Hydraulics Research
Wallingford

DEPOSITION OF FINE SEDIMENT FROM FLOWING WATER:

An investigation of dependence on concentration

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CONTRACT

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ABSTRACT

This report describes the first series of experiments undertaken in the newly commissioned Hydraulics Research Carousel. The Carousel is a 6m diameter circular flume designed to overcome the inability of conventional laboratory flumes to adequately reproduce the natural process of deposition from flowing water. The experiments were undertaken to examine the factors affecting the onset of deposition and in particular that of the concentration of suspended solids. A test comprised insertion of a mud suspension into the Carousel, running the Carousel at a high speed (ie high water flow rate), then reducing the speed in steps over several days while continually observing the suspended solids concentration. Each new test began with a different concentration, so covering the range normally experienced in muddy estuaries.

The results showed that in fact the critical flow condition which allows significant settling is independent of concentration. Above that threshold, some deposition occurs but is limited to a fixed proportion of the initial concentration. That proportion is partly governed by the level of energy in the flow. These important conclusions should be further investigated and quantified so that techniques for predicting siltation, controlling dredging, and assessing the environmental impact of civil engineering works in estuaries may be refined to a degree where they can be used confidently.

CONTENTS

1 INTRODUCTION

Studies of fine sediment deposition have wide engineering and environmental application. Prediction of siltation, control of dredging, assessing pollution transfer and environmental impact all depend significantly on evaluation of the pattern and rates of deposition of fine sediment. This evaluation depends upon a correct calculation of the balance between the hydrodynamic stresses, deposition rates and erosion rates. Thus accurate prediction of deposition is of primary importance and requires reliable practical definition of the circumstances under which deposition occurs and the factors controlling the rate of deposition. Deposition occurs when the kinetic energy in the flow is insufficient to maintain particles in suspension and they settle to the lower boundary. For a natural sediment there will be a range of conditions over which this occurs.

A major problem in studying deposition is the inability of conventional laboratory equipment to adequately reproduce the estuarine environment, the main difficutly being concerned with flocculation. Flocculation is the process by which fine particles adhere together, under certain fluid flow conditions, to form larger particles. Because the flocs are of a larger size than the individual particles they have higher still water settling velocities.

Recent studies by Stevenson and Burt[1,2,3] have already shown that settling velocities measured in the field in undisturbed samples were at least an order of magnitude higher than those measured in previous laboratory experiments due to different flocculation. This was attributed to the fact that in the field particles were maintained in suspension for several hours between phases of deposition and that flocculation could, therefore, fully develop.

To maintain fine sediment in suspension for several hours without destroying the flocs presents a problem in conventional flumes because of the action of the pumps. It would require a flume several km long (ie something equivalent to a typical tidal excursion distance in an estuary) to overcome this problem. It was not until the development of a circular (effectively infinitely long) flume that it began to be possible to study the process of deposition realistically from flowing water. Such a facility has recently been commissioned at Hydraulics Research (HR) specifically for this purpose[4]. The Carousel, as it is known, is illustrated in Fig 1.

Previous studies using a much smaller circular flume[5,6,7] have identified critical boundary shear stresses

below which all sediment deposits or above which none deposits. It is of great importance now to evaluate those circumstances under which sediment starts to deposit and the rate of deposition under specified conditions.

Krone[5] and Partheniades[6] both observed that in a given test when the energy is decreased a relatively rapid drop in suspension concentration is followed by an approach to a constant or steady state or equilibrium value.

Partheniades further observed that the ratio of the concentration at steady state to the initial concentration is a constant, indicating that a constant proportion of the initial concentration can always be carried in suspension at a given energy level.

These previous tests involved the maintenance of steady state conditions for many hours throughout the test. In practical circumstances in an estuary steady state conditions do not occur except for short periods of time. So it is the energy for the onset of deposition and the rate of deposition from a given concentration in relation to the energy path that is important. The tests reported herein comprise a preliminary evaluation of the relationship between the initial concentration of the suspension, the energy in the flume and the onset of deposition for a sample of estuary mud. The test programme, carried out in the HR Carousel, comprised insertion of a mud suspension, running the Carousel at a high speed then reducing the speed in steps over several days while continually observing the suspended solids concentration. Each new test began with a different concentration.

