the shape of bed roughness elements. Significant size sorting took place during entrainment, causing general fining and bimodality in some cases.

Introduction

The sorting of sediments by flowing water is a common phenomenon in nature and has important consequences in engineering, geomorphological and geological studies. The progressive decrease in the size of bed material along the length of a river is a result of hydraulic sorting (Rana *et al.,* 1973) and is closely related to the longitudinal profile of the river bed (Deigaard and Fredsoe, 1978). Bed armouring is another consequence of sorting whereby the finer fractions of the bed sediment are removed, leaving an erosion resistant surface composed of the coarser fractions. Some studies have suggested that it is not necessarily the finest, but rather intermediate-sized fractions which are most easily removed. Everts (1973), for example, showed experimentally that intermediate sizes could move over fixed rough beds while both larger and smaller grains were trapped. Russell (1968) explained the common occurrence of bimodal fluvial sediments as a result of this type of sorting. The formation of heavy mineral placers is a consequence of hydraulic sorting of great economic importance where sorting by density has occurred, as described, for example, by Slingerland and Smith (1986).

Slingerland (1984) defined four mechanisms for hydraulic sorting of sediments, viz. suspension, entrainment, shear and transport sorting. Entrainment (i.e. the process whereby sediment grains are picked up off the bed) is possibly the most important of these mechanisms in fluvial environments. Its significance in determining the characteristics of lag deposits in an erosional setting is obvious. It is also important, however, wherever sediment transport occurs because of the episodic nature of transport, whether as suspended or bed load. Every excursion by a sediment grain must be preceded by entrainment, which is therefore a continually repeated process during transport. The cumulative effect of entrainment is probably more important in sorting than the differential velocities of grains while in motion.

The entrainment of a sediment grain depends on a number of factors. The forces tending to move the grain are determined by the flow characteristics, most commonly represented by the bed shear stress. The resistance of the grain to motion depends on its size, shape and density and the roughness characteristics of the surface on which it rests. The relative size and geometric arrangement of adjacent grains determine the protrusion, exposed area and stability of the individual grains. For very fine-grained sediments the resistance to entrainment may be enhanced by intergranular cohesion. The nature and effect of cohesion are not well understood but it is an important factor for sediment with significant silt and clay content. Entrainment of grains on bed forms would also be influenced by the local bed slope and the spatial variation of bed shear stress. The resisting factors define a critical value of bed shear stress which must be exceeded for movement to occur. This critical value will be different for each grain type in a mixture and under given flow conditions different grains will be entrained with different relative ease, resulting in sorting.

The experiments described in this paper were conducted to investigate the effect of bed grain roughness on the entrainment of different sized grains in a sediment mixture and the resulting effect on the size characteristics of sediment permanently trapped in a fixed bed.

Experimental procedure

The experiments were performed in a 25 m long, 900 mm wide horizontal flume. Half-way along the flume a test section was installed, comprising five sediment-filled steel trays set in a recess formed by raising the bed of the flume, as shown in Fig. 1. Each tray was 500 mm long, 100 mm wide and 15 mm deep, and was filled with a different type of sediment, immobilised with epoxy resin. The graphic mean sizes of the tray sediments used are listed in Table 1. All of these sediments were fairly irregular in shape, except for the Philippi sand which was well-rounded, and were too coarse for cohesion to be significant. The trays were separated from each other and from the flume walls by strips (60 mm and

TABLE 1
GRAPHIC MEAN SIZES OF TRAY SEDIMENTS

Tray No.	Sediment type	Graphic mean size (mm)
1	River pebbles	6,10
2	River pebbles	3,20
3	Aeolian sand	1,34
4	Philippi sand	0,76
5	Chromite sand	0,31
6	Philippi sand	0,23
7	Philippi sand	0,36
8	Philippi sand	0,51

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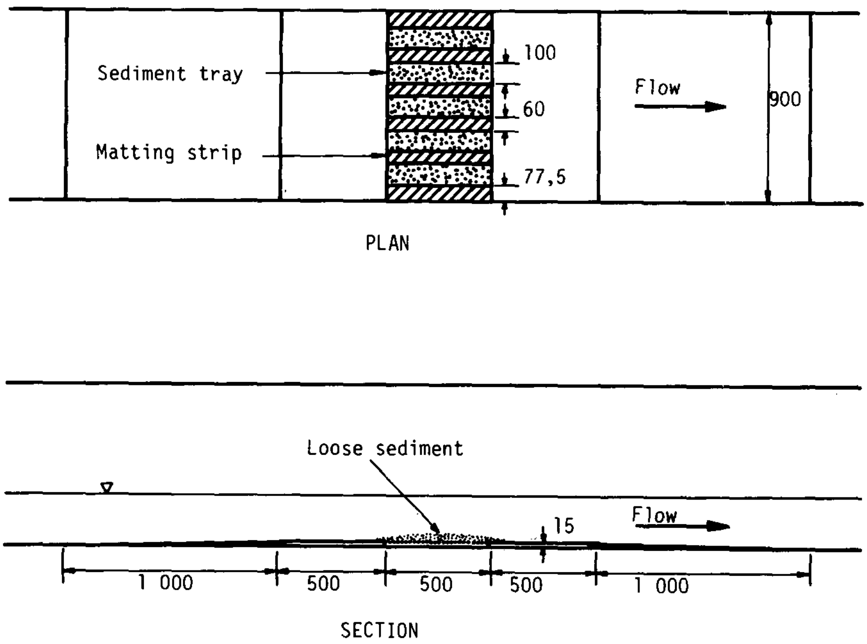


