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Development of Armoured Surfaces in Alluvial Channels

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1 INTRODUCTION

Bed materials in New Zealand's gravel rivers have mean particle sizes greater than 20 mm and geometric standard deviations that can exceed 4. In such cases the range of particle sizes may be two orders of magnitude. Bed forms are not significant features in these rivers the roughness being determined by the arrangement of individual particles and the spacing between the larger particles. These are both strongly dependent on the most recent flow which caused bed movement.

Two types of surface, depositional and erosional are commonly observed. The former occur on wide flood berms being formed by deposition of material transported by floods while the latter occur in incised main channels. These erosional surfaces are formed by selective erosion at low rates of sediment transport and are dominated by the larger stones which are lapped downstream. Consequently they are termed paved or armoured surfaces. The layer is normally only one particle diameter thick and immediately below it the original material is found.

Formation of an armoured bed requires low bed load transport rates and reasonably long periods of nearly constant flow. Such conditions pertain in unlined irrigation races and in canals through gravel material. The resultant roughness of the armoured beds is of major importance in the design of such waterways. One would like to predict this roughness from a knowledge of expected flows and the original lining material.

The work reported herein is the first step in a continuing study of armoured beds. Laboratory experiments and a set of field measurements are described. The results are compared with predictions made by other workers.

2 FORMATION OF ARMOURED BEDS

When a graded sediment is exposed to the action of a constant flow (assumed large enough to move sediment grains) there is initially a rapid erosion of material. Depending on the flow various amounts of the different size fractions will be in motion. If only small quantities of the coarser fractions are eroded then the bed degrades with a little or no change in slope - parallel degradation. After a short period the rate of erosion decreases significantly and eventually it approaches zero as a stable armoured surface develops.

Should a significant percentage of the coarse material be eroded then the degradation is rotational and the channel slope is thereby reduced. This reduces the erosive capacity of the flow allowing the larger particles to become stable and an armour surface is produced as before.

The formation of the surface is akin to the problem of initial motion with a graded sediment. Grass (1970) noted that in a bed of uniform sediment there is a distribution of critical shear stresses for individual grains because of their varying exposure to the flow. There is also a distribution of shear stresses applied to the bed. If the distributions overlap there will be motion and the degree of overlap will be a measure of the amount of motion. Extending this idea to a graded material one can visualise a critical shear stress distribution for each size fraction d_p (size for which p% is finer). In Figure 1(a) possible cummulative distributions for the d_{10}, d_{50}, d_{90} sizes are shown as is a distribution of applied shear stress which would result in particle motion.

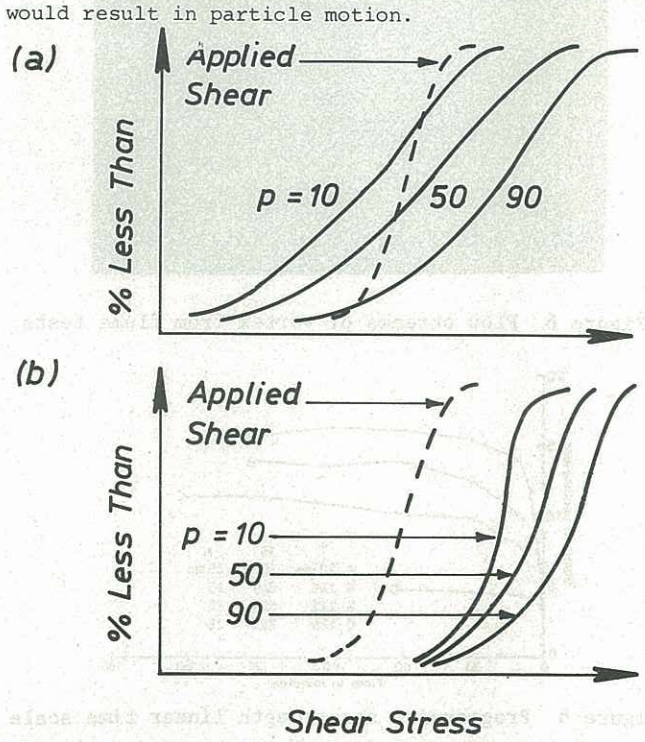

Figure 1 Critical shear stress distributions for size fractions d_p (a) before armouring and (b) after armouring

Both the applied and the critical shear stress distributions will change as armouring proceeds and when erosion ceases the situation may well resemble that of Figure 1(b)

The above implies a likelihood that particles of all sizes will be eroded and that particles of all sizes will remain in the armour layer. Further, the rates of removal of each fraction should be

related to both the size and the exposure of the particles in the fraction. The size distribution of the eroded material should change with time and reflect changes in bed composition as armouring proceeds. This is contrary to the idea that only particles below a certain size are eroded and precludes the concept of a size fraction which is about to be eroded.