2 PROCEDURE

Mud dredged from the approach channel to Cardiff Docks was mixed with borehole water (see Ref 4 for details) and pumped into the Carousel to give a 100mm deep suspension of specified concentration (see Table 1 for Experiment Number, Initial Concentration and Experiment Duration). When filling was completed the experiment began immediately.

The experimental sequence consisted of a series of step decreases in roof speed (energy) from an initial roof speed of 3.75rpm. After each decrease in roof speed the suspended solids concentration was monitored and the roof speed kept constant until either no significant change in concentration with time could be observed or the change in concentration with time began to approach the resolution of the measuring technique (photometer and gravimetric calibration). At this time the next step change in roof speed was

initiated. A schematised experimental sequence is shown in Fig 7.

The experiment ended when the amount of suspended solids left was about 2% of the inital suspended solids concentration.

Before changing the initial concentration for another experiment the deposited sediment was resuspended for a repeat run. On the repeat run the stepping down sequence was modified, introducing extra steps to look more closely at the critical region when rapid deposition was taking place. The tests were thus caried out in pairs, repeating the same procedure for each pair.

The suspended solids concentration was monitored at 0.5, 1, 1.5, 2, 4, 6 and 12 hour intervals after the step change in motor speed. At each sampling event 20 samples were taken in a grid pattern at 11, 20, 41, 62 and 84mm above the flume floor and 80, 160, 240 and 320mm across from the outside wall of the flume. This pattern of sampling was executed to allow evaluation of the suspended solids distribution across the test section. Samples were obtained using a hypodermic tube inserted into the flume (at the appropriate height) through self sealing rubber bungs and allowing the suspension to flow out into a 30ml collecting bottle.

3 RESULTS

3.1 Particle size analysis

Samples of the Cardiff mud used in the tests were subjected to standard seive and settling tube analyses to determine the particle size distribution. The result showed very little variation between samples and the average, as used in the flume, is shown in Fig 2. It is a fairly typical estuary silt comprising about 30% clay ($< .002$mm), 62% silt and 8% sand ($> .063$mm) when classified by particle size.

3.2 Flow field

It was convenient throughout the tests to use the setting on the motor speed control as a reference, indicating the general hydraulic conditions in the flume. The full justification for doing so is given in Ref 4 but summarised here for convenience.

Fig 3 shows the relationship between motor speed setting and roof speed. Fig 4 shows the relationship between roof speed and mean flow velocity (arithmetic average over a cross section of the flume). Fig 5 shows the way the flow is distributed in the flume cross section, as isovels normalised to the mean

velocity. [It should be noted here that these velocity calibrations were carried out with clear water in the flume. It is not yet possible to measure velocities in detail when high concentrations of mud are in the flume. It is reasonable to assume that the calibrations hold good for low concentrations, say less than 5000mgl^{-1}, but become invalid for higher concentrations.]

Finally Fig 6 shows the amount of energy which is required to sustain a given roof speed, ie that which is required to overcome energy losses.

3.3 Concentration field

Concentrations measured by sampling the suspension at 20 grid points in the flow cross section showed surprisingly little variation whatever the mean concentration of suspended solids. The standard deviation was about 5% of the mean. Because of this it is possible to represent the concentration of suspended solids in the whole cross section with a single value (the arithmetic mean) and this has been done in the ensuing presentation of results.

3.4 Concentration during a test

Time series plots were made for each test of the cross section mean concentration. They all showed the same trend which is schematised in Fig 7. Immediately following a step down in motor speed there would be a reduction in concentration at a rate which itself reduced with time, until eventually equilibrium conditions were reached where no further deposition was taking place. In practice it was not always possible to accurately define this point in time because some loss of concentration was always evident albeit very slowly. In some cases it took 24 hours to reach this state. The results of experiment No 9 (see Table 1) are shown in Fig 8 as an example of typical data obtained.

The obvious question, raised by the results illustrated, is whether or not a particular energy level in the flume (characterised by the motor speed) has a unique concentration associated with it. In other words can it only sustain a certain maximum concentration?

