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**LA THÈSE A ÉTÉ  
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Laboratory Investigation of  
Stream-bed Armouring Under Known Conditions  
of Upstream Sediment Input

by

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Submitted in Partial Fulfillment  
of the Requirements for the Degree of  
Master of Applied Science

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Preface

It can be of great economic importance to be able to predict effectively and to utilise the self-stabilizing tendency of alluvial channels. This phenomenon, known as stream-bed armouring, governs whether or not an open channel may be intrinsically resistant to excessive erosion or may require added structures to ensure long-term stability. Current engineering practice may apply knowledge of armouring to problems in river morphology, as well as erosion in artificial channels used for irrigation, navigation, and hydropower.

A typical case where such a problem may be of significance is in open channel construction. If a new channel can be designed so that stabilizing structures such as bottom linings are not necessary, costs may be lowered. Another example may be found in dam construction. When a dam is placed across an existing stream, erosion below the dam is increased. It is important that the extent of this increased erosion can be predicted so that if required, remedial measures can be planned before, rather than after, the fact.

Existing research has, in general, considered armouring under hydraulic influence only, with zero upstream sediment input. Knowledge of how armouring may be influenced under a broader range of conditions (i.e. with sediment input) may point out areas where current empirical formulae

can be improved for application to engineering problems.

It was intended that this research would help fill gaps in current understanding of the armouring phenomenon, as well as point out areas for further research.

Experiments were conducted which compared the final, armoured bed produced by sediment-free and by various sediment-laden flows of water. The sediment-laden water contained graded sediments of known composition which were transportable under existing hydraulic conditions, and which varied in size. Conclusions about the basic ways the sediment influenced armouring are made and further research is suggested.

In general, it was found that an armoured bed produced by sediment-laden water may differ materially from that produced by sediment-free water. Basic parameters such as amount eroded, roughness, and size composition of the armoured layer may all vary with the sediment input. The mechanisms of armouring vary with the properties of the sediment input and are related to the associated bedforms. This variation is significant and implies that empirical formulae could indeed be improved by consideration of the presence or absence of upstream sediment input. It is therefore suggested that research should be conducted to

refine further knowledge of this influence, and that  
the resulting information be considered for modification  
of existing empirical relationships.

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Notation

- A - Large particle axis
- b - Channel width
- B - Intermediate particle axis
- C - Small particle axis
- D - Characteristic grain size
- $D_n$  - Diameter which is greater than n% of the particles in the sample
- $D_s$  - Sieve diameter
- $D_{50}^n$  - Armoured  $D_{50}$  occurring with size n sediment input
- $D'_{50}$  - mean ( $D_{50}^n/D_{50}^0$ )
- $F^*$  - Shield's dimensionless shear parameter
- $k_1$  - B/A
- $k_2$  - C/B
- n - Mannings n
- $P_a$  - Size distribution of the armour coat
- $P_o$  - Probability density function of a mixture
- q - Probability that a particle remains in the mixture
- Q - Volume rate of flow
- R - Hydraulic radius
- S - Slope
- $\Delta'$  - (Erosion depth with input/erosion depth, no input)
- $\gamma$  - Specific weight of water
- $\gamma_s$  - Specific weight of sediment particles
- $\sigma$  - Standard deviation
- $\sigma_c$  - Standard deviation of critical shear stress

Notation (Cont'd)

$\sigma$  - (Armoured layer  $\sigma$ , with input/armoured layer  $\sigma$ ,  
no input)

$\tau_c$  - Critical shear stress

$\bar{\tau}$  - Mean shear stress

$\bar{\tau}_c$  - Mean critical shear stress

## 1.0 Introduction

For some time, it has been recognised that when water flows over widely graded alluvial beds at velocities high enough to induce movement of the smaller sized bed particles, but not so high as to erode all the bed material, a stable armoured layer will be formed. This layer occurs as smaller sized bed particles are removed from the surface of the bed by erosion. The layer is somewhat coarser than the original bed distribution and does much to slow or halt erosion in such channels.

Armouring is thus the result of selective erosion of finer fractions of a bed of aggregate by a flow lower than that required to induce a general movement of all bed materials. The smaller particles are removed to a greater extent than the larger so the net effect is that the armoured surface coarsens during formation. This is not to imply that all of any given fraction is removed. On the contrary, there is always some part of any given fraction which is eroded and some part which remains. For example, particles which are smaller than the critical size implied by hydraulic conditions may remain stable if protected by larger particles. Similarly, large particles which would otherwise remain in place might be dislodged if they are oriented in a way which makes them susceptible to flow, or if they are struck by smaller moving particles.

Armouring initially progresses rapidly, with a high rate of sediment transport, as exposed fine particles are removed by the flow of water over the bed. The rate of erosion gradually decreases, as the particles which are more sheltered are eroded. The rate of erosion finally drops to zero, and the final stable armoured layer remains. This layer will remain stable as long as flows are at or lower than the original armour-producing flow.

Considerable effort has gone into investigating some of the mechanisms governing the armouring process. However, little or no research has been conducted to investigate specifically the effect of sediment carried by the water as it passes over the stream bed during or after armoured layer formation. In fact, great care is normally taken to remove any traces of such sediment during an experiment. Since it is most likely that natural streams will contain some sediment, particularly in cases where a stream is undergoing the armouring process, this effect should be considered. This is especially so when empirical or semi-empirical results may be used to predict the outcome of an actual physical occurrence.

It was the object of this research to investigate some aspects of the influence of sediments carried in water on the armouring process.

The scope of this investigation includes:

- a) An examination of some of the basic physical parameters of the armouring phenomenon;
- b) Correlation of data and observations so as to suggest ways in which a sediment input might influence armouring; and
- c) An evaluation of data, observations and conclusions with an aim to identifying possible avenues for future research.

## 2.0 Literature Review

Armouring has been under investigation for some time. In 1950, Harrison (10) examined sediment loads associated with stream bed degradation and in particular investigated particle segregation under flows where not all bed particles are removed. He observed in part that under such conditions a stable surface layer is formed as erosion of finer particles progresses. The layer is composed of the remaining coarse bed particles and is arranged in a "shingled" formation which "paves" the bed and protects it from further erosion. He also noted that the rate of sediment transport over such a bed is proportional to the extent of accumulation of non-moving particles, and that the rate of transport decreases over time. Harrison's preliminary work showed armouring could occur in conjunction with dunes due to recirculated sediment, and showed sediment discharge to be less from the armoured bed than from the non-armoured bed. He also presented an analysis to indicate the grain sizes that take part in the armouring process and the ultimate depth to which a bed degrades.

Gessler ( 7 ) pointed out the importance of self-stabilizing channels, and the need for a method of predicting the nature of the final armoured bed as well as for determining what conditions will result in an armoured bed. Based on observed behavior of bed armouring, he proposed a

probabalistic approach to the armouring phenomenon. He stated that for armouring purposes, bed shear stress completely described hydraulic conditions, and related the probability that a particle would move to the relationship between the bed shear stress and particle critical shear. As conceived by Gessler, the sediment removed from the bed is at a distribution constant over time. This is suggested by the nature of the process. If the bed material is homogeneous, then the erosion of any particle will encover a surface identical to that which existed in the beginning. Thus, the probability of particle motion at the uncovered spot is constant, and since hydraulic conditions do not change, the nature of the eroded material is constant. Only the rate of erosion, determined by the amount of non-armoured bed remaining, will change.

Armouring is most common in broadly distributed sediments, since as the distribution of particles in a bed narrows, the difference between armoured and unarmoured bed decreases. There is some evidence that sediment gradations with standard deviations below certain limits will not armour. Little and Mayer (17), who attempted to extend Gessler's work, and examined the effect of gradation on armouring, determined that sediment distributions with geometric deviations less than 1.3 cannot armour. However, Kellerhals and Church (13) have indicated Little

and Mayer's work did not consider other important field and laboratory results and that some of their assumptions are possibly incorrect.

Day (4) examined armouring with steeper slopes and coarser bed material size fractions, and has to date studied armouring over a range of shear stresses. Current findings are that resistance relationships become non-linear as slopes become large.

The concepts of Grass (8) on initial bed instability, which consider that the individual grains of a bed are subjected to a distribution of shear stresses, were extended by Sutherland and Williman (23,25). They visualized a critical stress distribution for each fraction of a graded material, and noted that this precludes the definition of a particle size which defines erodible and non-erodible fractions of a bed. With this concept, all particles of a graded sediment would have some probability of either remaining in place or being eroded.

Garde et al (6) have considered the time-dependency of armouring, stating that the major coarsening of an armoured bed occurs quickly, and that subsequent armouring occurs extremely slowly. They propose a modification of Gessler's method to predict surface layer characteristics over time.

Kellerhals et al (14) examined the problem of sediment distributions and proposed a means of deriving the sieve distribution of an aggregate sample by using transect length distributions. Such methods have successfully applied in practice by Sutherland and Williman (23, 25)

Many authors have investigated the motion of sediment. Shields (20) in his classical study proposed a beginning of motion function based on shear stress and on particle resistance to motion. Shields' results were obtained from artificially flattened beds of non-cohesive sediments (20). Egiazaroff (5) suggested a modification of the Shields criteria to account for the sheltering effect of particles in a distributed sediment. As noted above, Grass (8) also investigated this phenomenon.

No research has yet been undertaken which specifically examines the inter-relationships between armouring and a known sediment load in the water. However there are some supportive results in a number of related papers. Of primary interest is the work by Hooke (11), who compared the results of water flowing over fine sand to water flowing over a similar bed of sand covered by a single layer of coarse granules. He noticed that granules tended to accumulate in troughs between dunes, and that a stable layer of granules tended to form. The dunes were observed to move over this layer, covering it and

uncovering it. Where troughs were deep, eddies were sometimes strong enough to dislodge the granular particles, and erode the granular layer.

Meland and Norrman (19) examined sediment transport velocities, and noted that large particles tended to sort out of the transported mixture, and tended to accumulate in dune troughs.

Finally, Gunter (9) considered the critical mean bed shear stress for a mixed bed. His study revealed longitudinal grooves in the transported bed load similar to those observed during the course of these experiments.

This thesis attempts to progress from the findings of the above researchers, and begin an investigation into this new area.

### 3.0 Theoretical Considerations

#### 3.1 Characterising the Armoured Layer.

The most critical aspect of this set of experiments lies in accurate evaluation of characteristic armoured layer parameters.

Such parameters as surface roughness and slope are sufficiently well established that little difficulty arises in determining proper techniques for measurement or evaluation. Measurement techniques for these parameters are summarized in Section 4.10. However, the measurement of the actual size distribution of the armoured layer requires consideration of special techniques. The layer is characteristically only one particle diameter thick, and the usual volume and sieve methods are therefore only applied with difficulty.

Consequently, a number of techniques have been used to sample the armoured layer. Greased pads pressed to the surface will remove the armoured layer, and melted wax poured over the surface will do the same. Samples may be physically removed from the surface one at a time, according to some pattern, or even photographed in situ and measured from the photo. However, these methods all have limitations. As shown by Day (4), grease pad and wax techniques are physically difficult. For example, wax tends to penetrate excessively, and remove sub-surface particles. Point sampling is impractical for small sediments, as are photographic

techniques. In addition, as noted by Kellerhals (12), measuring mass or volume distributions of a sample collected over an area requires corrections to distribution not normally considered. Further discussion of these problems may be found in Kellerhals (12) and Williman (25).

A transect length method of sampling and measurement was used in this set of experiments. Kellerhals (12) examined the problem of sampling sediments over points, lengths, areas, and volumes, and has suggested that suitable distributions may be derived from these samples in a number of ways. For transect samples, distribution by length measurements will establish a representation of aggregate characteristics which is unbiased relative to standard weight by volume distributions. However, the problem of converting the transect sizes to common measures such as sieve size still remains.

Kellerhals related sieve size to three transect axis length measures, defined as shown in Figure 1; apparent major axis, apparent minor axis, and longest axis in a given direction. These measures may be used to produce equivalent sieve size distributions, as follows.

#### Sieve Sizes From Longest Axis in a Given Direction

According to Kellerhals, there is a high correlation between the distribution measured and the actual sieve distribution.

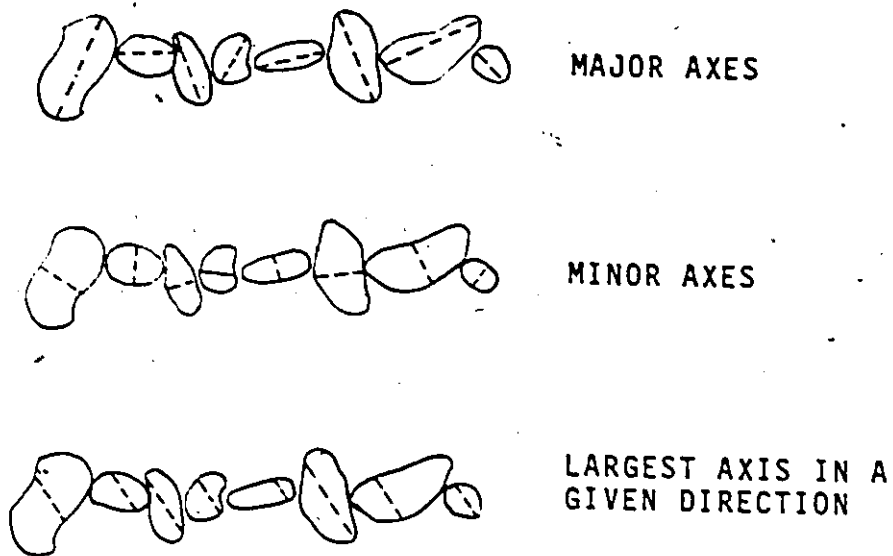


FIG 1. PARTICLE MEASUREMENT AXES

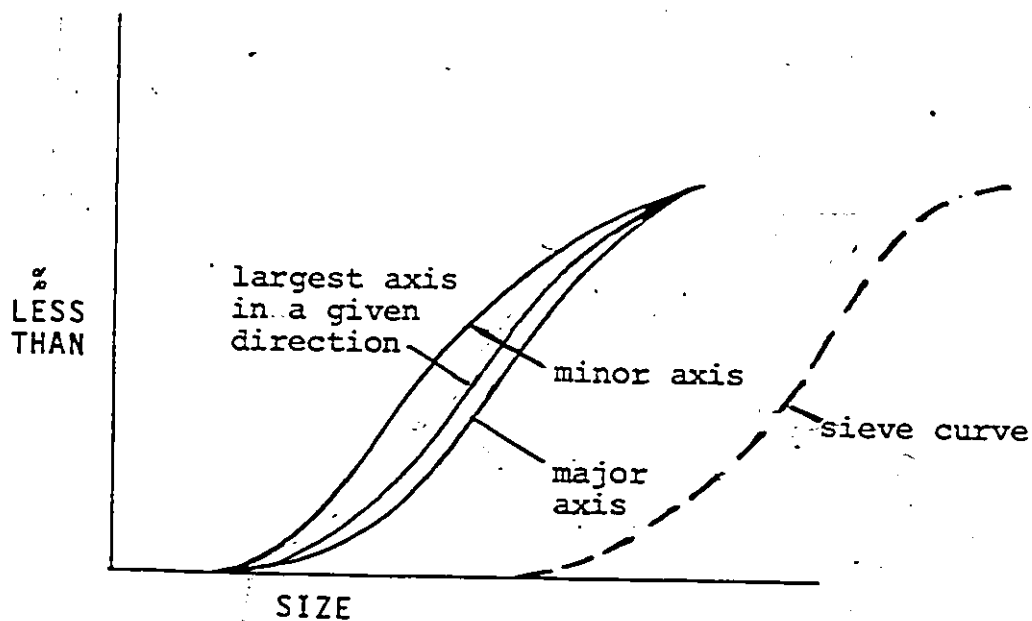


FIG 2. HYPOTHETICAL RELATION BETWEEN SIEVE SIZE AND MEASURED TRANSECTS

The measured distribution of this axis may therefore be taken directly to approximate the actual sieve distribution of the sample.