3 SAMPLING

Sampling is normally done by collecting a predetermined volume of material and analysing it on a percentage by volume (weight) basis. (Volume by volume or V/V sampling). Armoured surfaces cannot be sampled in this way because the sample volume cannot be predetermined as it depends upon the particle size. Typically, grease or wax sampling is used. This entails placing a grease pad on (Gessler 1970), or pouring wax over (Little and Mayer, 1976), the surface. Those particles adhering to the grease or wax, by definition, comprise the armour surface. This is areal sampling because an area of bed has been predetermined. If the analysis is done volumetrically it is area by volume, A/V, sampling.

Kellerhals and Bray (1971) discuss these procedures in detail and suggest ways of converting results obtained from one method into results that would have been obtained using another method. Such conversions are necessary in comparing armoured surface particle size distributions with distributions obtained from original material. One should not compare V/V distributions from the original material with A/V distributions from the armour surface.

Grease pad sampling does not satisfactorily define those particles comprising the surface nor does it record the location and orientation of the surface particles. To overcome these deficiencies a transect sampling method was developed. A 130 mm square mould was pressed through the dried sediment bed. Epoxy resin was poured into the mould without disturbing the bed material in sufficient quantity to fill the interstices and cover the surface. Once the resin had set the block of material from within the mould was sawn into five slices by vertical cuts made parallel to the flow direction.

Each cut face showed clearly the particles forming the surface and those comprising the underlying or original material. The former were defined as being observable in plan and those surface particles cut by the saw formed the transect sample. For each particle the maximum intersected chord length was recorded and a frequency distribution by length was derived. Kellerhals and Bray (1971) show that if a transect sample is analysed on a length basis then it is equivalent to a V/V sample. Results of the transect sampling described herein differ therefore from volume by volume sampling only in that the assigned linear dimension is the maximum intersected chord and not the sieve diameter.

A transect sample of the original material was obtained in the same way. The resulting distribution curves could therefore be directly compared with those of the armoured surface.

The above technique was impossible in the field tests where the particle size was 10 times that in the laboratory. A transect sample was obtained by selecting particles lying on a straight line traced parallel to the flow direction on the bed surface. A point gauge moved along the line served to identify the surface particles and to give a record of their position. The linear dimension used in the analysis was the 'b axis' or mean diameter which is close to the sieve diameter. This technique had the disadvantage of destroying the surface on analysis and no record of the original material was obtained.

4 ROUGHNESS

An important aspect of any stream bed surface is its roughness. This may be expressed using the Darcy-Weisbach friction factor, f or an equivalent sand grain roughness, k_s. Attempts have been made to relate the latter for an armoured bed, which has no bed forms, to one particular size fraction, e.g. d_{75} (Henderson 1966). However an equivalent grain size, k_s characterising the effect of all surface elements must be dependent upon both the size and the spacing of the elements. A measure of the size of identical roughness elements is their height, h. Their areal concentration, λ can be expressed as the combined area of all elements projected normal to the flow direction divided by the total area of the bed.

Rouse (1965) has summarised results obtained with surfaces made up of identical roughness elements (spheres, cubes, bars) and presents curves of relative roughness, k_s/h against λ. The curves show that maximum relative roughness occurs for $0.15 < \lambda < 0.25$ depending on the type of element.

In contrast to surfaces composed of identical roughness elements, an armoured surface is made up of elements having a range of sizes and at varying spacings. To characterise these beds the transect samples were used to determine effective roughness elements defined as those portions of the surface between successive upward zero crossings. A zero crossing is the intersection of the armour surface with the mean elevation of the surface. The element size, or height, was defined as the maximum difference in elevation between the successive upward zero crossing defining the element. The mean height of all elements will be a measure of the effective roughness height of the surface.

The effective roughness concentration was defined as the sum of the heights of all elements divided by the length of the sample. This is similar to the areal concentration defined by Rouse (1965).

5 EXPERIMENTS

The laboratory experiments were performed in a flume, 27.5 m overall with a 20 m length of working section (Hill, 1967). Adjustable side walls were set for a flume width of 0.62 m. Flows up to 0.09 m^3s^{-1} were obtained from a constant head supply and measured in calibrated pits. Eroded sediment was collected at the downstream end of the flume in a settling tank from which it could be removed at intervals for analysis.

Water surface and bed profiles were measured throughout the tests to ensure uniform flow. Discharge was constant (±2%) and temperature was constant (±2°C) during the seventy or eighty hours required for the bed to reach a stable state.

