9th AUSTRALASIAN
FLUID MECHANICS CONFERENCE,
AUCKLAND, 8-12 DECEMBER 1986

# Stream Bed Armouring

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## ABSTRACT

The mechanism of armour layer formation is experimentally investigated under steady approach flow conditions with no sediment supply from upstream. A concept for the critical armouring condition of a sediment is proposed. A relationship for this condition is defined (Figure 5) and this enables the critical median armour particle size and the associated flow condition to be estimated.

The results show that the critical dimensionless shear stress, $\theta_{ca}$ decreases as the range of sizes of a mixture increases and the critical armour layer has the minimum value of $d_{max}/d_{50a} = 1.8$. This value corresponds to a value of $\sigma_g = d_{34a}/d_{50a} = 1.5$ which is normally taken to be the boundary between uniform and non-uniform mixtures.

## INTRODUCTION

When the threshold of movement of a particle is exceeded, it moves. In a mixture, exposed finer particles tend to move first. As these least stable particles are eroded, more resistant coarser particles are left behind and these protect the finer particles underneath, thus forming an armouring layer on the surface. As bed shear stress increases, more and more particles begin to move leaving behind more resistant coarser particles, so that the armour layer coarsens. Eventually, a state is reached, called the "critical armouring state" beyond which a stable armour can not develop. Hence a mixture has a range of bed shear stresses at which its bed surface can armour. The range of armours depends on the parent bed material as well as the bed shear stress. A bed material with a wider range of particle sizes especially the coarser ones, tends to have a wider range of possible armour layers than that of a bed material with a smaller range of particle sizes. Thus, a near uniform material cannot form an armour layer since every particle has about the same mobility.

A typical armour is usually about one or two coarser particles in thickness. However, the boundary between an armour layer and the bed beneath is ill-defined and a rigorous definition of armour layer is therefore impossible. This makes accurate sampling of armour layers and the interpretation of samples difficult. The difficulty is further compounded by researchers using different sampling techniques which produce dissimilar results as discussed for example, by Kellerhals and Bray (1971). Often, this is unavoidable because of practical problems of sampling. Techniques used in the laboratory, e.g. areal sampling by adhesives are unsuitable for large gravels in the field.

All particle sizes of a bed material are also found in an armour layer in greater or lesser proportion. Thus there is no clear distinction between particle sizes that move and those that do not. The absence of such distinction creates a problem in choosing suitable 'characteristic' parameters to describe a non-uniform size distribution. A uniform sediment can be adequately described by the median particle size, $d_{50}$, but this is quite inadequate for a non-uniform sediment.

Armour particles tend to arrange themselves in a definite pattern, with their flatter faces sloping upward in the downstream direction like shingles on a roof. The shingling pattern is caused by fluid forces acting on the non-spherical particles. The effect of particle shape on armouring is significant. There are two main difficulties associated with particle shape. Firstly, the dynamics of particle movement involve several regimes of behaviour. Secondly, there is no direct method to measure shape.

In view of the many factors associated with armouring it is not surprising that no generally accepted armouring model is available. Existing models derived from laboratory studies give widely different results. Agreement with field data is even more remote. This is partly because there is no basis to ascertain if a particular flow in relation to the amroured bed is critical or not, the bed may be at the critical condition, but the flow may not, as is evident in data by Lane and Carlson (1953). The existing laboratory data are limited both in particle size composition and flow condition especially at relatively higher flows. The main objective of this study was to improve the understanding of the behaviour of non-uniform sediments and to define a criterion for the critical armouring condition.

## EXPERIMENTS

All experiments were carried out in a glass-sided flume with dimensions of 0.45 m wide, 0.44 m deep and about 19 m long. A false floor of 130 mm depth and constructed of sheetmetal was installed in the flume. The false floor extended throughout the length of the flume except the 1 m long sediment recess into which the sediment mixture was placed. The approach bed was roughened by attaching sediment particles corresponding to the coarsest fractions of the mixture under study.

The sediment recess was sited about 11 m from the upstream end of the flume this length being adequate for flows to be fully developed. A vertically adjustable table which supported the sediment, was installed within the recess. The initial bed level was made flush with the bed upstream. This bed level was maintained throughout an experiment by continually adjusting the table upwards. Thus the bed shear stress remained constant throughout an experiment.