Sieve Sizes From Major/Minor Axis

Measuring major and minor axes produces distributions as shown in Figure 2. The equivalent sieve distribution is related to these two distributions by factors which may be determined directly from particle size measure (k1 and k2, described below). As stated by Kellerhals, the relationships between particle axes and sieve size may be considered as follows:

$$A = \frac{2}{k_1} (2(1+k_2^2))^{-\frac{1}{2}} D_s \dots\dots\dots 1.$$

$$B = 2(2(1+k_2^2))^{-\frac{1}{2}} D_s \dots\dots\dots 2.$$

$$C = 2(k_2) (2(1+k_2^2))^{-\frac{1}{2}} D_s \dots\dots\dots 3.$$

where Ds - sieve diameter

A - major axis length

B - intermediate axis length

C - minor axis length

k1 = B/A

k2 = C/B

Measuring k1 and k2 from actual particles allows conversion of A, B, or C sizes to sieve sizes.

The relationship between sieve distributions and particle axis distributions is therefore quantifiable. As such there exists a means of experimentally determining the equivalent sieve distribution of the armoured layer from transect measurements.

3.2 Armouring Phenomenon

An examination of current analyses related to particle motion is helpful in gaining insight into the nature of the armoured layer.

Since armouring results from the removal of particles from the surface of the bed, beginning of motion criteria are significant to the occurrence of armouring. The Shields (14) criteria for the initiation of motion, relates a parameter  $F^*$  (the entrainment function) to the beginning of motion:

$$F^* = \frac{\tau_c}{(\delta_s - \delta) D_s} \dots\dots\dots 4.$$

Where  $\tau_c$  is the critical shear stress  
 $\delta_s$  is the particle specific weight  
 $\delta$  is the specific weight of water  
and  $D_s$  is the particle characteristic diameter

This parameter, the dimensionless shear stress, is in fact a ratio of drag force to gravitation force. Thus, Shields related particle motion to shear from the fluid and to the size and mass of the particles.

Egiazaroff ( 5) considered the sheltering effect of larger particles in a mixture, and modified the Shields beginning of motion criteria to reflect the effect of size variation in a mixture. He produced a relation in the form:

$$\frac{\tau_c}{(\gamma_s - \gamma) D_{50}} = \frac{0.1}{(\log \frac{D_{50}}{D_n})^2} \dots\dots\dots 5.$$

Where  $D_{50}$  is the median size of the sediment  
 $D_n$  is the average sediment diameter

A similar concept proposed by Grass (8), considers that the random shape, weight and placement of individuals of each size fraction will cause each particle to have a critical shear stress which is expressed as some probability distribution. He deduced that for particle motion,

$$\bar{\tau} = \bar{\tau}_c - z\sigma_c - \sigma \dots\dots\dots 6.$$

- where  $\bar{\tau}$  - mean applied shear stress
- $\bar{\tau}_c$  - mean critical shear stress
- $\sigma_c$  - standard deviation of critical shear stress
- $\sigma$  - standard deviation of applied shear stress
- $z$  - a factor relating applied and critical stresses

Thus, it has become recognized that variations in particle tendency to move are important in determining the removal of particles from the channel bed.

Researchers into the armouring phenomenon also related the armoured layer to particle motion. Gessler (7) has suggested

that if we assume shear stress fluctuations are normally distributed, then the probability that in a given flow the local shear stress acting on an individual grain is smaller than the critical shear stress of that grain is:

$$q\left(\frac{\tau}{\tau_c} < 1\right) = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{\left(\frac{\tau_c}{\tau} - 1\right) \frac{\tau_c}{2\sigma}} \exp\left(-\frac{x^2}{2\sigma^2}\right) \cdot dx \quad \dots\dots 7.$$

in which x is a dummy variable, and the critical shear stress of a particle  $\tau_c$  is obtained from the Shields diagram. For coarse material, the standard deviation of shear stress fluctuations  $\sigma$  was determined experimentally to be equal to  $0.57 \bar{\tau}$ .

If the initial bed grain size distribution is:

$$p_o(k) = \int_{k=k_{\min}}^k p_o(k) \cdot dk \quad \dots\dots\dots 8.$$

then the grain size distribution of the armoured coat is:

$$p_a(k) = \frac{\int_{k_{\min}}^k q \cdot p_o \cdot dk}{\int_{k_{\min}}^{k_{\max}} q \cdot p_o \cdot dk} \quad \dots\dots\dots 9.$$

where q is as defined by equation (7), and k is the grain size.

The nature of the final armoured layer is seen to depend on the threshold of motion for each particle and on the shear imposed by the flow of water, and it is recognised that the fluctuation in applied shear stress may be of fundamental importance to particle motion.

It is clear that the relation between particle resistance and motive force is complex. For purposes of this work, the important point to be gained from previous research is that particle motion is dependent on both:

1. Particle susceptibility, and
2. Fluid motion.

A variation in either property might therefore be expected to alter the nature of particle motion in the bed material.

## 4.0 Experimental Method

### 4.1 General

The influence of sediment on the armouring process was evaluated by comparing armoured layers created with and without sediment input in the water as armouring occurred.

A tilting recirculating flume owned by the Geological Survey of Canada was used to conduct experiments, and the bed material was obtained from local sources. Flow and slope in the flume were set to produce a stable armoured bed. For the first experimental run, sediment-free water was circulated through the flume, and the resulting armoured layer was measured. The experiment was then repeated under various conditions of controlled sediment input, with bed material replaced and hydraulic parameters held constant for each run.

A direct comparison of results could therefore be considered to reflect any influence input sediment might have on the armoured layer.

### 4.2 Experimental System

The system used is represented in Figure 3, and pictured in Figures 4, 5, 6 and 7. The flume has a tilting bed, with a channel section 18.3m long, 0.76m wide, and 0.6m deep. Pumps operate at constant speed, with control achieved by means of bypass valves. It was found that the

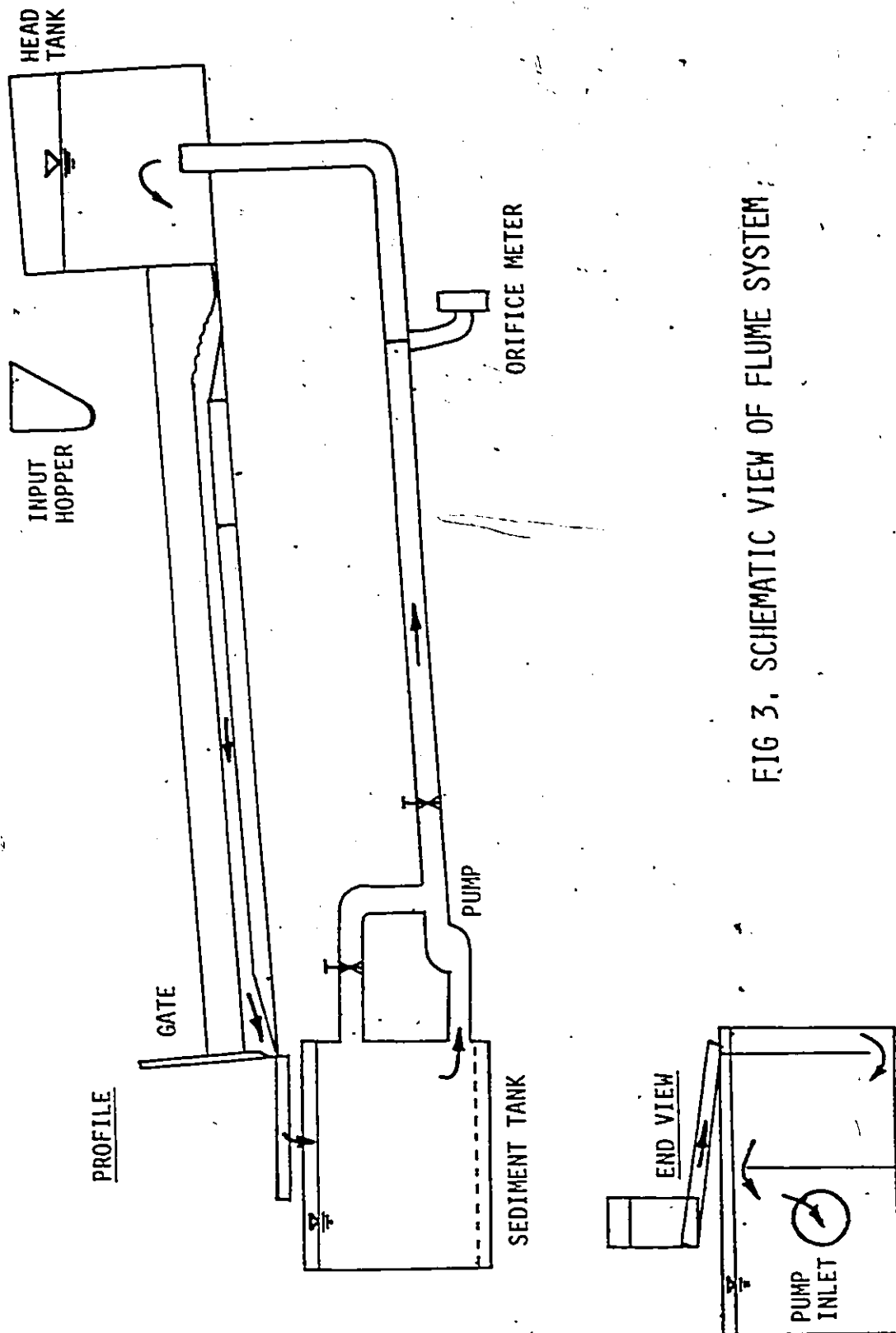


FIG 3. SCHEMATIC VIEW OF FLUME SYSTEM ;

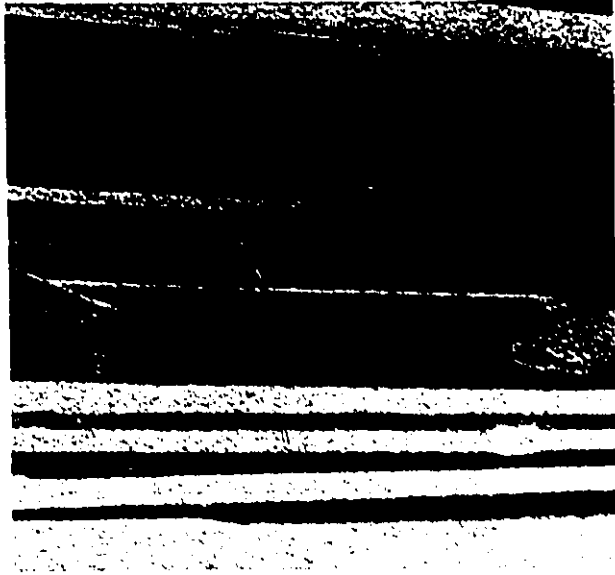


Fig. 4 UNDERFLOW GATE



Fig. 5 INPUT HOPPER

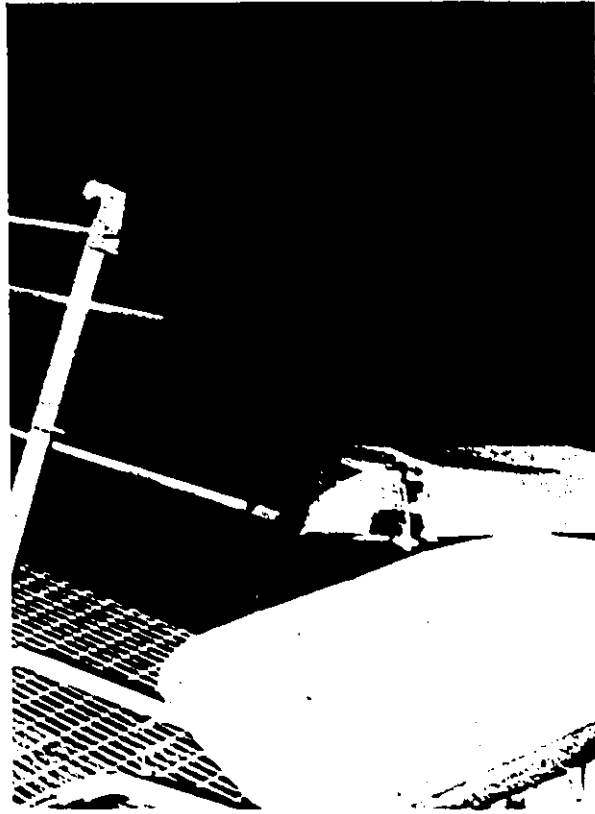


Fig. 6 STORAGE BINS AND CONVEYORS

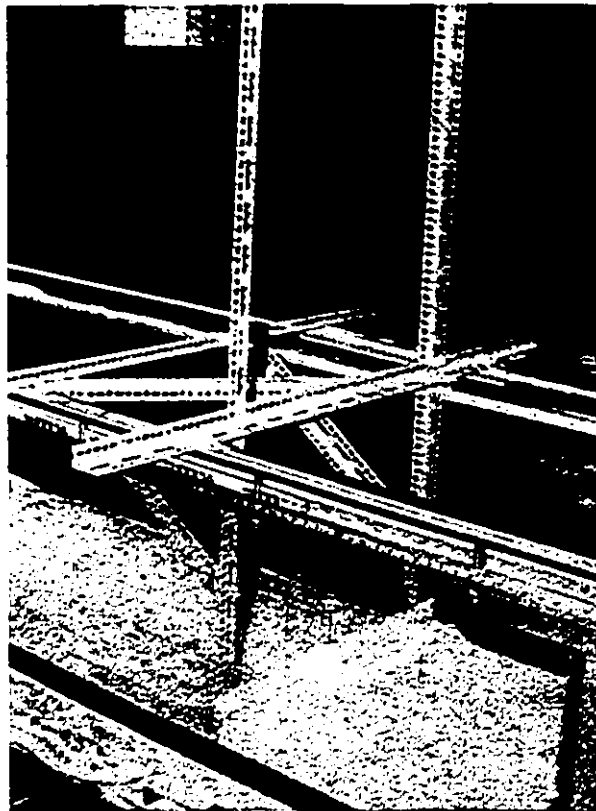


Fig. 7 SLIDING SAND SPREADER

system produced highly constant flows throughout the duration of any experimental run, provided that the head provided by the tank was kept constant. Flow measurements were achieved by a calibrated orifice meter coupled to a mercury manometer. The flume is described more completely by McDonald (18).

The sediment trap below the end of the flume was designed to remove sediment from the recirculated water. In this way, water flowing over the bed was known to contain only the sediment of known composition introduced from the hopper at the top of the flume. The hopper was capable of inputting sediment at a constant rate and even distribution across the flume (Figure 5). At the top of the flume, a heavy steel mesh combined with hand laid cobbles served to establish developed flow conditions quickly.

The sand covered a stretch of flume from approximately the 4m point to the 16m point (measured from the upstream end of the flume), and a working section from 6m to 14m. was used in measuring and sampling. Sand was input at the 1m point.

#### 4.3 Bed Description

A siliceous aggregate with a broad distribution was used as bed material. Based on a compromise between the desired bed properties and the availability of local aggregates of suitable quality, it was found that the best distribution was achieved by mixing several (three) size ranges of aggregates. Aggregates were obtained from local distributors of construction materials. Concrete sand, crushed stone, and bagged sand were found to be available in sizes which could be mixed to produce the required distribution, and analysis (described in Section 5.0 ) showed the various aggregate types to have compatible physical characteristics (shape, specific gravity)

The loose material (sand and gravel) was brought to the laboratory in a single load. This ensured that variations in distribution between different production lots were avoided. The bagged sand was ordered separately but also in a single lot. All bed material required for the entire experiment was mixed at one time, and stored in bins near the flume (Figure 6).