3.5 Equilibrium concentration vs roof speed

The results for experiments 2, 4, 6, 8 and 10 are shown in Fig 9, which demonstrates that the equilibrium concentration for a particular run only decreases slightly as the motor speed is reduced until, at a motor setting of 215, the material begins to settle. At this point it seems that there is no

longer an equilibrium concentration; the flow is not able to sustain any material in suspension. The results for the odd numbered runs were very similar but, because of the larger decrements in roof speed, missed the critical value where concentrations began to decrease rapidly.

Fig 9 also demonstrates that if a particular speed is able to sustain only a limited concentration then that concentration is in excess of 20,000mgl^{-1} (the highest tested). For example, compare experiment 6 with experiment 10. In experiment 6, when the motor speed was reduced from 600 to 400 the equilibrium concentration fell from 7,400mgl^{-1} to about 6,000mgl^{-1}. But at that same speed in experiment 10 an equilibrium concentration of about 20,000mgl^{-1} was maintained. This raises a most interesting and important question: why, in experiment 6, does anything settle from suspension at all? Conversely, how is it possible for the higher concentrations in experiment 10 to be maintained? It is not possible with present knowledge to offer an explanation but the results suggest that somehow the initial concentration is an important parameter and that subsequent equilibrium concentrations are a proportion of the inital concentration. In the next section we investigate this further.

3.6 Proportional settling

Fig 10 compares the concentration at motor speed setting 215 with the initial concentration for all the experiments. The result shows vividly that what settles out is a fixed proportion (35%) of the initial concentration.

This is generally confirmed for other motor speed settings in Fig 11 which shows the cumulative percentage lost from suspension for all the experiments. It is important to note here that zero loss at speed setting 600 is a consequence of making this the starting point. It has no other significance.

4 DISCUSSION

It is important to emphasize first that the experimental results and subsequent discussion are based on the strict definition of "loss of material from suspension" rather than "deposition on the bed". This is partly because no accurate measurements of bed thickness were possible and partly because it is possible for high concentration layers (fluid mud) to form near the bed, which, because of semi-fluid properties, cannot be called "the bed".

The observation that at a given energy, a constant proportion of the initial concentration is maintained in suspension is consistent with other results (eg Partheniades and Mehta[7]) although the proportionality constant is different. The explanation for this may lie in the relationship between size, density and settling characteristics of the sediment particles or flocs and the turbulent shear stress in the flume.

The primary particles will aggregate to produce an equlibrium floc size spectrum. The floc size and density are determined principally by the local hydrodynamics. The rate at which the material in the flume reaches an equilibrium floc size spectrum will depend on concentration for a given energy level.

If changes in suspended solids concentration result from settling related to the energy/particle size balance, it may be expected that a critical energy level will exist above which turbulent shear limits floc size and below which rapid floc growth is facilitated. The energy barrier separating this behaviour will depend on the particle surface charges and the strength of the aggregates formed.

The concentration vs motor speed plots are consistent with this since, irrespective of concentration, the size spectrum will be energy dependent and thus a given energy (motor speed) will support a similar fraction of the sediment.

The abrupt transition to rapid loss from suspension is also consistent with a transition from a limited size spectrum to one where energy levels allow rapid floc growth, settling and bed formation.

The abrupt change in settling around motor speeds of 215 indicate two radically different regimes of behaviour. In the higher energy regime energy may be reasonably proposed as the principal control on concentration, with initial concentration determining the actual mass in suspension. In the lower energy regime floc growth may be suggested as a dominant parameter. The rate of change from one regime to another is expected to be influenced by energy and concentration.

The nature of the change from an equilibrium condition to a depositional condition could be further

investigated by a detailed study in the motor speed setting range from say 300 to zero. This should include measurements of the near bed velocity and concentration field. Deposition is generally initiated onto the smooth plastic floor of the flume. It may be more appropriate to study deposition onto a mud substrate.