The bed shear velocity was determined from the velocity profile measured on the centreline of the flume. The lower portion of the flow depth exhibited a log-normal velocity distribution and was used to determine the shear velocity based on the Von Karman constant of 0.4 and a depth datum of 0.7 $d_f$ above the sheetmetal surface where $d_f$ is the median particle size of the roughened elements. The datum was chosen because it gives the best log-normal velocity profiles near the bed boundary so that the shear velocity could be clearly established. Nine mixtures were used and are shown in Figure 1. At the end of each experiment, the armour bed was sampled areally with wax and its composition determined.

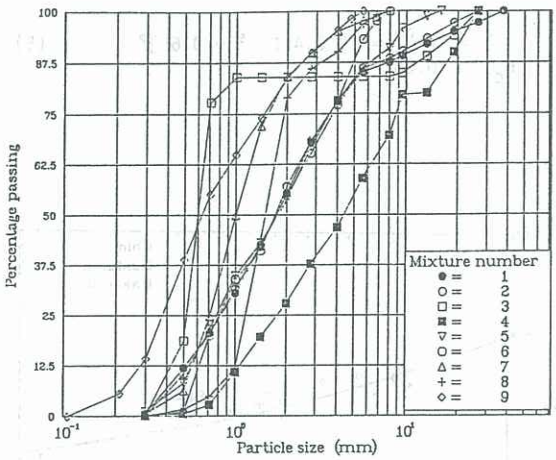


Figure 1. Bed Material Composition

## Threshold of movement

Conventional analysis of the threshold of particle movement of uniform material yields the following expression for the dimensionless shear stress $\theta_c$.

$$\theta_c = \frac{\tau_c}{(\gamma_s - \gamma)d} = \alpha \tan \phi \qquad (1)$$

where $\tau_c$ is the shear stress, d is particle size, $\gamma_s$ and $\gamma$ are specific weights for solid and fluid, $\alpha$ is packing coefficient and, $\phi$ is angle of repose. Shields (1936) showed that $\theta_c$ is a function of the particle Reynolds Number, $Re_*$ and is independent of $Re_*$ for large values of $Re_*$. For uniform bed particles, $\phi$ is well defined and is constant. However, the average $\phi$ value for a layer of armour particles is not constant, being a function of the relative size of the armour particles to the particles underneath.. Thus for an armour layer, with coarse particles such that $\theta_c$ is independent of $Re_*$,

$$\theta_a = \frac{\tau_c}{(\gamma_s - \gamma)d_a} = \frac{u_*{}^2a}{(S_s-1)gd_a} = f\left(\frac{d_a}{d_b}\right) \qquad (2)$$

where $\theta_a$ = dimensionless shear stress of armour layer
$d_a$ = effective particle size of an armour layer
$d_b$ = effective particle size of parent bed material
$S_s$ = specific gravity of particles
$u_{*a}$ = armour shear velocity

Suppose $d_a$ and $d_b$ can be represented by the median particle size $d_{50a}$ and $d_{50}$ respectively and assume that the sediment is coarse, so that equation (2) becomes

$$\theta_a = \frac{u^2_{*a}}{(S_s-1)gd_{50a}} = f\left(\frac{d_a}{d_b}\right) \qquad (3)$$

At the critical armouring condition, ie. the most resistant armour,

$$\theta_{ca} = \frac{u_{*ca}^2}{(S_s-1)g(d_{50a})_{max}} = f\left(\frac{(d_{50a})_{max}}{d_{50}}\right) \qquad (4)$$

where the subscripts 'c' and 'max' represent critical and maximum values respectively.