A total of 12000 Kg of aggregate was mixed 100 Kg at a time, using a portable revolving cement mixer. Aggregate proportions were measured by weighing quantities on a balance scale. The relatively small units used to measure

proportions, and the method of mixing and storing the bed material helped to ensure a homogeneous mixture. The final distribution was verified by subsequent sieve analyses, and appears plotted in figures 8 and 9.

A bed aggregate with a  $D_{50}$  of 0.6 mm and a size limit of about 7mm was produced. It was found that armour-producing flows were at a depth small enough that side-wall effects were minimized. In fact, a width:depth ratio of approximately 25:1 was used, making any requirement for side-wall corrections unnecessary.

#### 4.4 Hydraulic Conditions

To determine suitable hydraulic conditions for the experiment, preliminary work was undertaken on two smaller University of Ottawa flumes. This preliminary work was done to facilitate setting up the actual experimental conditions and to provide a basis for ordering materials. This was important, since all aggregates were ordered in batch lots.

Two flumes were used at the University of Ottawa. The first was a level bed flume 0.61 m wide, and 2.13 m long. The second was a tilting flume 0.3 m wide and 9.1 m long.

A bed of aggregate similar to that ultimately used in the main flume was prepared in the first flume, and flow was begun at a low level. Flow was increased until movement of particles at approximately the  $D_{75}$  (1mm) size was observed.

This flow was maintained, and it was noted that an armoured layer finally formed.

In the second flume, flow and slope were set to approximate conditions encountered in the first flume. For reasons of convenience, an aggregate bed was not used. Instead, a roughness element 2.7 m long was prepared by cementing coarse aggregate to a board and securing the board to the bottom of the flume. This approximated the roughness encountered during work in the first flume. Aggregate was then introduced above the element, and the sediment carrying capacity of the flow per unit width was established. It was therefore possible to estimate how much input sediment would be used over time in the subsequent tests.

In the main flume, slope and flow were set to duplicate conditions encountered in the preliminary work, and an aggregate bed was used. An armoured layer was again the result, so conditions were considered suitable for the remainder of the study. A slope of 0.005m/m and a flow of  $1.65 \times 10^{-2} \text{ m}^3/\text{s}$  were used.

#### 4.5 Flume Loading

Bed aggregate was moved from storage bins to wheelbarrows on the flume deck with electric conveyor belts (Figure 6). It was then shovelled into the flume by hand, remixed, and

levelled using a sliding sand spreader (Figure 7). Sand was maintained in a slightly moist condition throughout, to help prevent segregation. This system for handling aggregate produced a consistent and uniform flat bed of known slope and elevation.

On startup, water was introduced to the bed very gradually to eliminate the possibility of stratification; this took approximately 20 minutes. It was found that saturating the bed produced a uniform drop in surface level of 1.0 mm.

#### 4.6 Input Sediment

Input was limited to a sediment composed of particles similar to those comprising the bed material. For simplicity, and in accordance with experimental objectives, the inputs were of sands with narrow distributions and were varied, as nearly as possible, only in size. Input sediments were from commercially available silica sands. Sands were selected to cover a range of sizes which could be transported under existing hydraulic conditions. The relation between input sediment and bed material is shown in Figure 10. As shown, the input sizes were equivalent to a range of fractions present in the bed material.

#### 4.7 Removal of Input Sediment

Sampling of the armoured layer was impossible with deposited input sediment remaining in situ above the armoured layer. Not only did the input sediment cover the layer, but

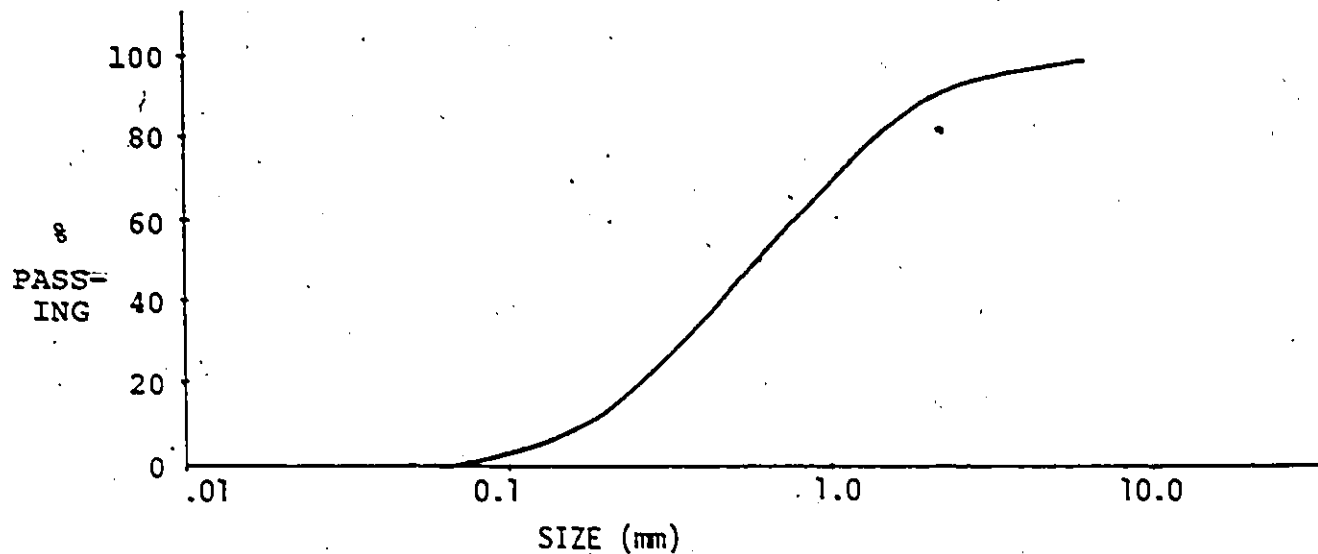


FIG 8. FINAL MIXED BED MATERIAL DISTRIBUTION (SEMI-LOG PAPER)

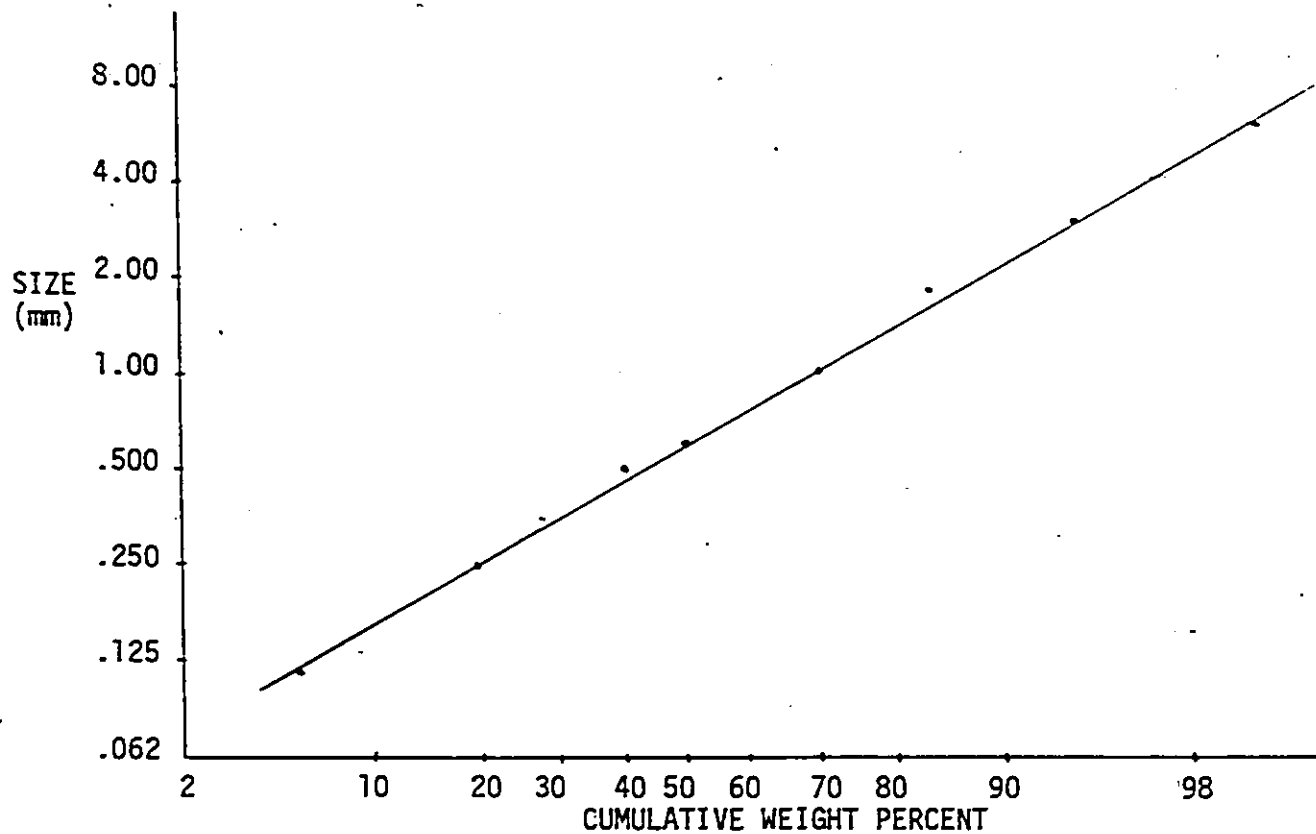


FIG 9. FINAL MIXED BED MATERIAL DISTRIBUTION (LOG-NORMAL PAPER)

Figure 10 - SIZES OF INPUT SAND

<u>RUN NUMBER</u>	<u>INPUT SAND SIEVE SIZE</u>			<u>RELATION TO BED MATERIAL</u>
	D <sub>16</sub> (mm)	D <sub>50</sub> (mm)	D <sub>84</sub> (mm)	(Equivalent bed size of D <sub>50</sub> of input)
1	-	-	-	N/A
2	.13	.16	.21	D <sub>8</sub>
3	.33	.43	.54	D <sub>38</sub>
4	.33	.50	.66	D <sub>42</sub>
5	.34	.60	.83	D <sub>50</sub>
6	.90	1.20	1.60	D <sub>75</sub>

precise deliniation of the interface between the layers was impossible.

To enable a characterization of the armoured layer, a method of separating the input sand was needed. It was decided to remove the input sand by allowing clear water to continue flowing after sand input was finished. This gradually removed the remaining input sand, and exposed the armoured layer.

It was noted that during this period of clearing, no particles were removed which were visibly ( by colour ) part of the armoured layer formed from the bed material. This does not eliminate the possibility that input sand mixed with or part of the armoured layer was removed or left behind during this part of the experiments. However, it is also noted that:

- a) Since no major change in the armoured layer was observed at this time, the observations of erosive depth remain valid.
- b) Since bed roughness is determined to a large extent by the largest particles, which did not move, Manning n calculations may be assumed to be reasonable estimates of actual values.
- c) Measurements of point surface elevation standard deviation were largely related to the largest surface particles, which did not move, and may thus be assumed

to be a reasonable representation of the armoured surface roughness.

- d) It is acknowledged that biases in  $D_{50}$  measurements may result from changes in distribution as fines are removed or deposited during the clearing period.

#### 4.8 Input Concentration

To allow comparison between different experimental runs of different input sizes, the rate of sediment input must be held constant. A simple constant concentration by mass or volume was not considered reliable, since the effects of armouring of a given mass concentration may vary with particle size. The use of some constant such as "percent of stream power used" or "percent of total which can be carried" depends on which formula is used to compute rate of input. It is generally recognised that none of these formulae is very exact, and predictions vary widely.

It was therefore decided to input sediment in such a way that the hydraulic conditions in the flume determine the rate of input. A bed of sand of the same composition as the input sand was placed upstream of the bed to be armoured, of length great enough that water passing over the first bed picked up and carried the maximum amount of sediment possible. The amount of sand entering the water passing over the downstream bed was therefore the maximum which the water could carry under the given hydraulic conditions, regardless of the sediment size used. Since the hydraulic conditions were constant for each test, input was constant as well. The length required for fully developed flow with each input sediment was determined by experiment prior to the armouring runs.

A long bed of input sand was placed in the flume, and water flow was initiated. The furthest upstream point where developed conditions existed was determined from physical parameters. It was assumed that where slope, depth and bed-form parameters were constant, developed flow existed and sediment concentration was therefore stable. The length of input bed required to reach this condition was measured, doubled, and used in experimental runs as the length of input bed. As transport progressed, the upstream sand bed was naturally lowered. The electric sand input hopper was placed at the upstream end of the input bed (Figure 5) to replace losses in the upstream bed. In practice, it was found to be a simple matter to adjust the input rate so that the input bed was kept at a constant average depth.

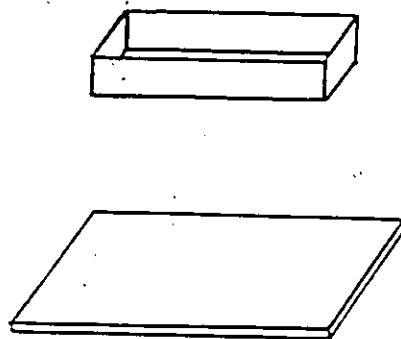
#### 4.9 Armoured Layer Sampling Technique

After repeated trials, it was found that the most satisfactory system for sampling the armoured layer was as shown in Figure 11.

A plastic base was placed in the flume under the aggregate bed, prior to each loading for an experimental run.

Plastic was selected for rigidity, non-buoyancy, and economy.

At the conclusion of the run, the mould section was pushed through the sand to contact the base. The base was then removed from the flume, together with the mould ring and enclosed sample.

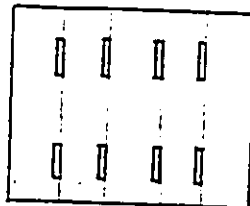


MOULD- 4"x10"x10" waxed steel, or  
- 4" of 12" diameter waxed commercial concrete mould

BASE- 3/4" hard plastic

FIG 11. MOULD USED TO SAMPLE ARMoured LAYERS

ORIGINAL  
DIRECTION  
OF FLOW



SLIDE SECTION LOCATION

FIG 12. CONFIGURATION OF SLIDE SAMPLES

The ring was sealed to the base with wax poured around the outside, and clear casting plastic was carefully introduced into the mould. The plastic was slowly poured down the side of the mould so that the surface of the sample was disturbed as little as possible.

Once the plastic hardened, the sample was removed from the mould and sections were taken with a diamond saw as shown on Figure 12.

The sections were mounted on glass slides with a catalytic cement, fixed with a geological sample sealing solution, and ground and polished to a thickness of approximately ten microns. Cover slips were attached, and the slides were viewed through a projection microscope. Preparation of each slide took approximately 30 minutes.

To determine the amount of disturbance resulting from insertion of the mould, a sample of alternating light and dark sand was prepared under conditions similar to those encountered experimentally.

A mould was inserted, and the sample was cast in plastic. After slicing the sample with a diamond saw, the radius of disturbance was clearly evident in the sand (Figure 13).