Figure 1
Test section in flume

77,5 mm wide respectively) of "Nomad" matting, a spun filament material with an open pile. This was done to minimise wall effects and to prevent any possible exchange of sediment between the trays during experiments.

For each experiment the desired flow condition was established by setting the required discharge with a valve in the supply pipe and the flow depth with an adjustable weir at the downstream end of the flume. The discharge was measured using a Venturi meter in the supply pipe and the flow depth over the test section using a pointer gauge with a Vernier scale. Boundary shear stresses were also measured using a Pitot-static tube as a Preston tube, linked to a pressure transducer with an analogue display unit. This instrument was calibrated by measuring velocity profiles over all the trays and computing shear velocities from the plotted profiles.

Before beginning each run the flume was flooded to a depth of about 70 mm over the test section and a layer of loose sediment was placed over the entire test section. Water was then allowed to flow at the previously established discharge and flow depth. The loose sediment was washed off the trays, exposing the immobilised surfaces but leaving some particles permanently trapped on the surfaces. The experiment was ended when no movement of sediment over the tray surfaces could be seen. The flume was then drained and the trays removed. The sediment remaining on each tray surface was recovered in a washing basin, oven-dried, sieved into different size fractions and weighed.

A total of sixteen experiments were performed. For the first twelve experiments trays 1 to 5 were installed. Three sediment types were used and four hydraulic conditions were applied for each. The sediment types were the same as used for making test trays 3, 4 and 5, i.e. aeolian sand, Philippi sand and chromite sand. The last four experiments were run with trays 4 to 8, using only the 0,76 mm Philippi sand as sediment and four different hydraulic conditions. The first twelve experiments were intended to show the effects of bed roughness size on entrainment sorting and the last four the effects of the shape of the roughness elements. The conditions for all experiments are listed in Table 2.

TABLE 2
EXPERIMENTAL CONDITIONS

Run no.	Discharge (ℓ/s)	Flow depth (mm)	Flow velocity (m/s)	Sediment type
1	60,0	152	0,44	Aeolian sand
2	71,0	133	0,60	
3	60,5	124	0,59	
4	58,0	127	0,51	
5	55,0	140	0,44	Philippi sand
6	60,0	160	0,42	
7	51,0	115	0,50	
8	61,0	134	0,51	
9	60,0	146	0,46	Chromite sand
10	60,0	133	0,50	
11	71,0	132	0,60	
12	60,0	123	0,55	
13	60,0	134	0,50	Philippi sand
14	51,0	135	0,42	
15	53,0	124	0,48	
16	68,0	146	0,52	

Results

The effects of hydraulic conditions on entrainment are shown in Figs. 2, 3 and 4 for the aeolian sand, Philippi sand and chromite sand as sediments respectively. The sediment retained by the bed (expressed as a mass concentration) is that which was not able to be entrained by the applied flow. In these diagrams hydraulic conditions are represented by average velocity (computed from discharge and flow depth measurements); use of local boundary shear stress shows similar trends. In each diagram a separate curve is plotted for each tray and the roughness (K), defined here as the graphic mean size of the immobilised sediment, is indicated. (The use of broken lines for some curves is for clarity only and has no physical significance). These curves show that there is generally a decrease in mass of sediment retained with increasing flow velocity and decreasing bed roughness. It will be noticed that the mass retained on the chromite sand tray is greater than that on the next largest (Philippi sand) tray in all cases. This is clearly inconsistent with the trend indicated by the other data and, as will be discussed later, is associated with the difference in shapes of the bed sediment grains.