## RESULTS AND DISCUSSION

In order that an armour layer can form, erosion of bed particles must occur. The depth of erosion at which a bed surface becomes stable for a given flow is called the equilibrium depth, $d_{se}$. Figure 2 shows a typical plot of the development of depth of erosion with time. The general trend, as with

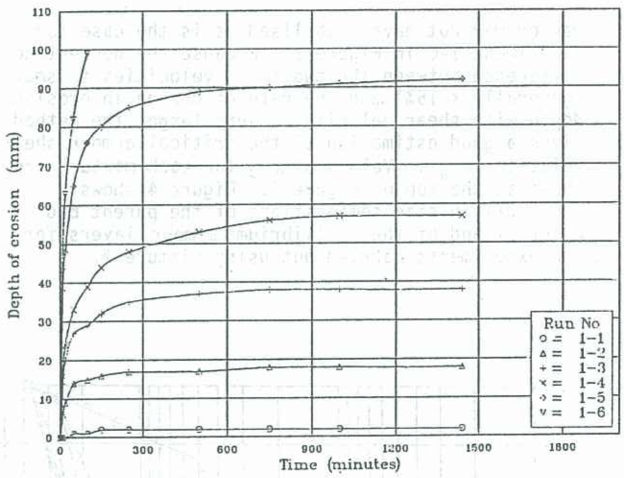


Figure 2. Development of depth of erosion with time for Mixture 1. Shear velocity increases in direction of increasing erosion depth

all other mixtures, is that the depth of erosion increases rapidly during the initial stages, and the equilibrium depth is approached asymptotically. The six curves shown each represents an experiment conducted at a different armour shear velocity, $u_{*a}$. The depth of erosion increases with $u_{*a}$.

Experiment 1-6 was stopped when the depth of erosion was about to reach the depth of the sediment bed. At this stage it was uncertain whether the bed could be armoured or not. Figure 3 shows the equilibrium depth of erosion as a function of $u_{*a}$, for all the mixtures. For each mixture, there is a lower limiting value of $u_{*a}$ required to cause erosion and produce armouring. This value increases with the median particle size of the bed material, $d_{50}$. As the armour shear velocity, $u_{*a}$ increases the equilibrium depth of erosion increases gradually at relatively lower values, then much more rapidly, and eventually for each mixture a critical armour shear velocity is reached which corresponds to an infinite depth of erosion ie. no stable armour layer can be developed. In this study, the critical shear velocity for each mixture is defined as the average value of two experiments - one corresponds to the maximum depth of erosion that can be measured in the flume, and the other slightly greater. For the larger flow, the bed

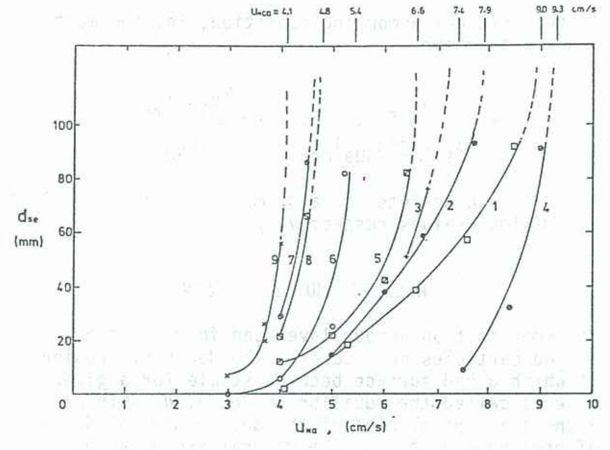


Figure 3. Depth of erosion as a function of shear velocity (mixture numbers are indicated)

may or may not have stabilised as is the case for experiment 1-6 in Figure 2. Because the percentage difference between the two shear velocities is small (generally < 15%) and the rate of change in erosion depth with shear velocity is very large, the method gives a good estimation of the critical armour shear velocity, $u_{*a}$. Values of $u_{*a}$ for each mixture are shown at the top of Figure 3. Figure 4 shows the particle size compositions of the parent bed material and of the equilibrium armour layers for the experiments carried out using mixture 1.