5 CONCLUSIONS

1. Concentrations of suspended solids in the flume cross section were homogeneous.

2. There were two distinct phases of settlement of solids from suspension.
   Phase 1 (motor speed setting > 215)
   Phase 2 (motor speed setting < 215)

3. Phase 1

   (a) The amount settling out was limited to a fixed proportion of the initial concentration.

   (b) The proportion depended on the energy level in the flume. The maximum proportion was 35% at a motor setting of 215, just above the threshold for Phase 2 settling.

4. Phase 2

   When the motor speed setting was less than 215 everything in suspension was able to settle out.

5. The critical motor speed setting was only very slightly dependent on concentration.

6. Further studies should be undertaken to

   i investigate the critical condition more closely so that it can be more precisely defined in terms of bed shear stress or other parameters which will make it more useful for field applications.

   ii investigate tidal cycle deposition. In estuaries the hydrodynamic character of the flow changes far too rapidly to allow equilibria to develop (in some experiments they took up to 24 hours of steady state conditions to develop in the flume).

   iii examine the behaviour of other estuary muds under both of the above conditions.

6 ACKNOWLEDGEMENTS

The authors wish to acknowledge the contribution to this study given by Dr W R Parker who made useful suggestions regarding the analysis and interpretation of the experimental data.

7 REFERENCES

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2. STEVENSON J and BURT T N "Further studies on field settling velocity of Thames mud". HR report SR 10.

3. BURT T N "Field settling velocities of estuary muds". Paper presented at Cohesive Sediment Dynamics Workshop, Tampa, Florida, Nov 1984.

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Table

TABLE 1

XPT NO	INITIAL CONCENTRATION mgl^{-1}	Ph	SALINITY mgl^{-1}	DURATION OF XPT HOURS
1	270	8.045	300	30.50
2	275	8.35	40	56.10
3	1700	8.51	150	77.20
4	1840	8.45	140	94.70
5	6602	-	-	98.25
6	7400	8.39	140	78.85
7	13200	7.80	180	73.60
8	13300	7.95	180	99.70
9	27000	8.08	290	95.70
10	24280	7.63	230	119.52