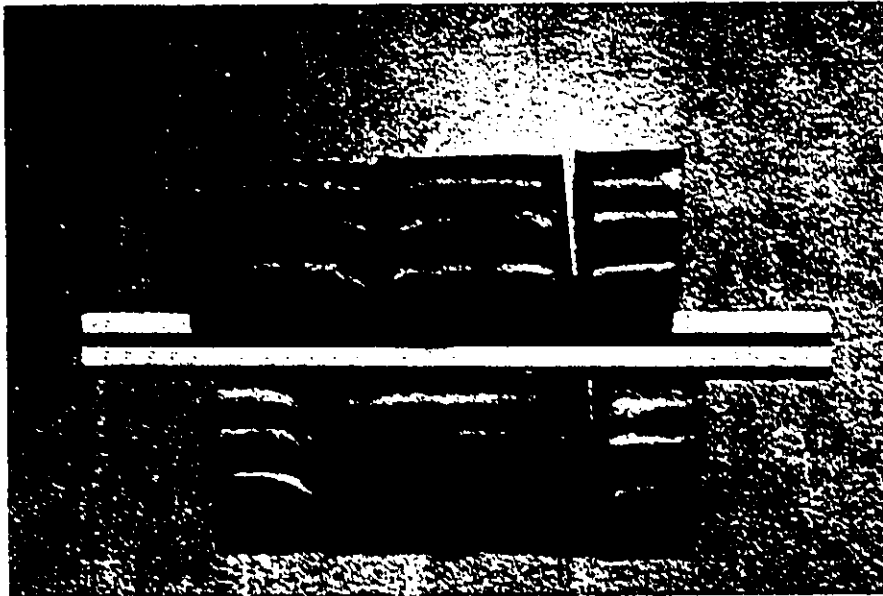


Fig. 13 SECTION FOR DETERMINATION  
OF MOLD DISTURBANCE

Repeated measurements showed a visible disturbance extending approximately 3cm from the edge of the mould. A radius of 6cm was therefore taken as the minimum distance from the mould for sampling.

#### 4.10 Methods of Measurement

Based on availability of equipment and on experimental requirements, the following general measurement techniques were applied:

1. A self-adjusting level was used to measure the slope of the flume bed and flume equipment rails.
2. Bedform and water elevations were measured using a vernier point gauge attached to a sliding table mounted on rails along the top of the flume.
3. Microscopic dimensions of slide sections were measured by tracing projected images of the slides on paper, and measuring particle dimensions from the image using a calibrated magnified scale.
4. Small changes in bed elevation were measured using vernier calipers mounted on the sand spreader.
5. Distributions of input sands and mixed bed aggregate were measured using standard sieve analysis methods.
6. Temperatures were recorded by a thermometer suspended in the head tank at the upstream end of the flume.

### 5.0 Analysis of Data

The method devised by Kellerhals to determine the equivalent sieve distribution of the transect axes of a sample depends on an accurate determination of the parameters  $k_1$  and  $k_2$ . However, as noted by Kellerhals, accurate determination of  $k_1$  or  $k_2$  directly from particles may be difficult, and result in errors during application of the conversion equation (equations 1, 2 and 3). For example,  $k_1$  and  $k_2$  are calculated from microscope measurements of individual particles, and the minor axis in particular is difficult to estimate.

In order to investigate the relationship between observed axes in the transect and the measured sieve size distribution, a sample of the bed distribution was measured and plotted as follows.

An aggregate with the size distribution established by standard sieve techniques was sectioned after being cast in plastic. The resulting transect samples were analysed microscopically and curves relating sieve and transect sizes were produced as shown in Figure 14. With these measurements made, one set of transect distributions was known to correspond to a certain size distribution. Thus, for this particular distribution, for any measured size of a transect axis fraction, the corresponding sieve size was known.

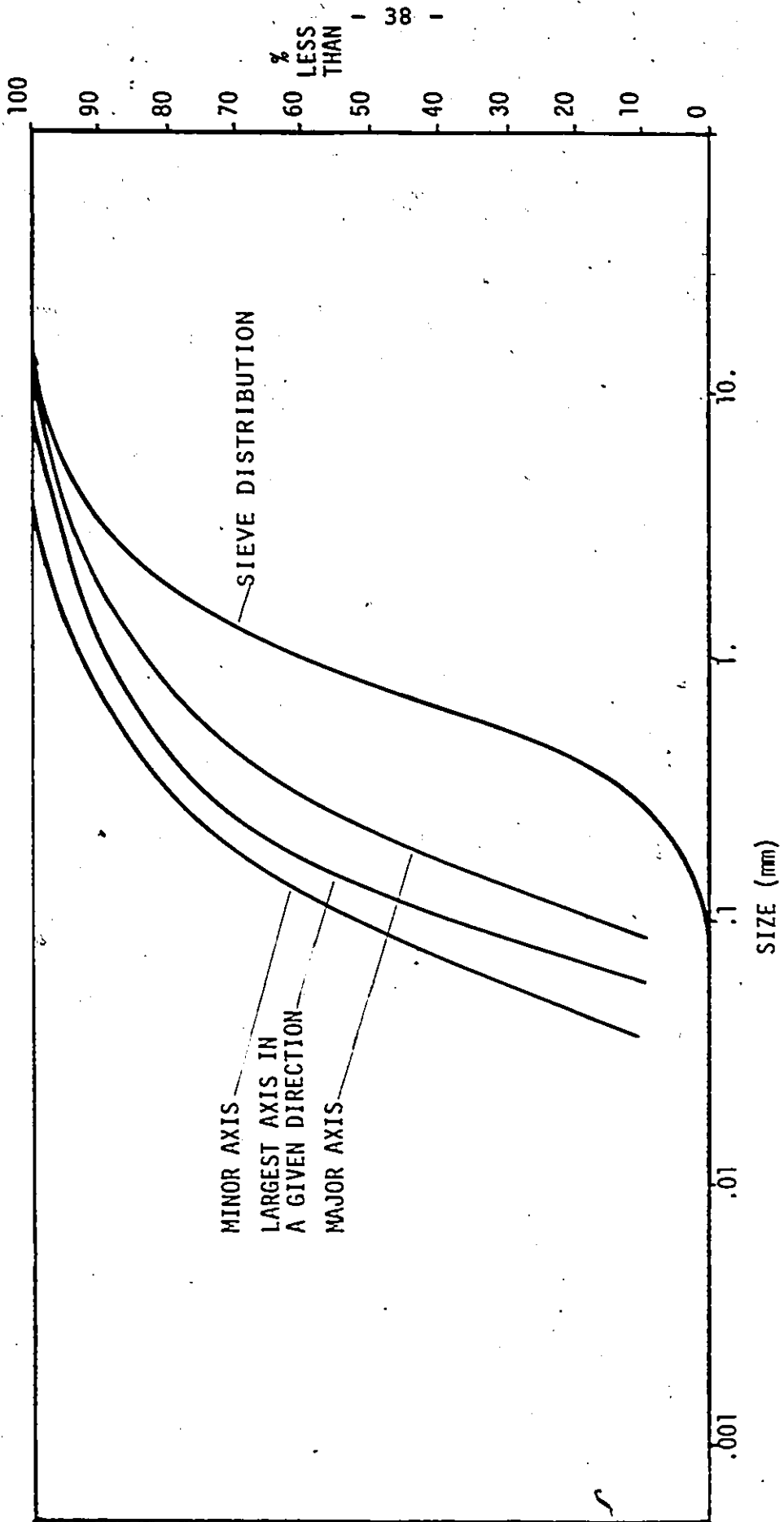


FIG 14. TRANSECT AND SIEVE DISTRIBUTIONS OF A KNOWN SAMPLE

It is of interest to note the horizontal spacing of the transect axis curves. This consistency reflects the consistent shapes of particles at all size fractions. As shown in Figure 15, the ratio of major axis size to minor axis size is quite constant over the whole range of bed sizes.

Because of the difficulties in relating measured axes to sieve size distributions for a variety of distributions of unknown characteristics, it was decided to use only the observed axes for comparative purposes. The  $D_{50}$  values of the three observed transect axes were then taken to be representative of the armoured distribution. Since this method was used consistently, we have a basis for comparing grain size distributions for any armoured layer. It was the change in the layer which was important here, so to represent this change, the following convention was used. The relative change in the armoured layer was expressed as the mean value of the ratios of the transect axis for the armoured layer with sediment input to the transect axis for the armoured layer with no input. In other words, a ratio was produced relating armoured  $D_{50}$  from input and no input cases for each measured axis. The mean value of the resulting ratios express the change in the armoured layer.




FIGURE 15 - INTERPOLATED RESULTS OF FIGURE 14,  
TRANSECT CURVES

s passing	Transect Axes			Minor Major
	Major (mm)	Minor (mm)	Largest Horizontal (mm)	
10	0.09	0.035	0.06	0.389
25	0.13	0.047	0.08	0.362
50	0.20	0.087	0.14	0.435
75	0.58	0.210	0.32	0.362
90	1.80	0.700	1.30	0.389

## 6.0 Observations

### 6.1 Qualitative Observations

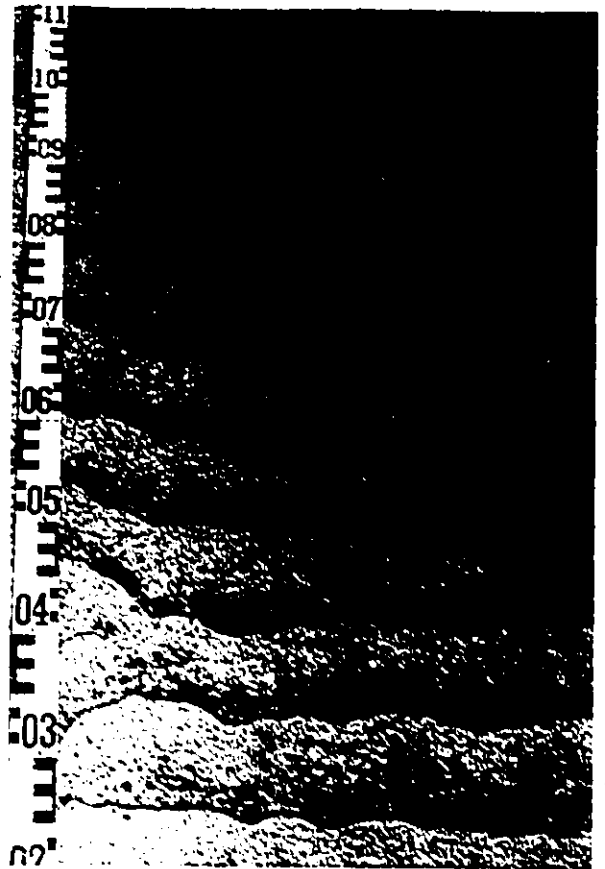
#### 6.1.1 No Sediment Input

When water containing no sediment load flowed over the flume bed, armouring occurred. Smaller particles were removed from the surface of the bed, and larger particles moved little if at all.

When the flowing water contained a sediment load, armouring again occurred, but several different mechanisms were observed.

#### 6.1.2 Fine Sediment Input

In the case of the smaller sized inputs ( $D_{50}=0.16\text{mm}$  and  $D_{50}=0.43\text{mm}$ ), parallel transverse bedforms appeared (Figure 15) in the sand of the input bed, and gradually moved down the length of the flume. These dunes augmented the normal effect of the water flow, in a manner depicted in Figure 17. The dunes began by moving along the bed, spaced apart, with original bed material visible between the dunes (Figure 17a). Particles larger than the previous (no input) threshold size were observed in motion between the dunes, and erosion was clearly deeper than in the no input case (Figure 17b). As the dunes moved downstream, the scouring followed (Figure 17c). The darker bed material was seen to mix with the white input sand forming the dunes. Finally, the system stabilized (Figure 17d).

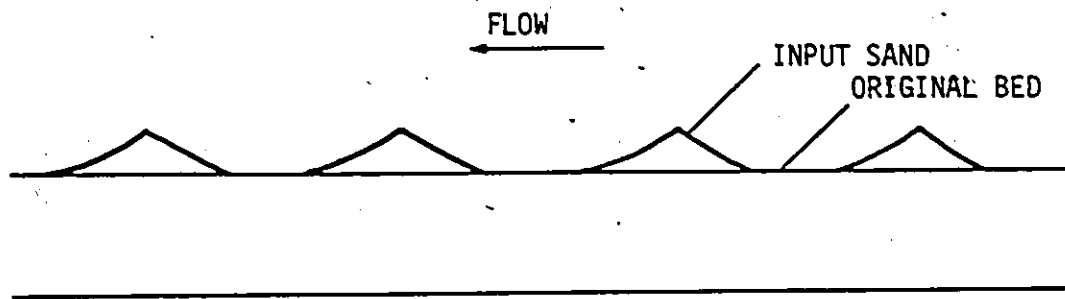


16 a) CLOSE VIEW

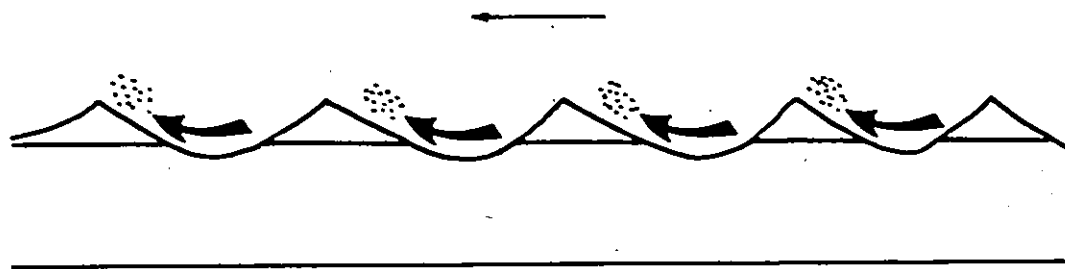


16 b) GENERAL VIEW

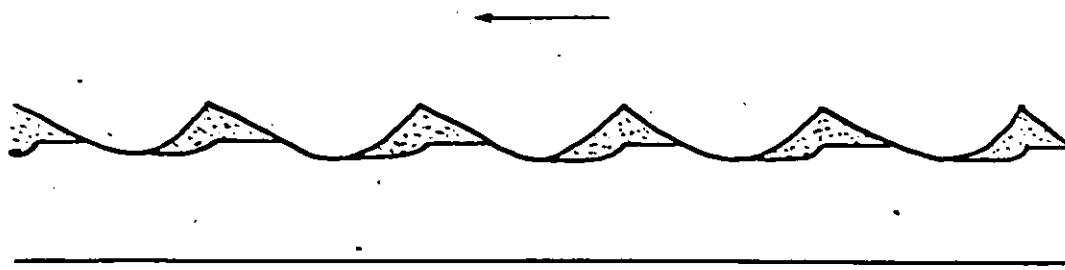
Fig. 16 BEDFORM ASSOCIATED WITH FINE SAND INPUT



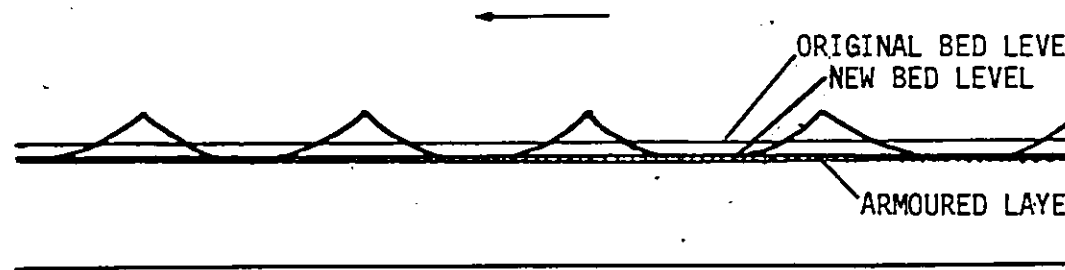
17a. RIPPLES OVER BED



17b. SCOURING BETWEEN RIPPLES



17c. RIPPLES MOVE DOWNSTREAM



17d. ARMOURING OCCURS

FIG 17. ARMOURING UNDER FINE SAND

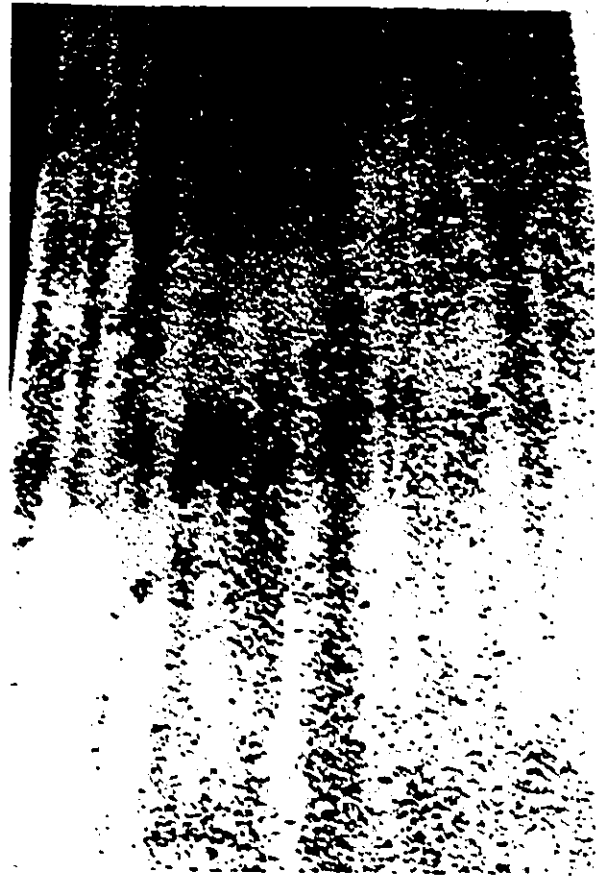
The bed surface was lowered, the dunes moved over the bed as before, and an armoured layer protected the bed from further erosion. As no more bed material was being eroded, the dunes gradually cleared of the darker bed material, and regained their original white appearance.