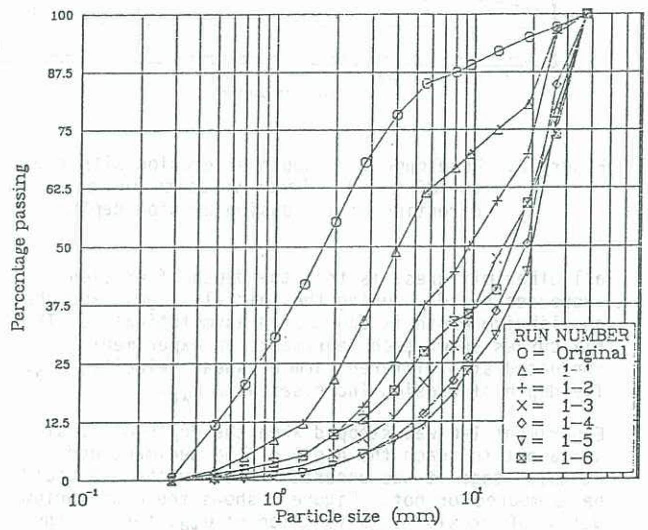


Figure 4. Variation of armour grain size distributions with shear velocity for a given size original mixture (mixture 1.)

The parent material was sampled volumetrically while the armour layer was sampled areally. There are problems related to these two sampling techniques which are still unresolved. The samples obtained were used directly without conversion, in order to avoid introducing uncertainty. The curves of the armour distributions rotate about two pivot points - the maximum and minimum particle sizes, $d_{max}$ and $d_{min}$ respectively, and skew progressively towards the right with increasing $u_{*a}$ until $d_{max}/(d_{50a})_{max}$ reaches 1.8 at the critical armouring condition. A similar value for this ratio was obtained with the other sediment mixtures studied. The critical value corresponds to a value of $d_{84a}/d_{50a}$ equal to about 1.5 - a criterion which is used to distinguish uniform and non-uniform materials, where $d_{84a}$ is the armour particle size with 84% finer. A summary of the experimental results is available in Chin (1985). Figure 5 is the plot of $\theta_{ca}$ versus $(d_{50a})_{max}/d_{50}$ (called $\Gamma$) and shows the functional relationship of equation (4). The curve in figure 5 can be described by

$$\frac{\theta_{ca}}{\theta_c} = \frac{\theta_{ca}}{0.05} = [\ 0.4\ \Gamma^{-0.5} + 0.6\ ]^2 \qquad (5)$$

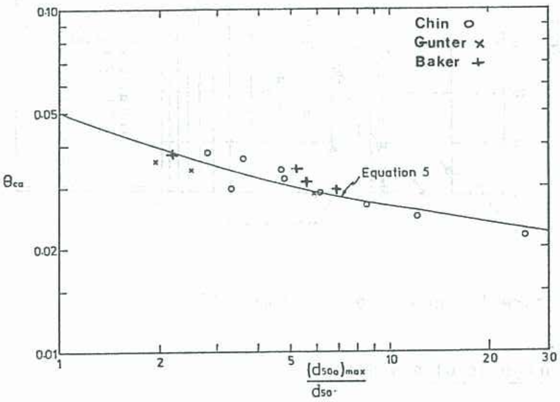


Figure 5. Variation of dimensionless shear stress, $\theta_{ca}$ with relative maximum mean armour particle size $(d_{50a})_{max}/d_{50}$

Since $d_{max}/(d_{50a})_{max}$ approaches 1.8, $\Gamma$ can be rewritten as $d_{max}/1.8\ d_{50}$. This means that for a given $d_{max}$, a bed material with a smaller $d_{50}$ (ie. larger $\Gamma$) has a lower critical resistance than that of a larger $d_{50}$ (ie. smaller $\Gamma$). This is consistent with the fact the former requires more degradation in order to accumulate sufficient stable coarser particles than the latter. This can be illustrated by mixtures 2 and 4 in Figure 3 in which mixture 2 being a relatively finer material always has a correspondingly larger $d_{se}$ than mixture 4 for a given flow or alternatively, for a given $d_{se}$, the former always has lower $u_{*a}$ than the latter.

## CONCLUSIONS

The stability of an armour layer can be described by equation (3) and the critical armour layer by equation (4). The functional relationship of equation (4) is shown in Figure 5.

The $d_{max}/d_{50a}$ value decreases as $u_{*a}/u_{*ca}$ increases and reaches a minimum value of 1.8 at the critical armouring condition. The minimum value corresponds to a value of 1.5 for geometric standard deviation of the mixture (defined by $d_{84}/d_{50}$) which has been used as a criterion for the boundary between uniform and non-uniform mixtures.

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