The slopes of the curves relating mass retained to average flow velocity are steeper for the trays containing the coarser materials than for those containing the finer materials. This indicates a greater dependence of sediment retention (or removal) on hydraulic conditions for rough beds than for relatively smooth beds. It is also noticeable that the differences between mass retained on progressively smoother trays are reduced, i.e. the curves get closer together as the roughness decreases, although the ratios of

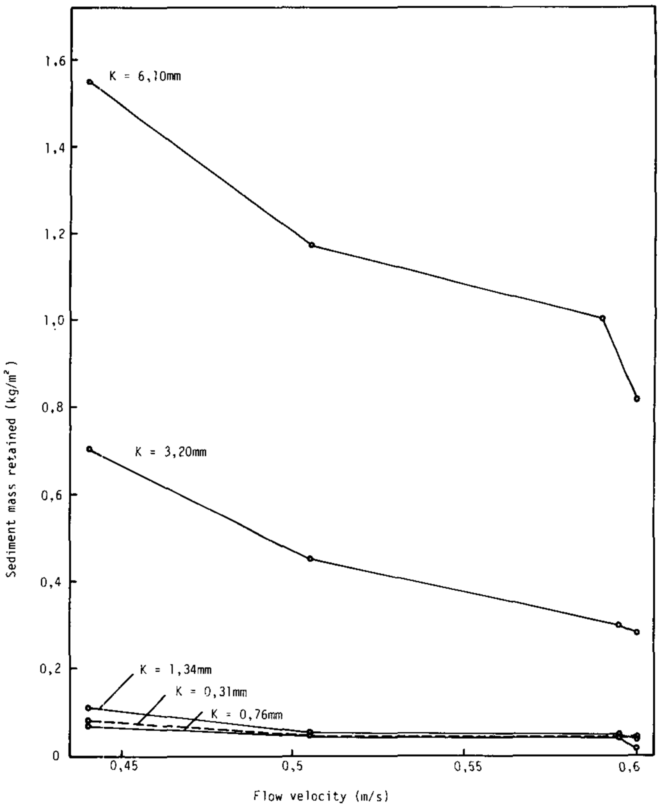


Figure 3
Effect of flow condition on sediment mass retained in experiments with Philippi sand

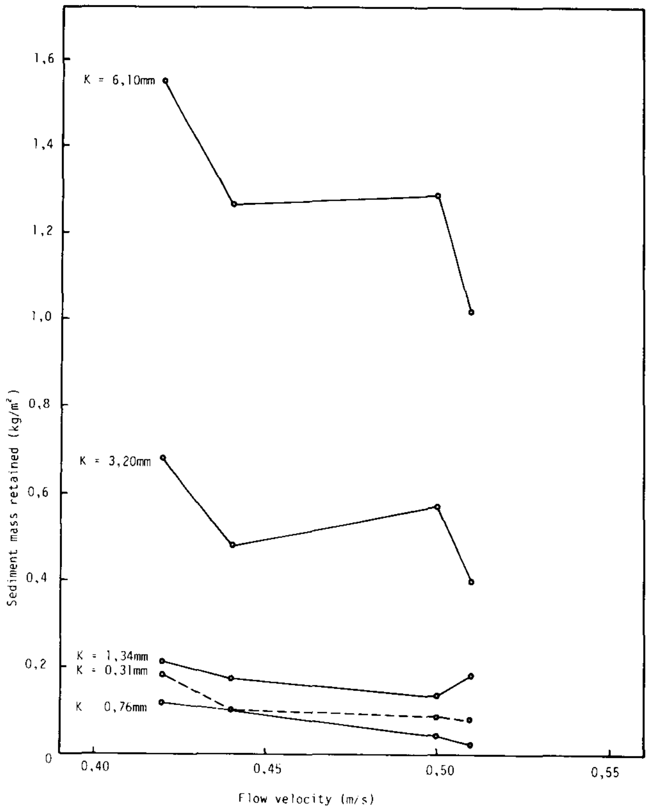


Figure 2
Effect of flow condition on sediment mass retained in experiments with aeolian sand