#### 6.1.3 Medium Sediment Input

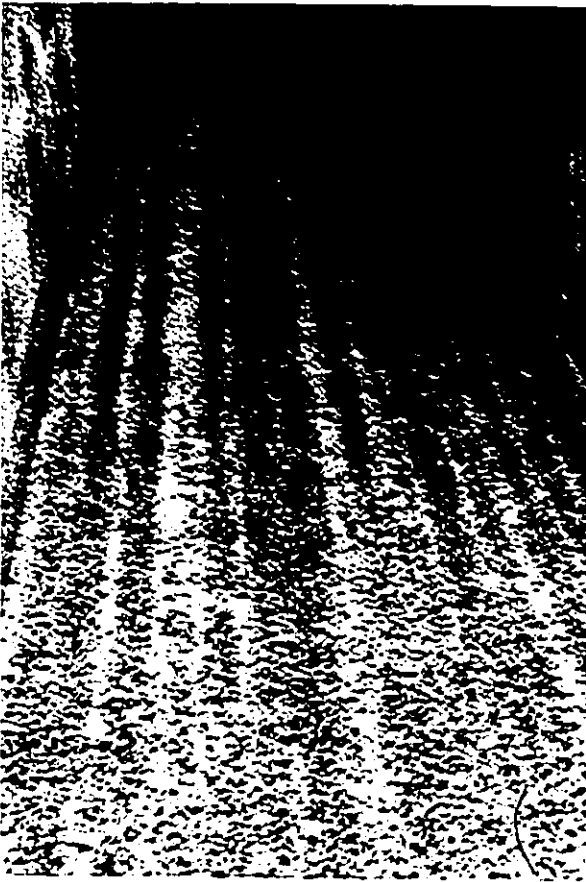
When medium sediment was input to the water ( $D_{50}=0.5\text{mm}$  and  $D_{50}=0.6\text{mm}$ ) an entirely different phenomenon was observed. The input sand formed irregular, broad, indistinct dunes in the input bed but moved over the experimental bed in thin sheets marked by longitudinal grooves. The original bed was not completely covered. No dunes were present in the input sand over the working section of the flume (Figures 18, 19a). Mixing of the input sand and the bed material was again observed, (Figure 19b), and an armoured layer gradually formed in the original bed exposed below the moving input sand. When the armoured layer became stable, the input sand cleared of bed material, and continued to move over the bed in thin sheets as noted above (Figure 19c).

#### 6.1.4 Coarse Sediment Input

In the case of the coarsest input sand ( $D_{50}=1.2\text{mm}$ ), there was no armouring observed. The input simply moved along the bed in a smooth covering layer. This layer stabilized above the original bed material, and prevented any further development in the bed below. As long as the input sand was added, no other changes occurred (Figure 20).



18 a) CLOSE VIEW



18 b) GENERAL VIEW

Fig. 18 BEDFORD ASSOCIATED  
WITH MEDIUM SAND INPUT

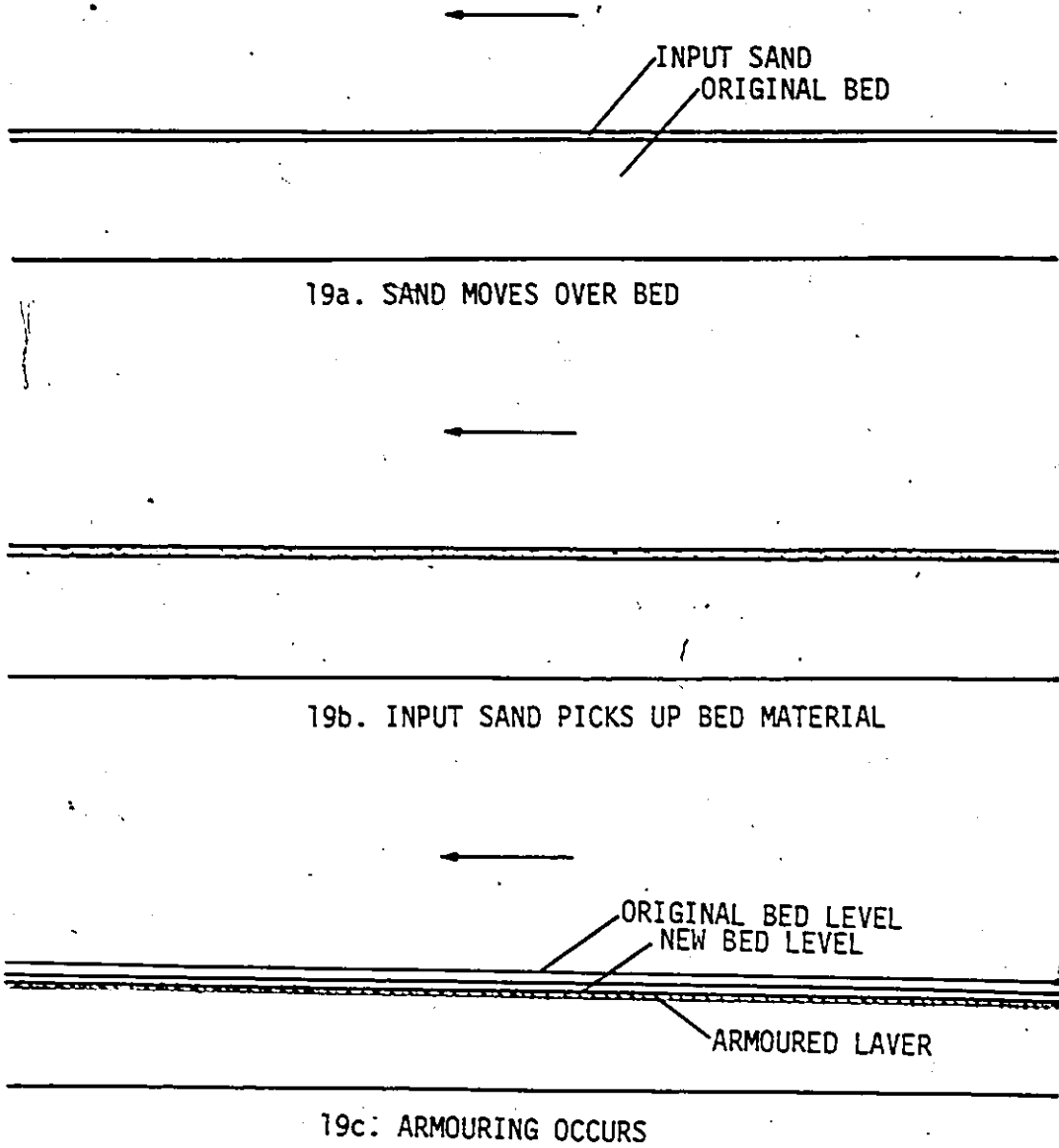


FIG 19. ARMOURING UNDER MEDIUM SAND



20 a) CLOSE VIEW



20 b) GENERAL VIEW

Fig. 20 BEDFORM ASSOCIATED  
WITH COARSEST SAND  
INPUT

### 6.1.5 General Observations

A further general observation may be made. When any armoured layer was complete, some of the input sand remained as part of the armoured layer. This is reasonable since the difference between original bed sand and input sand was in colouring, not physical characteristics. No quantitative means of assessing the degree to which this occurred exists. However, it was visually very evident that in the case of the medium ( $D_{50}=0.6\text{mm}$ ) sand, more input sand was finally present in the armoured layer than occurred for any other armouring run.

Using Simons and Richardsons (21) chart of bedforms under given hydraulic conditions, the observed bedforms were compared to expected bedforms. The median fall diameters plotted were those of the input sediment. It was noted (Figure 21) that the dune bedforms were in reasonable agreement with the chart, but that the planar bedforms were not. However, this type of result is not unusual, due to the wide amount of scatter inherent in this type of research. In addition, observation of the chart shows that little data is present in the zone between 0.5 to 0.9 mm, and 0.006 mm to 0.1 ft.lb./sec.ft.<sup>2</sup> (0.009 to 0.149 kg.m/sec./m<sup>2</sup>), which is the area in which these experiments were conducted. It is possible that planar bedforms are to be expected here. It is also possible either that the mix of dislodged bed particles achieved a total characteristic size which would exist as a planar bedform, or that the

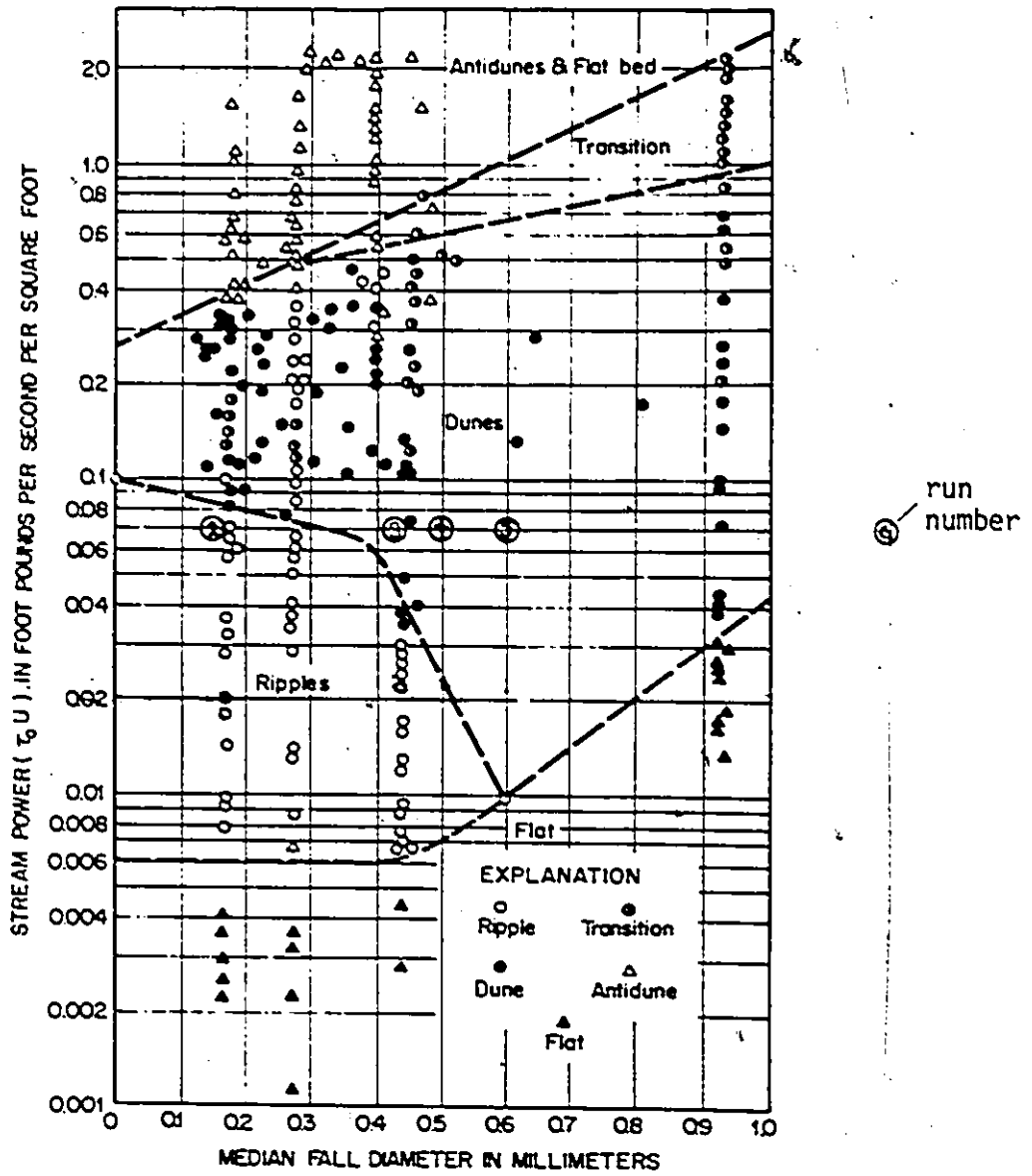


FIG 21. RELATION OF BED FORM TO STREAM POWER AND MEDIAN FALL DIAMETER (After Simons and Richardson, 1966)

the coarser bed underneath the input sand acted to prevent dune formation. However, the data presented does not lead to conclusions regarding this effect. The important observation is that the bedforms existed, and acted as observed. Further research related to alluvial bedforms with different sediment inputs could resolve the reasons for their occurrence.

## 6.2 Quantitative Observations and Calculations

For purposes of this investigation, results were reduced to four basic parameters which would best define the final system:

- a) Size characteristics of the armoured layer;
- b) Amount eroded from the bed during armouring;
- c) Hydraulic roughness of the armoured layer;
- d) Final bed slope and shape.

The above were evaluated in relation to a given size of sediment input.

These parameters were chosen bearing in mind that it is the armoured layer itself which is of primary interest here. The above parameters represent changes to such a layer.

Appendix A contains basic data for each run.

Both the magnitude of each experimental run (about 1360 kg of aggregate each) and the limited availability of suitable graded aggregates (five different input sizes plus one zero input run was used) resulted in a small sample space. The exact mechanisms at work here are therefore not clear. However, significant trends in quantitative results are evident and are outlined below.

6.2.1 Characteristic Size of the Armoured Layer

Using the procedures described above (Section 4), the armoured layers were sampled and measured. Measurement data was coded directly onto computer mark-sensing sheets, and a set of simple programs sorted and ordered the results (Appendix B). The uncovered size distributions appear tabulated and plotted in Figures 28-33 in Appendix A.

Using the methods described in Chapter 5 (Analysis of Data), the raw size distributions were converted to  $D_{50}$  values.

For comparative purposes, the calculated armoured sizes were non-dimensionalized as follows:

$$D_{50}' = \text{mean}(D_{50}^n / D_{50}^o) \quad \dots\dots 12$$

where  $D_{50}^o$  is the  $D_{50}$  resulting from sediment-free water, and

$D_{50}^n$  is the  $D_{50}$  resulting from water containing sediment input size  $n$

and  $D_{50}'$  is the relative change in size of the armoured layer.