Sediment mixtures were prepared to a log-normal specification (volume by volume) by mixing locally available river gravels. Each mixture had a maximum particle size of approximately 13 mm. This size could be easily moved by the available flow and ensured fully rough flow conditions (particle Reynolds numbers exceeding 200). The mixtures were placed in the flume to a depth of 150 mm and the surface scraped to ensure the correct bed slope. Sediment sampling was done before

TABLE I

EXPERIMENTAL CONDITIONS

Run	Unit Discharge (m^2s^{-1})	Hydraulic Radius (m)	Slope	Shear Velocity ms^{-1}	Reynolds Number	Bed Material Volume by Volume	
						d_{50} (mm)	σ_g
B	.150	.140	.0049	.082	800	7.72	1.30
C	.123	.128	.0031	.062	850	6.09	1.43
D	.108	.120	.0032	.062	800	3.84	1.82
E	.120	.131	.0032	.064	900	3.47	2.08
V1	.74	.38	.0084	.177	14500		
V2	.73	.36	.0095	.183	15000		
V4	.58	.40	.0082	.181	5900		

d_{50} = mean particle diameter: σ_g = geometric standard deviation

(grease pad) and after (grease pad and transect) each run.

The experimental conditions for each run are shown in Table I. Hydraulic radii have been corrected for side wall effects and Reynolds numbers are based on the d_{90} size of the original material and the shear velocity.

Armoured surfaces in an irrigation race were sampled at three sites (V1, V2, V4) using the techniques described earlier. Flow conditions at the sites are shown in Table I, the Reynolds numbers being based on the d_{50} size of the armoured surface.

6. RESULTS

6.1 General Observations

Initial conditions were such that rapid erosion occurred. Particles of all sizes were in motion with size distribution curves of eroded material being very similar to the original material size distribution. After some twenty hours the erosion rate dropped sufficiently for individual particle movements to be observed. Particles of all sizes were still moving but the larger ones required a considerable degree of exposure prior to movement.

After about thirty hours the characteristic appearance of an armoured bed was seen where the stones are lapped downstream and the surface layer had obviously coarsened. This armour state appeared fully developed after seventy hours by which time careful observation was required to observe particle movement.

6.2 Particle Size Distribution

Table II shows values obtained for the mean particle size d_{50} and geometric standard deviation σ_g.

TABLE II

PARTICLE SIZE DISTRIBUTIONS

Run	Original Material		Armour Layer	
	d_{50} (mm)	σ_g	d_{50} (mm)	σ_g
	area by volume			
B	7.75	1.34	8.38	1.36
C	5.72	1.50	5.97	1.62
D	4.24	1.02	5.84	1.72
E	3.56	2.64	7.87	1.75
	transect			
C	7.01	1.56	7.24	1.70
D	5.08	1.84	6.73	1.71
E	4.11	2.08	7.87	1.84
V1			76.2	1.81
V2			76.2	1.75
V4			30.5	1.73

Values of d_{50} from the area by volume sampling are approximately 20% smaller than those from the transect sampling. Since a transformation from V/V to A/V sampling will increase the value of d_{50} (Kellerhals and Bray, 1971) this is an unexpected result. It must reflect the slicing of particles at arbitrary positions and suggests that the maximum intersected chord on average exceeds the sieve diameter.

Cummulative distribution curves are shown for transect sampling in Figure 2. The most obvious feature is the general coarsening that occurs during armouring. Of equal interest is the presence of particles

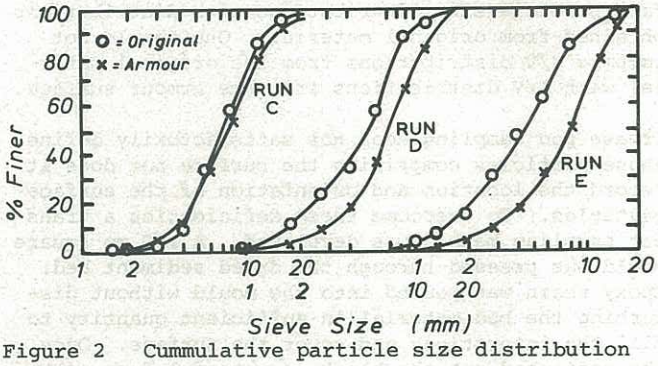

Figure 2 Cummulative particle size distribution curves

from all size fractions contained in the original mixture and the armour surface. This is in accord with observations of Lane and Carlson (1953) in irrigation canals and emphasises the necessity for a theoretical approach to consider a spectrum of critical shear stresses for each size fraction.