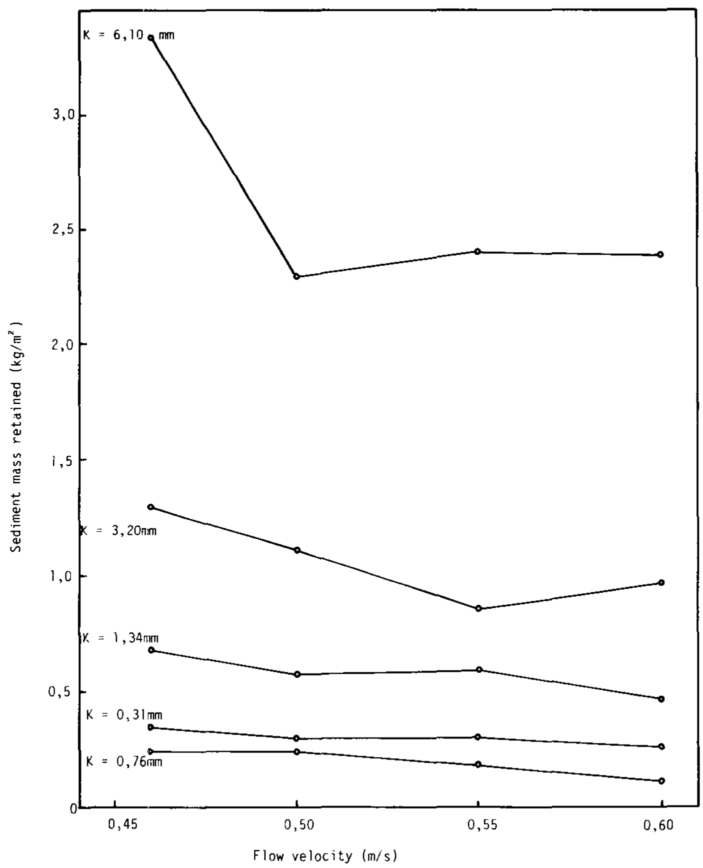


Figure 4
Effect of flow condition on sediment mass retained in experiments with chromite sand

successive roughness sizes are fairly constant. This becomes more pronounced as the size of the sediment increases. This suggests that the dependence of entrainment on bed roughness increases as the size of the sediment relative to bed roughness reduces.

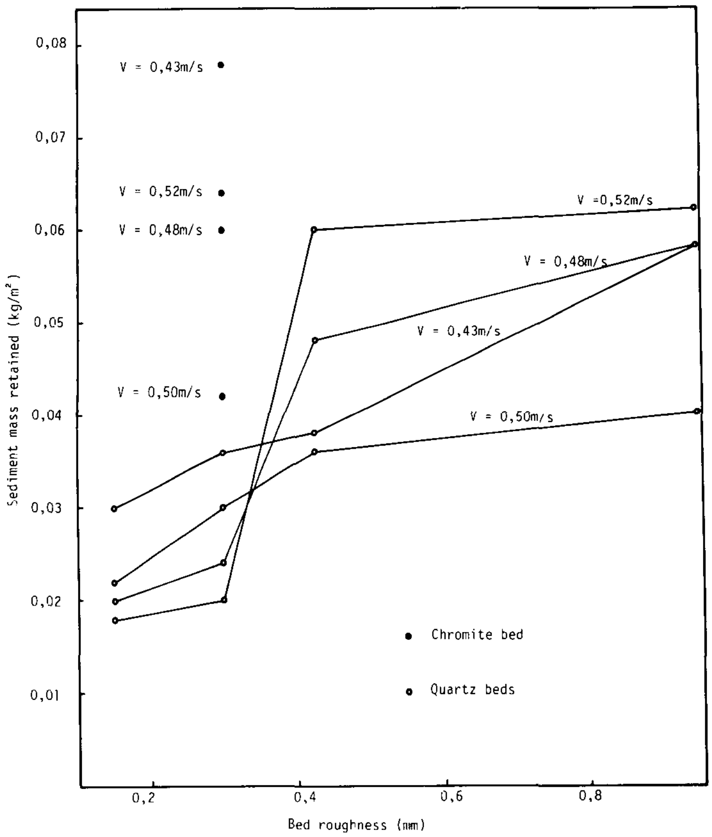
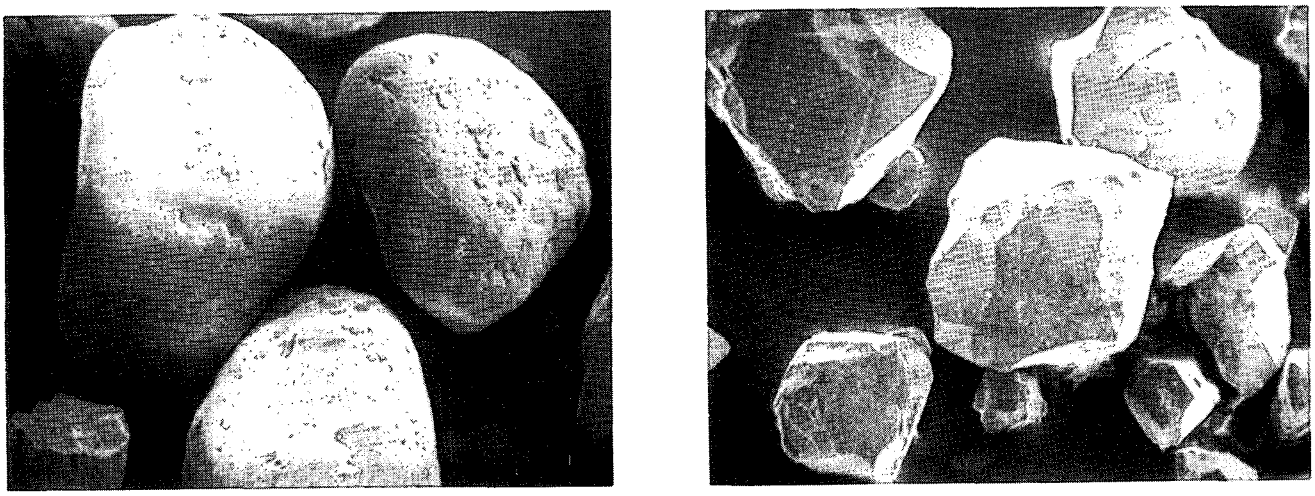