Figures

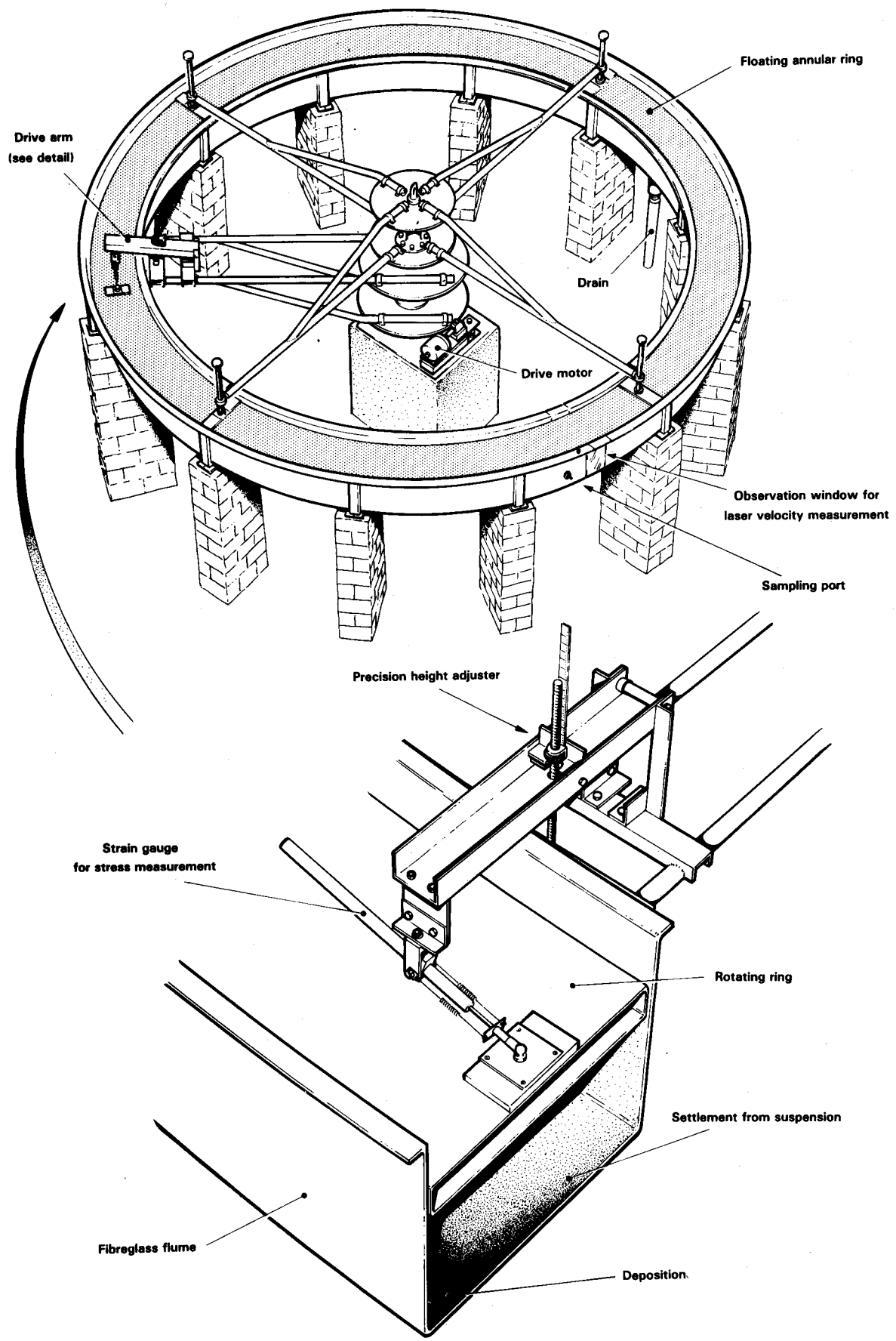


Fig 1 The Carousel

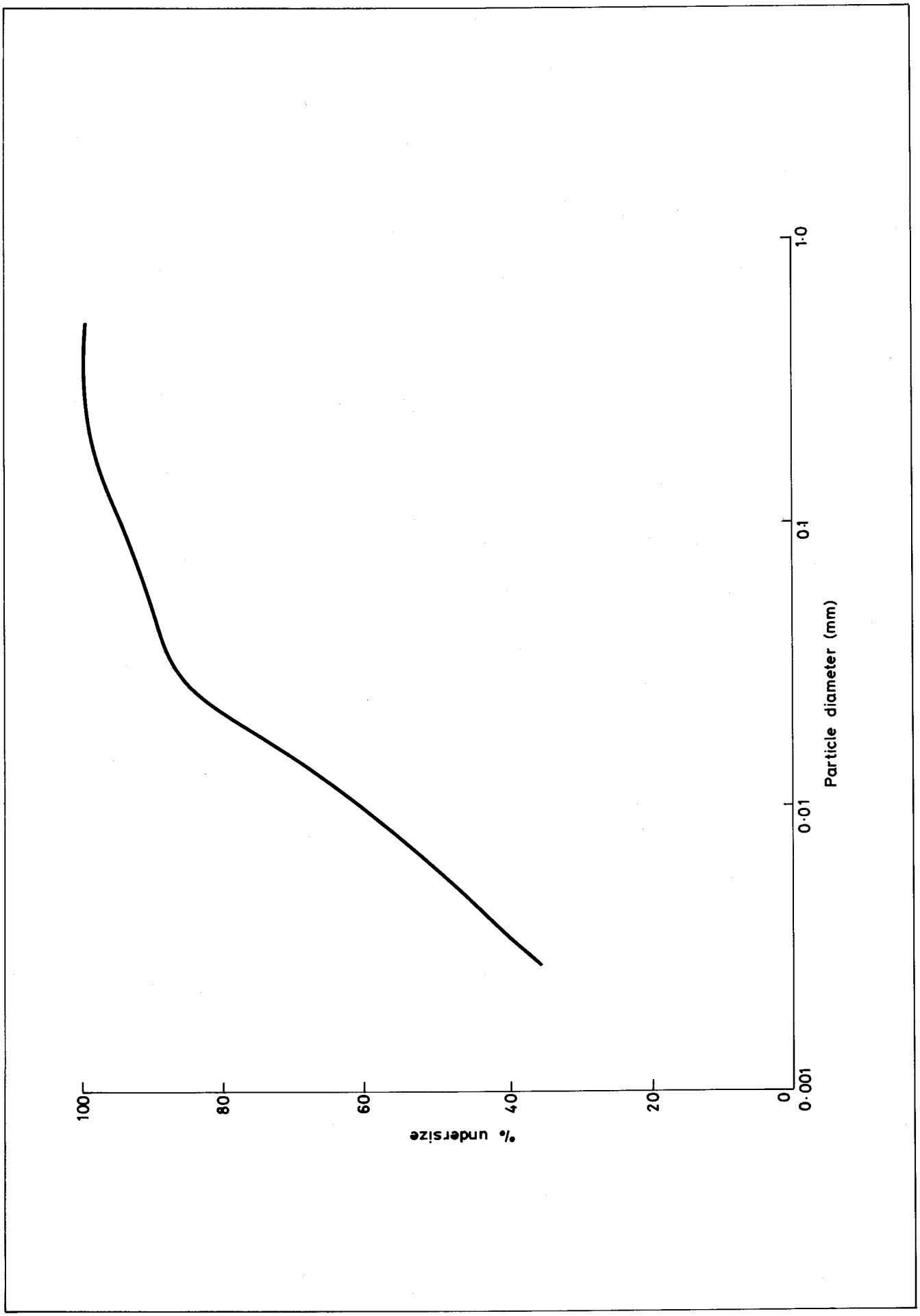