Derived distribution curves (percentage within a given size range against size) show clearly the changes in particle size distribution that occur during armouring (Williman, 1975). For Run C in which σ_g increased with d_{50} remaining constant there was a small increase in the percentage of larger sizes and also in the finest sizes with the associated decrease occurring in the percentage of medium sizes.

For Run D the percentage of larger particles increased at the expense of the finer sizes only, thus decreasing σ_g and increasing d_{50}. Similarly in Run E there was a marked decrease in the percentage of fine material and an equally marked increase in the coarser fractions. This run had the largest σ_g for the original mixture and thus the greatest proportion of fines since the d_{90} sizes were similar. As a result the d_{50} value more than doubled.

6.2.1 Comparison with predictions

TABLE III
COMPARISON WITH PREDICTIONS

Run	Armour Surface		Little & Mayer		Gessler	
	d_{50} (mm)	σ_g	d_{50} (mm)	σ_g	d_{50} (mm)	σ_g
B	8.38	1.36	13.6	1.30	8.50	1.30
C	5.97	1.62	8.23	1.39	6.80	1.41
D	5.84	1.72	9.47	1.59	5.70	1.68
E	7.87	1.75	10.9	1.68	6.67	1.96

Little and Mayer (1976) and Gessler (1970) have presented methods for predicting the properties of an armoured surface. The methods assume a volume by volume analysis of the original material and predict the area by volume distribution of the armour coat. Comparisons between calculated and measured values are shown in Table III.

Little and Mayer's predictions give values of d_{50} which are too high and σ_g values that are consistently low. However the range of values of σ_g is reduced by armouring as their equation predicts. Their prediction that with constant shear stress and original d_{50} a larger σ_g will result in a larger armour d_{50} is only partially borne out in that Run D seems out of place. Note that herein d_{90} remains constant and Run B had a larger shear stress (see Table I).

Gessler's predictions are in better agreement with the measured values and do predict a d_{50} value for Run D less than that of either Run C or E.

6.3 Roughness

Results obtained from the geometry of the armoured surfaces are shown in Table IV. The friction factor is calculated from the values shown in Table I and the equivalent sand grain roughness is calculated from $1/\sqrt{f} = 2 \log (12.24R/k_s)$, where R is the hydraulic radius.

TABLE IV
ROUGHNESS PARAMETERS FOR ARMOURED SURFACES

Run	mean diameter d_{50} (mm)	mean height H (mm)	concentration e	friction factor f	sand grain roughness k_s (mm)
C	7.24	4.19	.18	.049	8.38
D	6.73	4.31	.20	.054	10.7
E	7.87	4.57	.19	.058	13.2
V1	76.2	52.3	.20	.093	127.
V2	76.2	41.9	.17	.093	122.

Values of k_s correspond to d_{60}, d_{80}, d_{86}, d_{88} and d_{86} respectively for the runs shown. The average height, H of the effective roughness elements ranges from 0.55 d_{50} to 0.69 d_{50}. Thus the variation in surface elevation about the mean is less than d_{50}, the actual value depending on particle shape and arrangement.

An interesting result in Table IV is the consistency shown by the values of e. The mean value, .19 is within the range of values for which Rouse's (1975) results show maximum relative roughness.

Further, these maxima range from 2.5 to 4, depending on element shape, while herein the range of k_s/H is 2 to 2.9. Consequently it appears that the particles forming an armoured surface are arranged so that the effective roughness elements have the concentration required to produce maximum hydraulic roughness for their size. Yang (1976) contends that a stream will adjust to ensure that the unit stream power (velocity times slope) is a minimum. With the beds examined being formed by constant discharges at constant slopes a minimum velocity slope product can only be achieved by roughening the surface to reduce the velocity. The maximum possible roughness displayed by the armour surface may therefore be seen as evidence for Yang's (1976) hypothesis.

7 CONCLUSIONS

Initial studies of a continuing investigation of stream bed armouring have shown:

(i) Armoured beds contain all size fractions present in the original mixture. Consequently theories of armour surface formation based on initial motion concepts must consider the distribution of critical shear stresses within each size fraction.

(ii) The importance of using consistent and compatible methods of sampling. In quoting results for particle size distributions the method of sampling must be noted.

(iii) Little and Mayer's (1976) relations for 1 mm sediment do not predict results obtained herein with coarser sediments. Gessler's (1970) method gives better agreement.

(iv) Armoured beds have a restricted range of geometric standard deviations. In contrast to d_{50} which always increases with armouring, values of σ_g for the armour surface may exceed or be less than those of the original material.

(v) The process of selective erosion seems to fashion an armoured bed displaying maximum hydraulic roughness consistent with the size of the material.

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