Figure 5
Effect of bed roughness shape on sediment mass retained

The anomalous deposition on the chromite sand bed was investigated in experiments 13 to 16. In these experiments trays 4 to 8 were used, i.e. the same chromite and Philippi sand trays as for experiments 1 to 12, as well as three additional trays made of Philippi sand with a range of mean grain sizes encompassing that of the chromite. The variations of sediment mass retained on the different bed roughnesses for the four hydraulic conditions tested are shown in Fig. 5. The general trend of increasing mass of deposits with increasing bed roughness observed in the earlier experiments is confirmed over the lower range of bed roughnesses. The mass retained on the chromite tray is greater than on any of the other trays in every case, even when the roughness is greater by a factor of 2,5. The greater trapping effectiveness of the chromite is attributed to the difference in the grain shapes of the chromite and Philippi sand. As shown in Fig. 6, the chromite grains are much more angular than the Philippi sand grains.

The size characteristics of the sediments retained on all but the coarsest bed material were significantly different from those of the original materials. In Figs. 7, 8 and 9 the graphic mean sizes of the sediments retained in experiments 1 to 12 are plotted against bed roughness for the three sediment types. (The results for experiments 13 to 16 are similar but the scatter is greater because of the smaller size of the samples). The graphic mean sizes of the original sediments are also indicated on these diagrams. A clear, direct relationship exists between bed roughness and the size of the retained sediment. Except for one case with the aeolian sand, all retained sediments are finer than the original materials. This suggests that larger particles are generally more mobile than smaller ones and that their mobility increases with decreasing bed roughness. This tendency is associated with effects of relative size, protrusion and particle area exposed to hydrodynamic forces. The relationship between mobility and particle size is not simple, however. The size frequency curves for the material retained in all trays for three experiments (4, 6 and 10) with the three different sediments are presented in Figs. 10, 11 and 12. Each diagram is typical of all results for the same sediment type and the distribution of each original material is almost identical to that retained in



a) Philippi sand **b) Chromite sand**

Figure 6
Shapes of Philippi and chromite sand grains

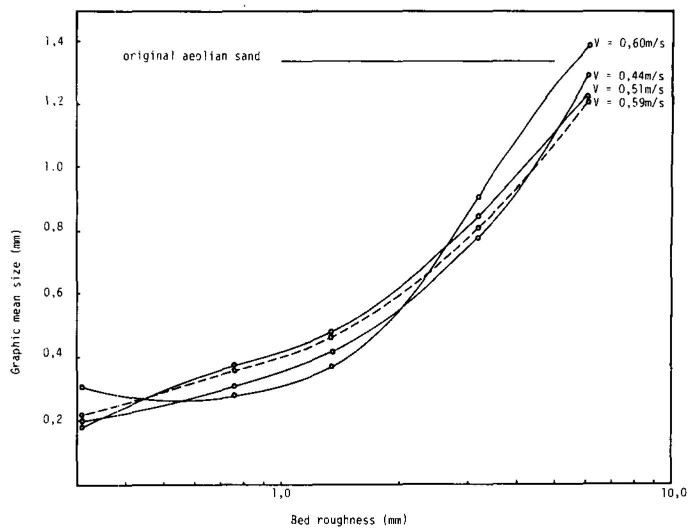


Figure 7
Effect of bed roughness on size of retained sediment for experiments with aeolian sand