Fig 2 Particle size distribution of mud

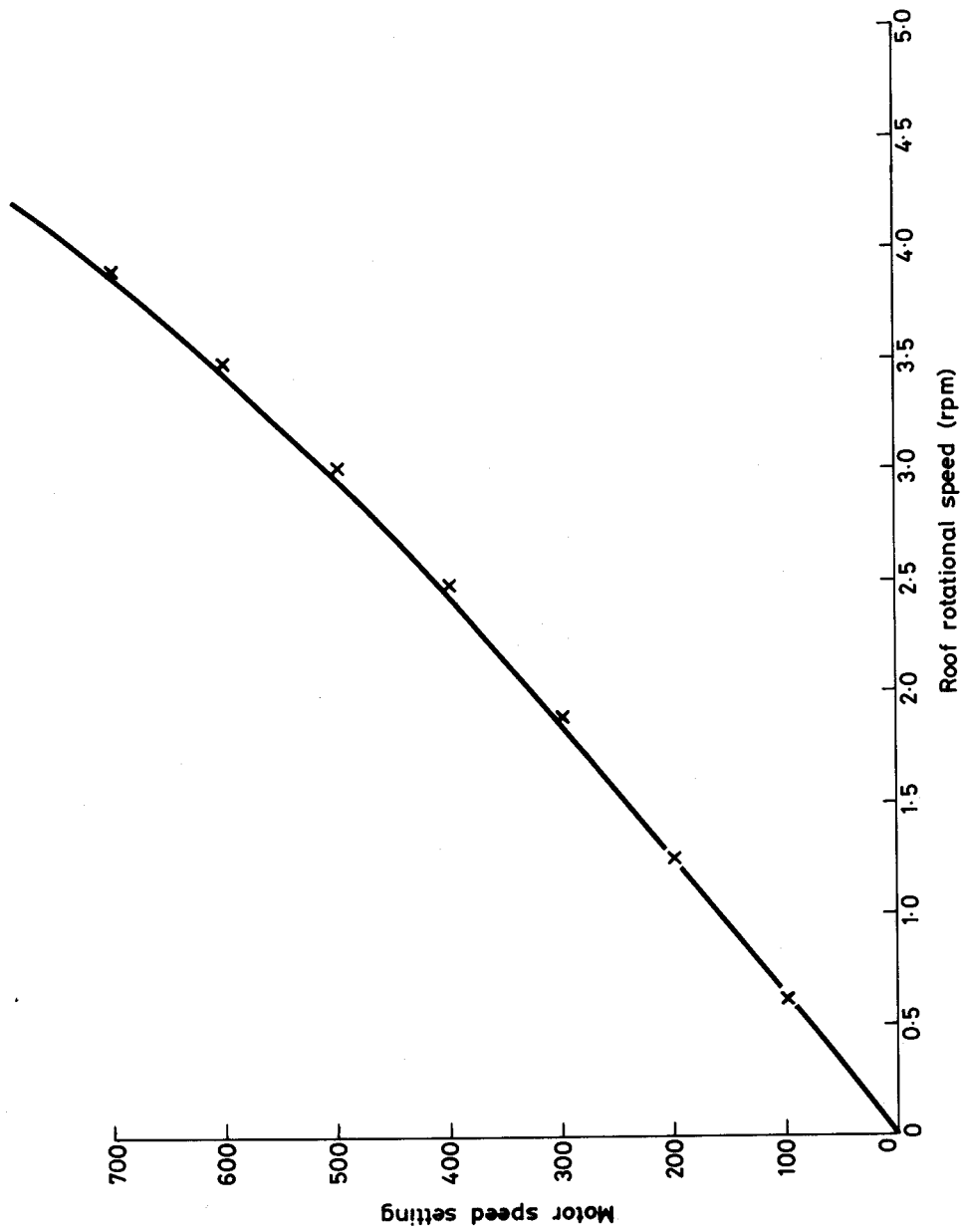