In other words, the ratio  $D_{50}'$  indicates the degree of difference between armoured layers produced with and without sediment input. Where the ratio is greater than 1, the input sediment has caused a coarsening of the layer. Tabulated results for these experiments appear plotted in Figure 23.

As can be seen from Figure 23, there is a definite trend in size for sediments falling within the range of this research. As the sediment present in the water flow decreases in size, the resulting armoured layer becomes coarser, and in all cases the armoured layer produced when sediment input is present is coarser than the layer produced where water alone was present.

#### 6.2.2 Amount Eroded During Armouring

The sheer volume and mass of aggregate involved in this study made any direct measurement of sediment erosion (weight, or volume eroded) inordinately difficult. As a result, the simple method of using the drop in bed elevation as an indication of erosion was adopted. Results of measurements appear tabulated in Figure 24. The extent of erosion is shown as:

$$\Delta' = \frac{\text{Depth eroded, with input}}{\text{Depth eroded, no input}} \dots\dots 13.$$

where  $\Delta'$  expresses the relative amount eroded.

FIGURE 22 - CHARACTERISTIC SIZE OF THE ARMoured LAYER

Input Size $D_{50}$ (mm)	$D'_{50}$
0.16	1.90
0.43	1.59
0.50	1.52
0.60	1.35
none	1.00

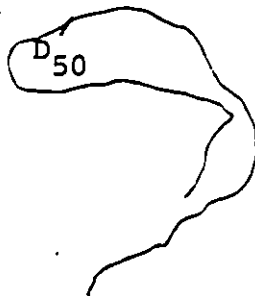
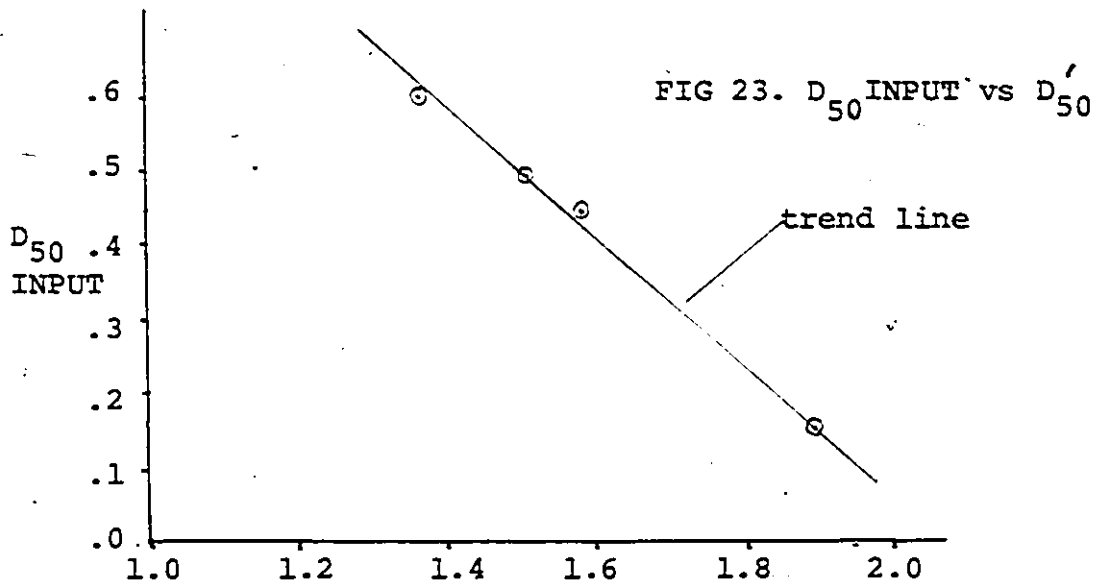
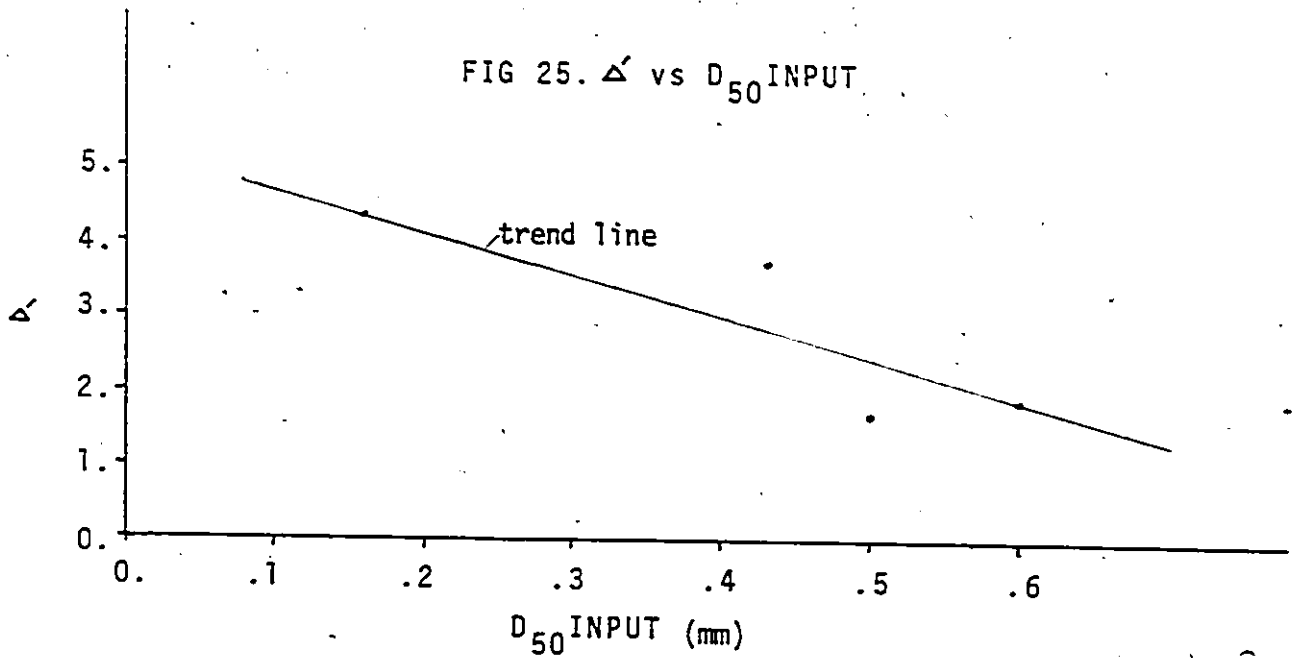


FIGURE 24 - TABULATED EROSION DATA

Input Size (mm)	Erosion Depth (mm)	$\Delta' =$ $\frac{\text{(Erosion With Input)}}{\text{(Erosion, No Input)}}$
0.16	13.22	4.363
0.43	11.30	3.729
0.50	5.24	1.729
0.60	5.87	1.937
-	3.03	1.000



It is quite evident that the largest amount of erosion resulted when the input sediment was finest, and the smallest amount of erosion resulted from the coarse input fractions (Figure 25).

### 6.2.3 Hydraulic Roughness of the Armoured Layer

Two measures of roughness were adopted. First, a simple indication of roughness was derived from the measurements made to determine the ultimate drop in bed elevation.

These measures were in each case determined from the mean of 80 point measurements of bed elevation. The standard deviation of these 80 measurements can be related to surface roughness of the bed. The rougher the bed, the greater the standard deviation.

Secondly, the Manning n can be determined from the measurements of water depths, slope, and rate of flow. For a wide rectangular channel:

$$\frac{1}{n} = (Q/b) / R^{5/3} S^{1/2} \quad (\text{S.I. Units}) \quad \dots\dots 14$$

where n - Manning roughness coefficient

Q - volume rate of flow

R - hydraulic depth

S - stream bed slope

b - width

Results of the above calculations appear in Figures 26 and 27.

The relative roughness is shown as:

$$\sigma' = \frac{\sigma(\text{with input})}{\sigma(\text{no input})} \dots\dots 15$$

where  $\sigma$  = standard deviation of surface elevation measures.

and  $\sigma'$  expresses the relative roughness shown by direct measures.

$$\text{or } n' = \frac{n(\text{with input})}{n(\text{no input})} \dots\dots 16$$

where  $n$  = Mannings  $n$

and  $n'$  expresses relative roughness as calculated.

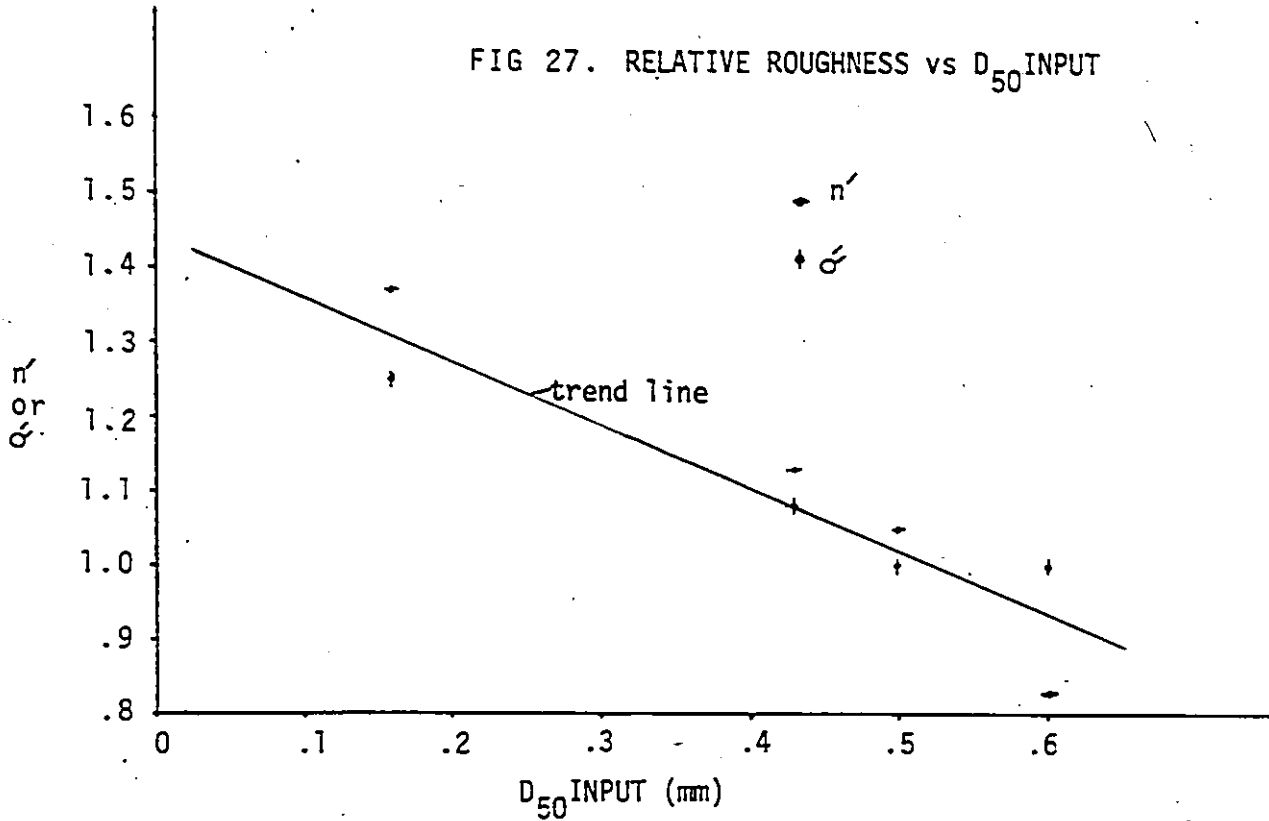
The results are in general agreement. The highest roughness measures occur for cases where input sediment is fine, and the lowest roughness occurs where input sediment is coarse.

#### 6.2.4 Slope and Bed Shape

As noted by Gessler (7), the final stream bed in an armouring experiment is, provided slopes are not excessive, parallel to and lower than the original bed. This was the case in this series of experiments. Although some changes in bed slope were observed, they were neither consistent nor large.

FIGURE 26 - TABULATED ROUGHNESS DATA

Input Size (mm)	n (Manning)	$\sigma$	$n' = \frac{n(\text{with input})}{n(\text{no input})}$	$\sigma' = \frac{\sigma(\text{with input})}{\sigma(\text{no input})}$
-	0.012	0.19	1.00	1.00
0.16	0.015	0.26	1.25	1.37
0.50	0.012	0.20	1.00	1.05
0.43	0.013	0.21	1.08	1.13
0.60	0.010	0.19	0.83	1.00



The bed remained flat and close to the original slope for all experimental runs (Appendix A).

## 7.0 Discussion

Several basic trends are evident from the observed data. The relatively small sample space involved makes definitive statements difficult. However, it is felt that the consistent trends from these experimental runs yield certain tentative conclusions. These conclusions can be useful in directing further research in this area.

For these runs it was noted that the input sediment resulted in coarser armoured layers, with the finest input fractions producing the coarsest, roughest armoured layers. This apparent contradiction becomes reasonable if one considers the factors affecting the selective erosion of surface layers of bed material.

As outlined above, Grass (8) examined the problem of initial instability of fine sands, and noted that not only the turbulent shear stress varied, but that the critical shear for the individual particles varied according to some probability distribution. He stated that the problem of initial instability was one of determining both the critical shear stress distribution of the bed material, and the shear stress distribution applied to the bed. Gessler (7) also noted this dependence on fluctuations in shear stress.

From this work, it appears that any phenomenon tending to increase turbulence, and hence the breadth of the turbulent shear stress distribution, would tend to increase the likelihood that a particle would be eroded. This in turn implies that, where armouring occurs, the amount of erosion before armouring would increase. Since the smaller particles are still removed in preference to the larger ones, it seems reasonable that the armoured layer would be somewhat coarser than otherwise. Thus, the implication of the above is that an increase in turbulence may cause a coarsening in the armoured layer.

The observed bedforms associated with various sediment inputs could explain why such sediment results in coarser armoured layers. The pronounced dunes due to the fine sand inputs are able to induce high local turbulences. This is amply verified by the observed general movement of larger bed material particles. The less pronounced forms associated with the coarser inputs also induced higher turbulences, but not to such an extent. This was deduced from qualitative observations of particle movement. It may be speculated that turbulence produced by the bedforms associated with sediment inputs influence armouring as a result of changes in bottom turbulence.

Changes in roughness show reasonable agreement with the above noted changes in size of the armoured layer. The inputs in general increase the roughness of the armoured layer, but the medium input with  $D_{50}$  of 0.6mm appears to have little effect on roughness. In fact, the results tend to indicate the layer may actually be smoother in this case. These results are reasonable, since the armoured layer is flat, and roughness must therefore depend on the nature of the surface particles. The finer inputs produce coarser and hence rougher armoured layers. The medium ( $D_{50}$  of 0.6mm) input does not coarsen the armoured layer to the same degree, and the surface is thus not as rough.

This work was not intended to define general hydraulic relationships between armouring and sediment input. Of necessity, variable parameters were kept to a minimum, and in addition, the influence of surface wave effects was not considered. It is not possible to relate these results directly to rivers flowing at lower Froude numbers where wave effects might be less significant. It is also not possible to consider the experimental flume as a model for larger prototype rivers. However, some trends indicating the influence of input sediment on the armouring process have been identified for the conditions of these runs.

## 8.0 Conclusions

For the hydraulic and sediment conditions used in this study, the important results are summarized as follows:

- a) A high concentration of transported sediment can significantly alter the final nature of an armoured layer.
- b) A high concentration of fine input sediment can cause greater impacts than a coarse input sediment, but both tend to:
  - i) increase erosion prior to armouring, and
  - ii) result in a rougher, coarser armoured bed,

unless the input sediment is extremely coarse, in which case the armoured layer may be finer and smoother.