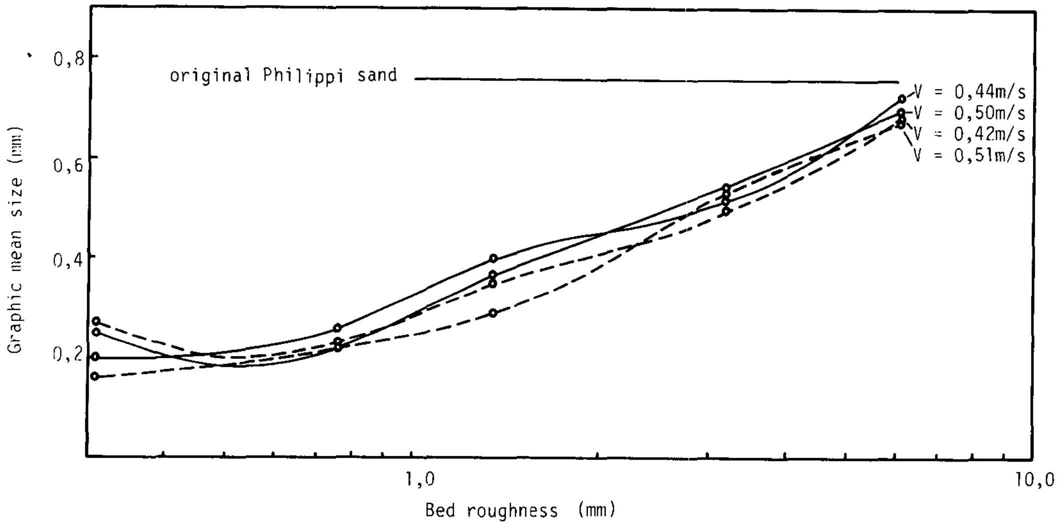


Figure 8
Effect of bed roughness on size on retained sediment for experiments with Philippi sand

the roughest bed. It is clear that the retained material is bimodal in many cases, suggesting that intermediate sized particles are more mobile than either smaller or larger ones in the mixture. Bimodality does not occur in all cases, however, and appears to be related to the size of the sediment (D) relative to the bed roughness (K). Bimodality is most significant in the coarsest of the three sediments (aeolian sand), less so in the intermediate sediment (Philippi sand) and totally absent in the finest sediment (chromite). (The different behaviour of the chromite sediment is believed to be a relative size effect and not associated with the difference in density between the chromite and other sediment. It has been shown (James, 1989) that sediment density affects the absolute magnitude of the critical dimensionless shear stress at entrainment, but not its variation with relative size). The results for the aeolian and Philippi sands indicate that distinct bimodality occurs when the ratio D/K is greater than about unity; this value is not exceeded in any case for the chromite sediment. Although the occurrence of bimodality appears to be related to D/K, no consistency is found in the value of D/K corresponding to the most deficient size fractions in the various distributions.

Conclusions

Entrainment of sediment from a rough bed increases with increasing flow velocity or bed shear stress and decreases with increasing bed roughness. The dependence on these factors reduces as the sediment size increases relative to the bed roughness.

The shape of the bed roughness elements has a significant effect on entrainment, with increased angularity inhibiting entrainment.

Significant sorting by size occurs during entrainment. Generally, the coarser grains in the mixtures tested were more easily entrained than the finer ones, a tendency which increased with decreasing bed roughness. Under certain conditions intermediate sizes were more easily entrained than both finer and coarser ones, suggesting that entrainment sorting could be a cause of the bimodal fluvial sediments common in nature.

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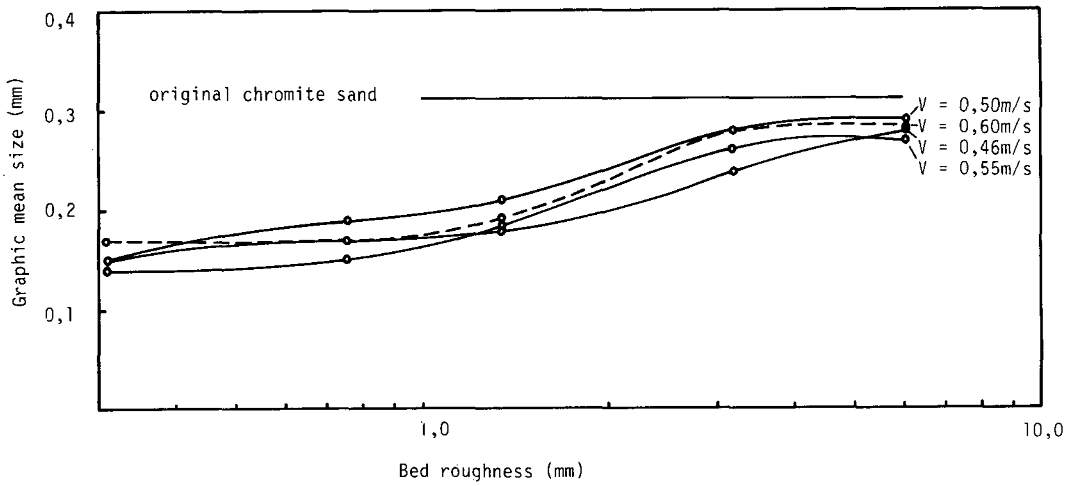

Figure 9
Effect of bed roughness on size of retained sediment for experiments with chromite sand