Fig 3 Calibration of motor speed setting

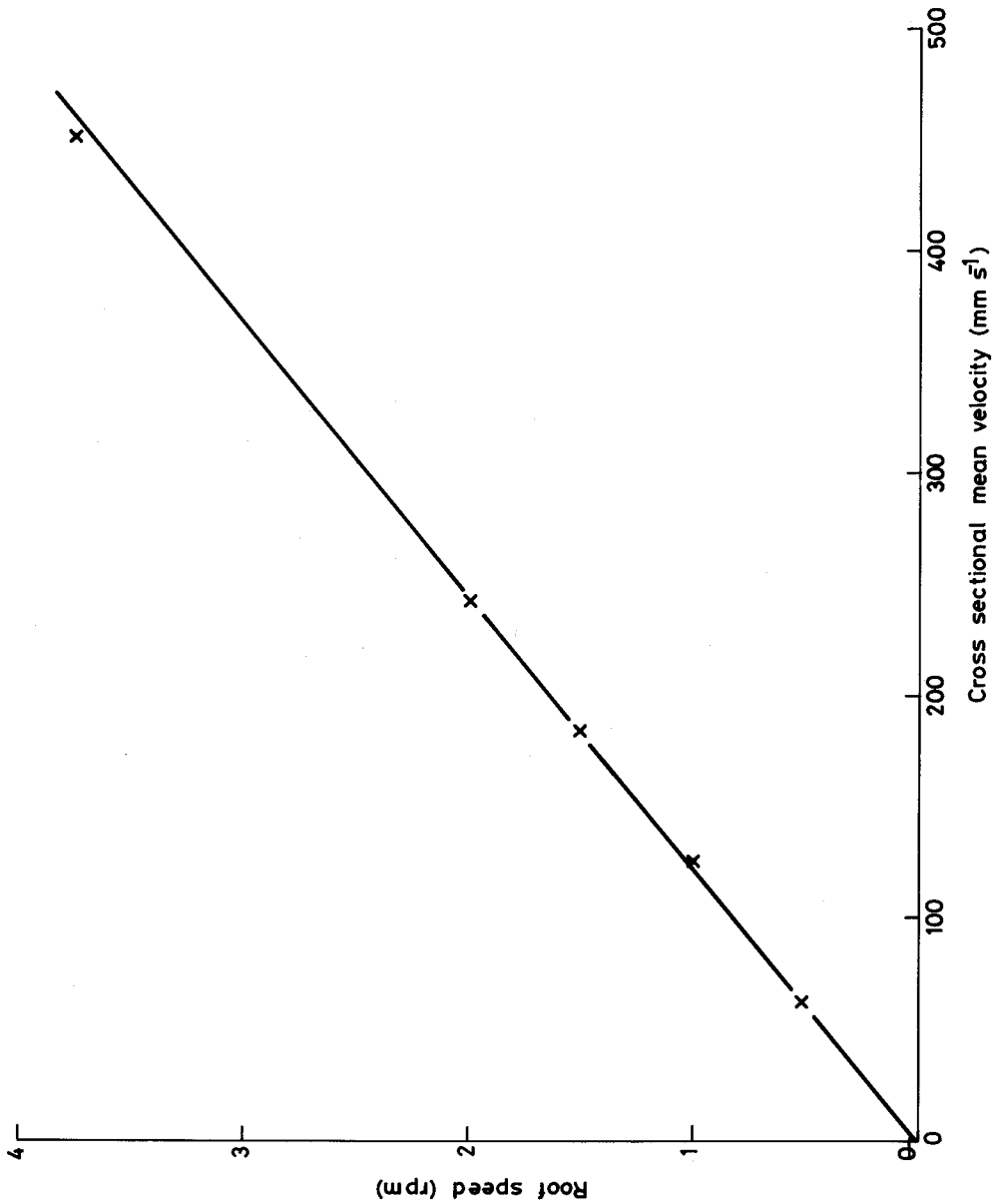


Fig 4 Calibration of