- c) If the input sediment is so coarse that it is transported as a planar bed load, the underlying sediment may be covered and armouring delayed indefinitely.

9.0 Suggestions for Future Research

In view of the importance of the armouring phenomenon as a mechanism for stabilizing alluvial beds, and in view of the apparent impact of input sediments on this phenomenon, additional experiments should be undertaken to investigate the influence of input sediment on armouring. The influence of the following factors should be carefully studied:

- a) different concentration of input sediment;
- b) various distributions of input sediment;
- c) several sizes for each bed regime of the input sediment, so the effect at each regime bedform might be studied;
- d) tests should also be conducted over a wider range of hydraulic conditions, to determine whether the trends identified in these experimental tests have a more general applicability.

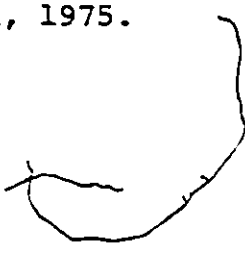
References

1. Cooper, R.H.,  
"A Study of Bed Material Transport Based on the Analysis of Flume Experiments",  
thesis presented to the University of Alberta, at Alberta, Canada, in 1970, in partial fulfillment of the requirements for the degree of Doctor of Philosophy.
2. Cooper, R.H., Peterson, A.W., and Blench, T.,  
"Critical Review of Sediment Transport Experiments",  
Journal of the Hydraulics Division, ASCE, Vol. 98, No. HY3, Proc. Paper 8873, March, 1970.
3. Davies, B.E.,  
"The Armouring of Alluvial Channel Beds",  
Master of Engineering Report, University of Canterbury, Christchurch, New Zealand, 1974.
4. Day, T.J.,  
"Preliminary Results of Flume Studies Into the Armouring of a Coarse Sediment Mixture",  
From: Report of Activities, Part C;  
Geological Survey of Canada, Paper 76-1c(1976).
5. Egiazaroff, I.V.,  
"Calculation of Nonuniform Sediment Concentrations",  
Journal of the Hydraulics Division, ASCE, Vol. 91, No. HY4, July, 1965.
6. Garde, R.J., Ali, K.S., and Diette, S.,  
"Armouring Process in Degrading Streams",  
Journal of the Hydraulics Division, ASCE, Vol. 103, No. HY9, Technical Notes, September, 1977.
7. Gessler, J.,  
"Self-Stabilizing Tendencies of Alluvial Channels",  
Journal of the Waterways and Harbours Division, ASCE, Vol. 96, No. WW2, Proc. Paper 7263, May, 1970.
8. Grass, A.J.,  
"Initial Instability of Fine Bed Sand",  
Journal of the Hydraulics Division, ASCE, Vol. 96, No. HY3, Proc. Paper 7139, March, 1970.
9. Gunter, A.,  
"The Critical Mean Bed Shear Stress in the Case of an Armour Coat and Turbulence - Induced Fluctuations in the Shear Stress",  
Translation from the German, Doctoral Thesis, Erdgenossische Technische Nedissh, Zurich, 1970.

References (Cont'd)

10. Harrison, A.S.,  
"Report on Special Investigation of Bed Sediment Segregation in a Degrading Bed",  
Report, Institute of Engineering Research,  
University of California, Berkeley, Calif.,  
Series No. 33, Issue No. 1, September, 1950.
11. Hooke, R. Le B.,  
"Laboratory Study of the Influence of Granules on Flow over a Sand Bed",  
Bulletin, Geological Society of America, Vol. 79,  
No. 4, April, 1968, pp. 495-500.
12. Kellerhals, R.,  
"Stable Channels with Gravel-Paved Beds",  
Journal of the Waterways and Harbours Division, ASCE,  
Vol. 93, No. WW1, February, 1967.
13. Kellerhals, R. and Church, M.,  
"Stability of Channel Beds by Armoring",  
Discussion, Journal of the Hydraulics Division, ASCE,  
July, 1977, pp. 826-827
14. Kellerhals, J.S., Shaw, J., and Arora, V.K.,  
"On Grain Size From Thin Sections",  
Journal of Geology, University of Chicago, Vol. 83,  
1975.
15. Komura, S.,  
"Sediment Transport Technology",  
Water Resources Publications, 1976.
16. Lane, E.W., and Carlson, E.J.,  
"Some Factors Affecting the Stability of Canals Constructed in Coarse Granular Materials",  
Bureau of Reclamation, United States.
17. Little, W.C., and Mayer, P.G.,  
"Stability of Channel Beds by Armouring",  
Journal of the Hydraulics Division, ASCE, Vol. 102,  
No. HY11, Proc. Paper 12519, November, 1976.
18. McDonald, B.C.,  
"The Geological Survey of Canada Sedimentation Flume",  
Geological Survey of Canada, Paper 71-46.
19. Meland, N., and Norrman, J.O.,  
"Transport Velocities of Individual Size Fractions in Heterogeneous Bed Load",  
"Geografiska Annaler, Vol. 51A, No. 3, 1969, pp. 127-144.

References (Cont'd)

20. Shields, I.A.,  
"Sediment Transport Technology",  
Water Resources Publications, 1976.
  21. Simons, D.B., and Richardson, E.V.,  
"Sediment Transport Technology",  
Water Resources Publications, 1976.
  22. Simons, D.B., and Senturk, F.,  
"Sediment Transport Technology",  
Water Resources Publications, 1976.
  23. Sutherland, A.J., and Williman, M.E.,  
"Development of Armoured Surfaces in Alluvial  
Channels", Draft (Unpub.), 1977.
  24. Vanoni, V.A., (Editor), Harrison, A.S., 1950,  
"Sedimentation Engineering",  
American Society of Civil Engineers, 1975.
  25. Williman, E.B.,  
"The Development of Armoured Surfaces in  
Streambed Channels",  
Master of Engineering Thesis, University of  
Cantebury, Christchurch, New Zealand, 1975.
- 

Appendix A

Data Summary

1. Initial Hydraulic Conditions, All Runs

Flume slope - 0.005m/m

Flow rate -  $1.65 \times 10^{-2} \text{ m}^3/\text{s}$

Temperature  $\approx 5.8^\circ\text{C}$

2. Input Summary

<u>Run</u>	<u>Nominal Input Size</u>	<u>Measured D<sub>50</sub> (mm)</u>	<u>Input Rate (kg/hr)</u>	<u>Associated Bedform</u>
1	nil	-	-	-
2	natural	0.16	10.5	dunes
3	#40	0.43	4.8	dunes
4	#70	0.50	4.0	planar, slight waviness
5	#24	0.60	3.9	planar, and streaked
6	#16	1.20	3.0	planar

3. Dune Bedforms

<u>Run</u>	<u>Length (cm)</u>	<u>Height (cm)</u>	<u>Spacing (cm)</u>
2	12.5	2.1	15.6
4	4.9	3.0	13.6

4. Final Conditions, Armoured Layer

Run	Depth of Flow (mm)	Erosion Depth $\bar{x}$ (mm)	$\sigma$	Manning n	Armoured $D_{50}$ (mm)	Slope	Froude no.
1	34.3	3.03	1.91	.012	0.80	.0053	1.09
2	38.3	13.2	2.60	.015	1.19	.0052	0.92
3	34.6	5.24	2.00	.012	1.11	.0053	1.07
4	33.8	11.3	2.10	.013	1.02	.0063	1.11
5	30.6	5.87	1.86	.010	1.11	.0053	1.30
6	-	-	-	-	-	-	-

5. Specific Gravity of Various Particle Fractions

Aggregate	S.G.
Source 1 of aggregate for bed mix	2.69
Source 2 of aggregate for bed mix	2.65
Source 3 of aggregate for bed mix	2.69
Input sands (all)	2.66

6. Fall Velocity of Smallest Particles

Measured fall velocity of smallest visible particles in aggregate bed mix - 0.03m/s

7. Vertical Velocity in Settling Tank

Calculated mean vertical velocity in settling tank at experimental rate of flow - 0.004m/s calculated by  $V=Q/A$