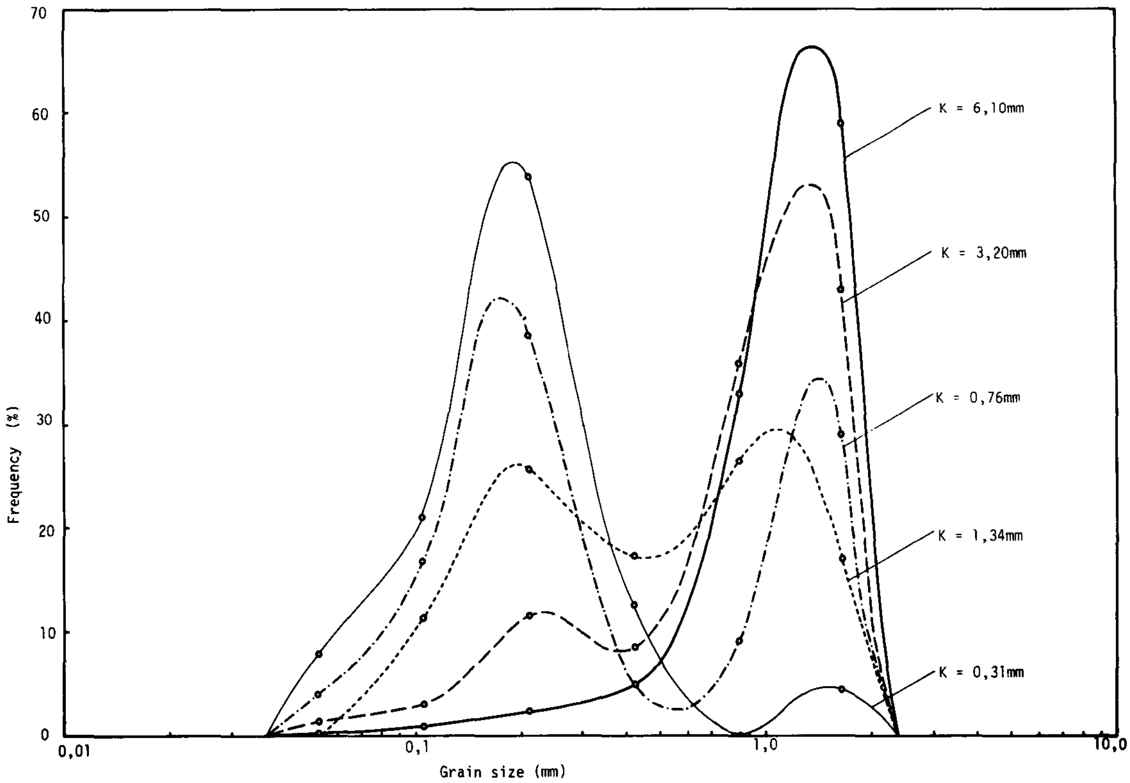

Figure 10
Size distributions of aeolian sand retained in Experiment 4

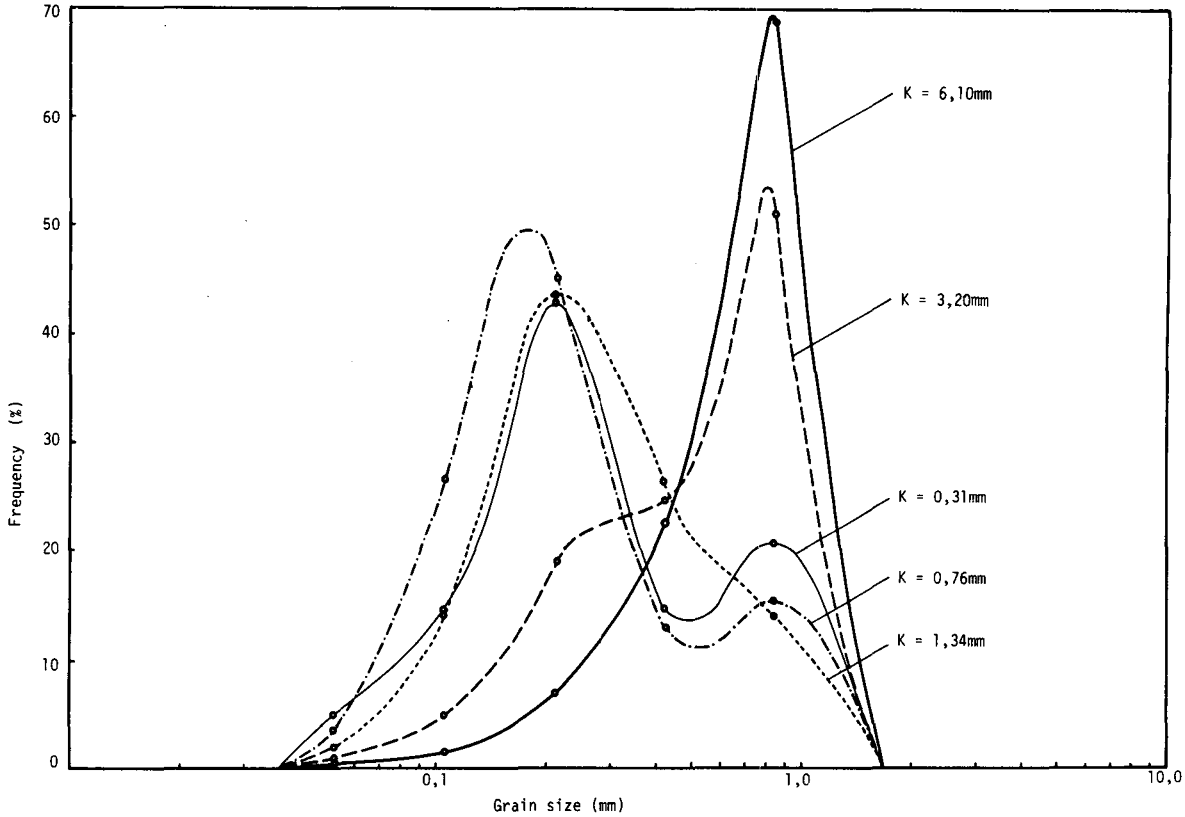

Figure 11
Size distributions of Philippi sand retained in Experiment 6

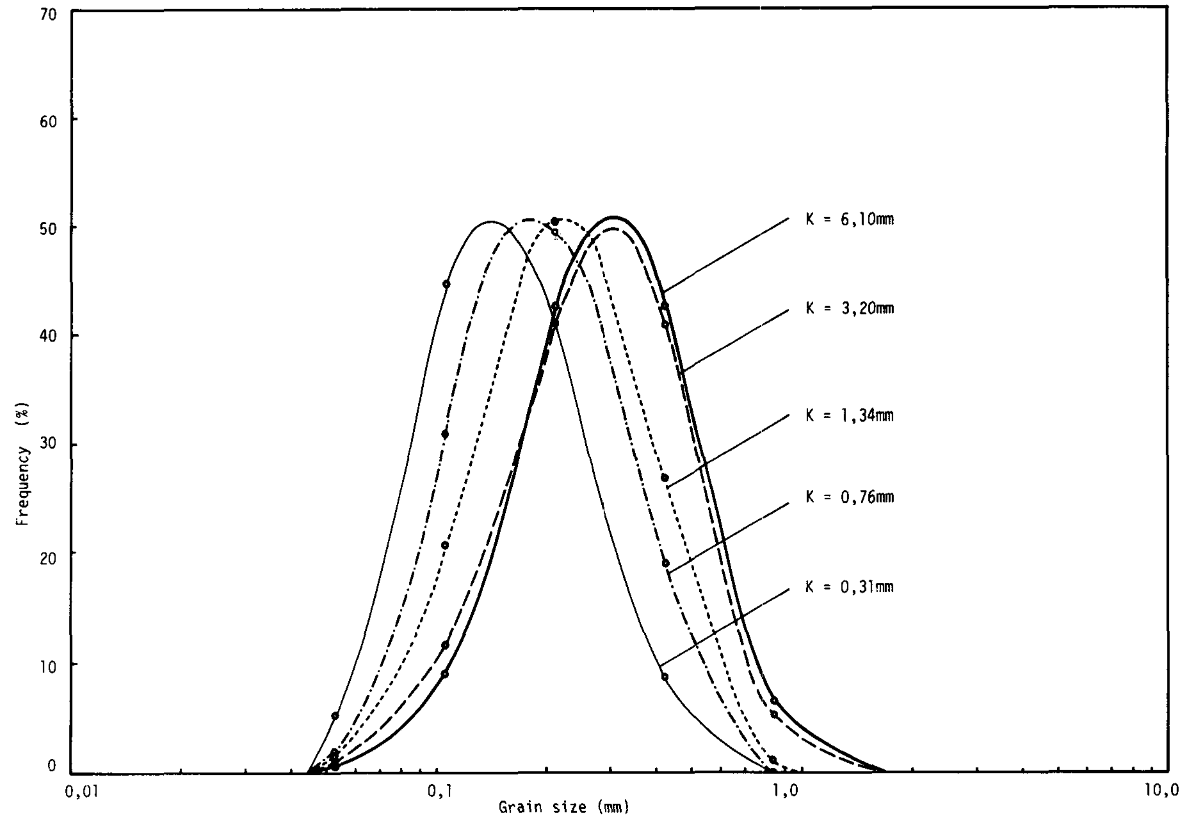

Figure 12
Size distributions of chromite sand retained in Experiment 10

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