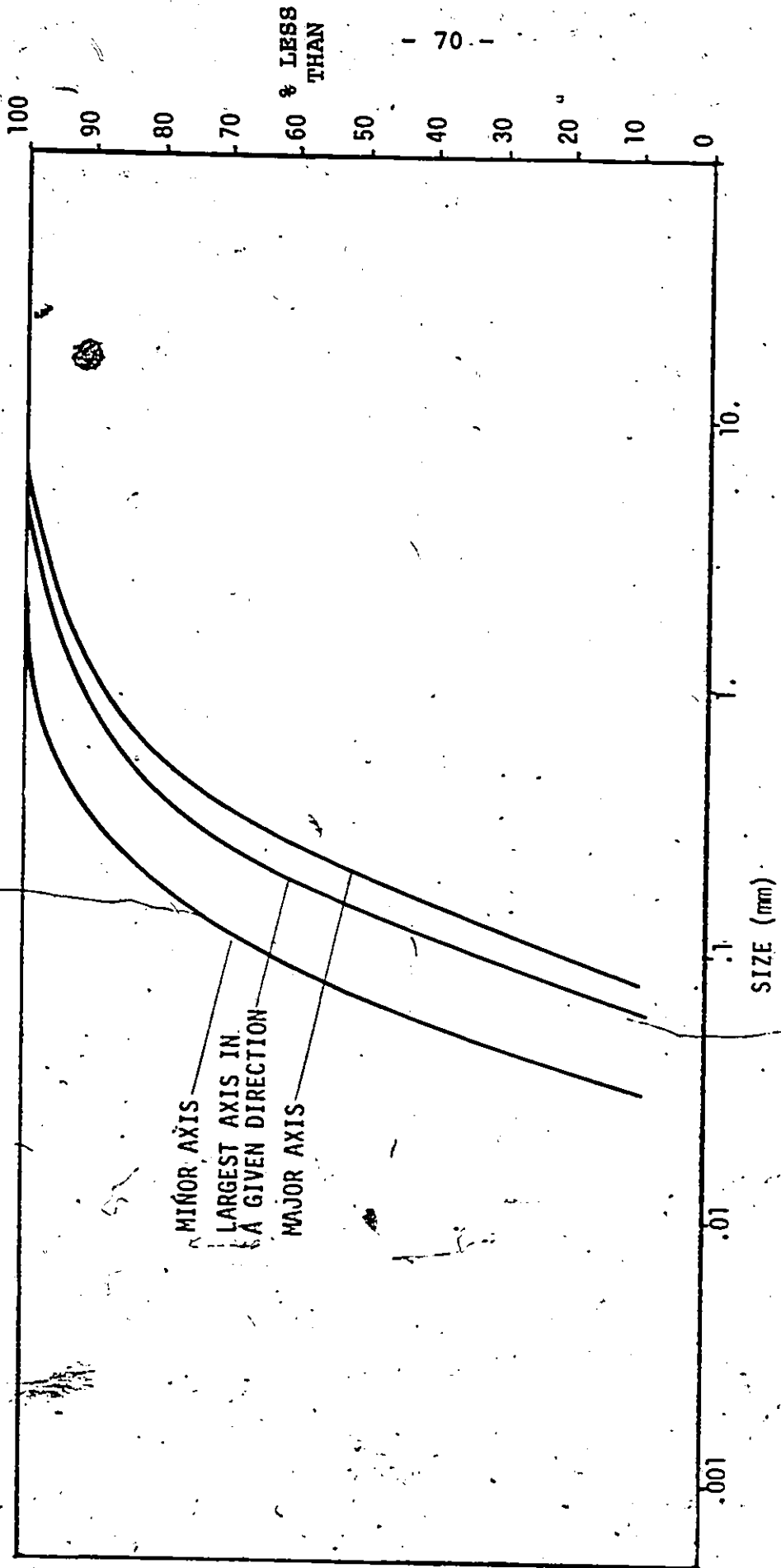


FIG 28. TRANSECT DISTRIBUTION - NO INPUT SEDIMENT

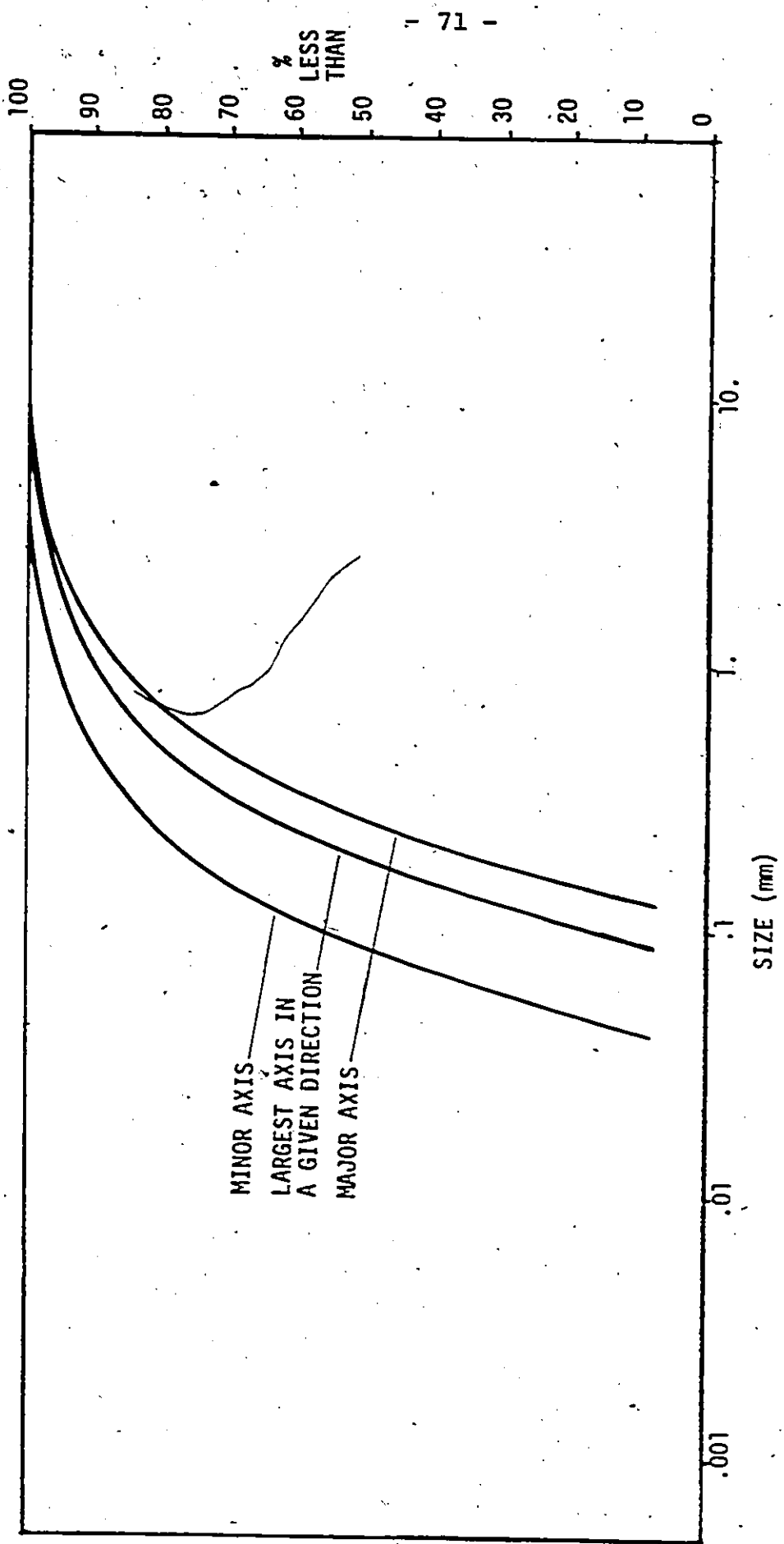


FIG 29. TRANSECT DISTRIBUTION - 0.6MM INPUT

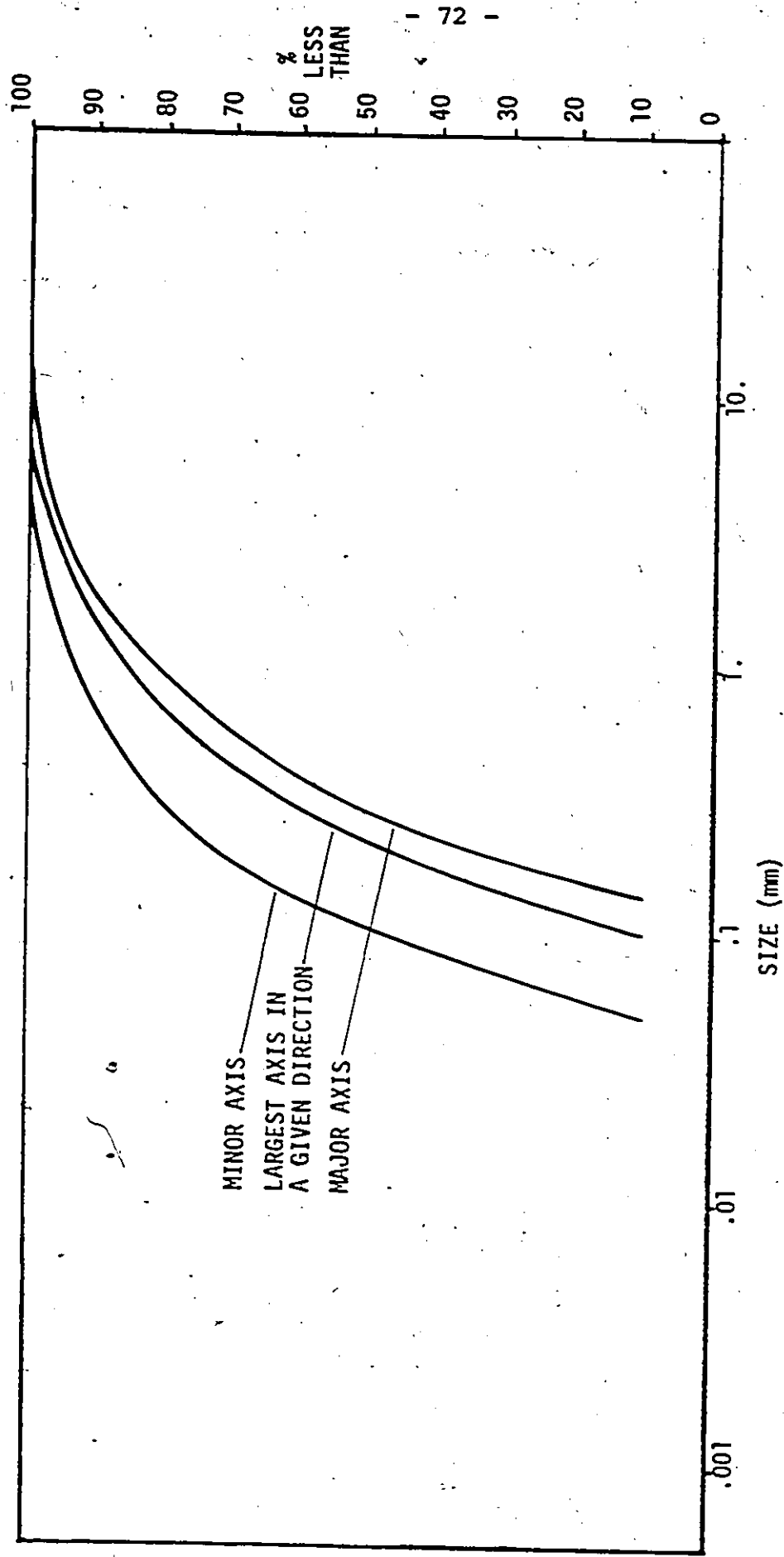


FIG 30. TRANSECT DISTRIBUTION - 0.5MM INPUT

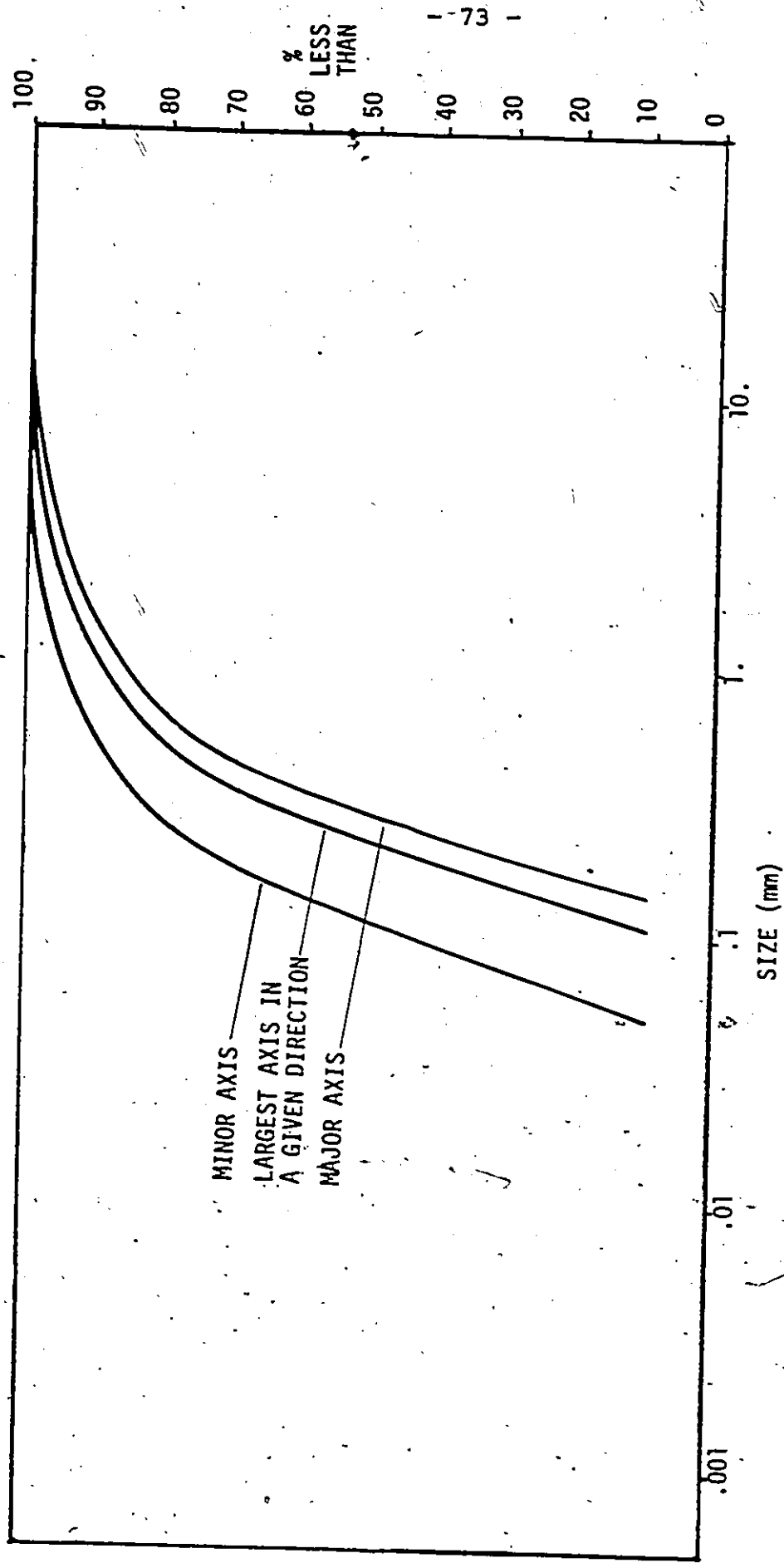


FIG 31. TRANSECT DISTRIBUTION -- 0.43mm INPUT

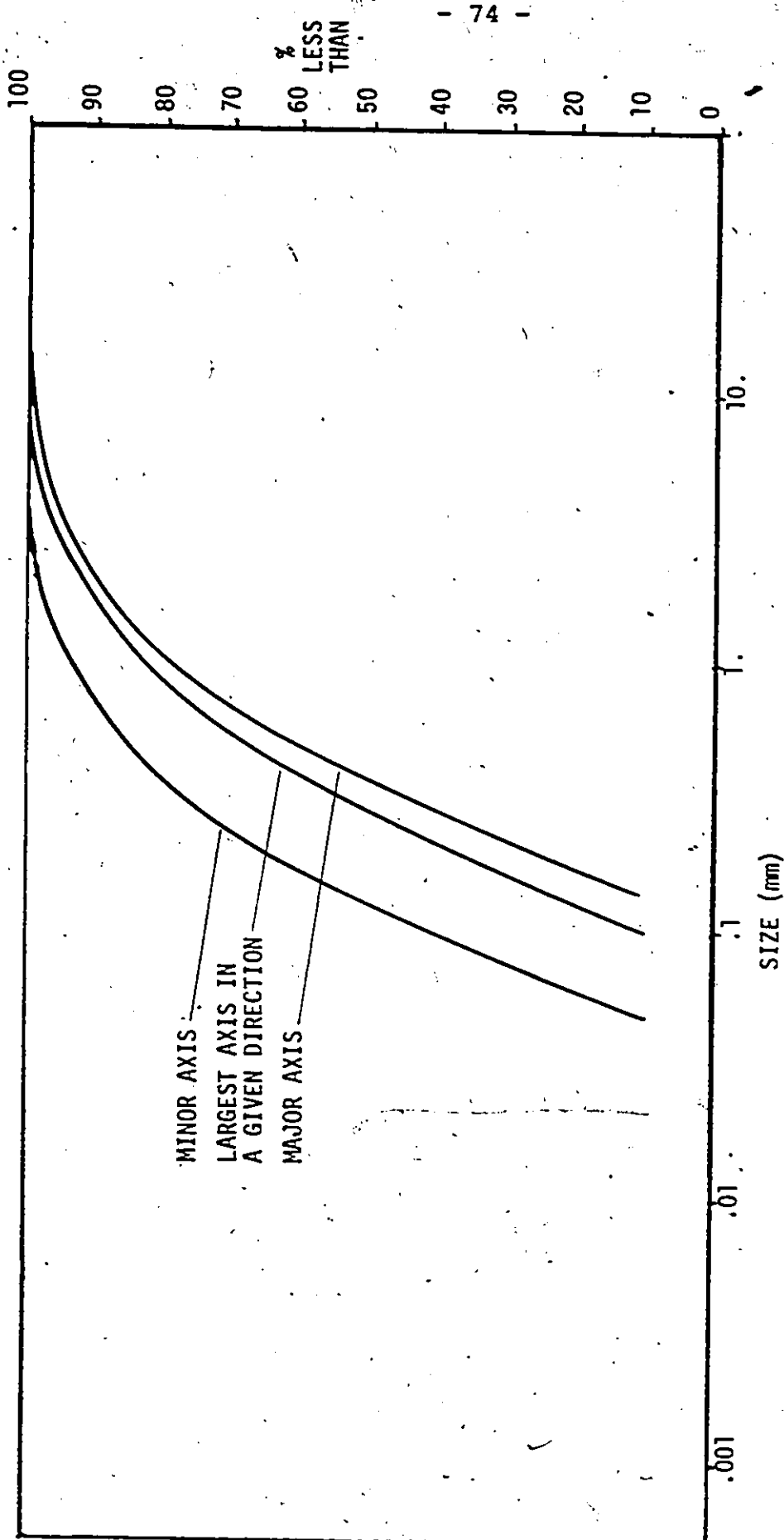


FIG 32. TRANSECT DISTRIBUTION - 0.16MM INPUT

Appendix B

Computer Programs

1. Program to Sort Data

SCONTROL USLINIT

C  
C THE FOLLOWING PROGRAM READS A LARGE NUMBER OF INTEGER NUMBERS  
C AND CONVERTS THEM TO REAL VALUES DIVIDED BY 100. NUMBERS  
C ARE OUTPUT LINE BY LINE TO THREE DIFFERENT DEVICES. THE  
C RESULT FOR THIS WORK IS TO TAKE RAW DATA FROM CODE SHEETS,  
C AND SORT INTO A, B, AND C-AXIS DATA, IN A FORM SUITABLE FOR  
C ORDERING BY SIZE. PROGRAM HALTS AT DUMMY VARIABLE 9999;  
C PROGRAM OUTPUTS DUMMY VALUE 999. AT END OF EACH GROUP, FOR  
C USE IN ORDERING PROGRAM.  
C

INTEGER A,B,C,D,E,F,G,H,I,J  
REAL K,L,M,N,O,P,Q,R,S,T  
8 CONTINUE  
DO 23 INT=1,3  
READ(5,10)A,B,C,D,E,F,G,H,I,J  
10 FORMAT(10I5)  
IF(A.EQ.9999)GO TO 99  
K=REAL(A)/100.  
L=REAL(B)/100.  
M=REAL(C)/100.  
N=REAL(D)/100.  
O=REAL(E)/100.  
P=REAL(F)/100.  
Q=REAL(G)/100.  
R=REAL(H)/100.  
S=REAL(I)/100.  
T=REAL(J)/100.  
IF(INT.EQ.1)WRITE(2,11)K,L,M,N,O,P,Q,R,S,T  
IF(INT.EQ.2)WRITE(3,11)K,L,M,N,O,P,Q,R,S,T  
IF(INT.EQ.3)WRITE(4,11)K,L,M,N,O,P,Q,R,S,T  
11 FORMAT(10F6.2)  
23 CONTINUE  
GO TO 8  
99 CONTINUE  
END=999.  
WRITE(2,12)END  
WRITE(3,12)END  
WRITE(4,12)END  
12 FORMAT(F6.2)  
STOP  
END

## 2. Program to Order Data

\$CONTROL MAP,STAT,LOCATION,LINES=57

C  
C  
C  
C  
C  
C  
C

THE FOLLOWING PROGRAM READS A LARGE NUMBER OF RANDOM NUMBERS AND ORDERS THEM BY SIZE, LARGEST TO SMALLEST. OUTPUT INCLUDES TOTAL NUMBER OF NUMBERS ORDERED, AND OUTPUTS NUMBERS IN A FORMAT MAKING COUNTING SIMPLE. PROGRAM STOPS AT NUMBER 999, DUMMY INPUT VALUE.

```
DIMENSION A(4000)
REAL LARGE
DO 11 I=1,4001,10
  READ(5,10)(A(J),J=I,(I+9))
10  FORMAT(10F6.2)
  IF(A(I).EQ.999.)ICOUNT=I
  IF(A(I).EQ.999.)GO TO 12
11  CONTINUE
12  ICOUNT=ICOUNT-1
  IF(A(ICOUNT).NE.0.)GO TO 13
  GO TO 12
13  INUMBER=ICOUNT
  J=1
14  CONTINUE
  DO 15 I=(J+1),INUMBER
  IF(A(I).LE.A(J))GO TO 15
  LARGE=A(I)
  A(I)=A(J)
  A(J)=LARGE
15  CONTINUE
  J=J+1
  IF(J.NE.INUMBER)GO TO 14
  WRITE(6,16)INUMBER
16  FORMAT(2X,15,' ORDERED NUMBERS')
  DO 20 I=1,4001,100
  WRITE(6,17)
17  FORMAT(////)
  IT=I
  IS=I+99
  IF(IS.GT.INUMBER)GO TO 19
  WRITE(6,18)(A(J),J=I,(I+99))
18  FORMAT(10F7.2)
  GO TO 20
19  WRITE(6,22)(A(JT),JT=IT,INUMBER)
22  FORMAT(10F7.2)
  GO TO 21
20  CONTINUE
21  STOP
  END
```