mean flow velocity

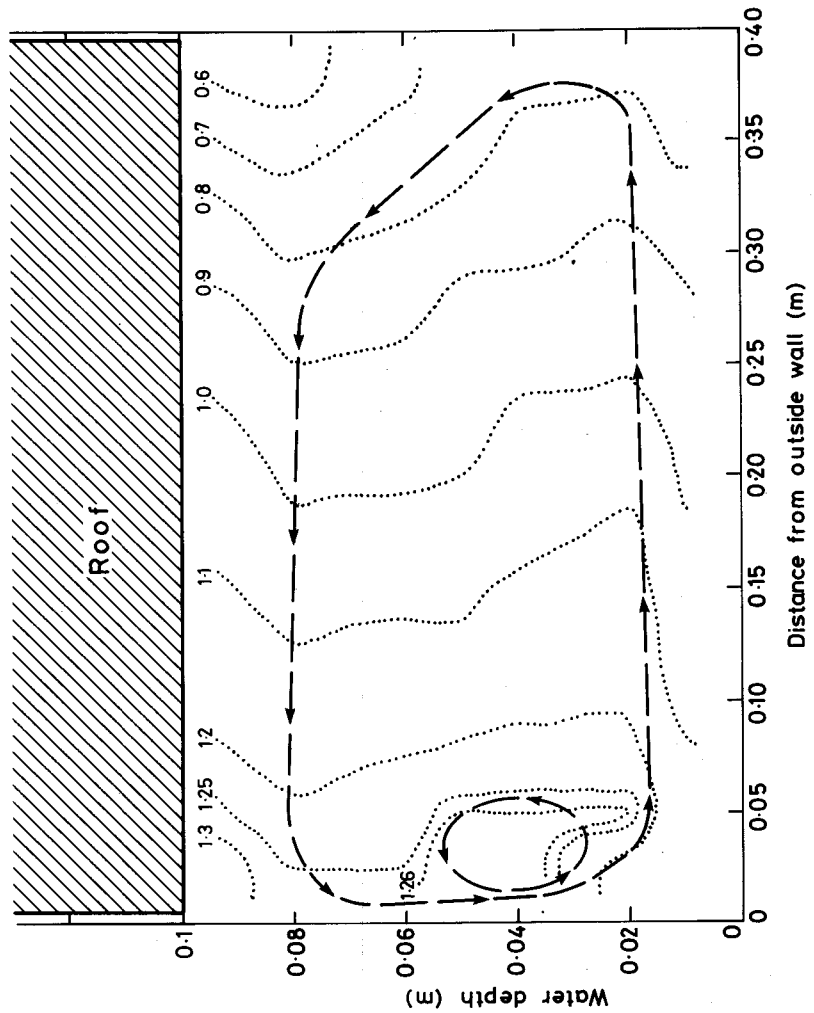


Fig 5 Distribution of flow in the flume

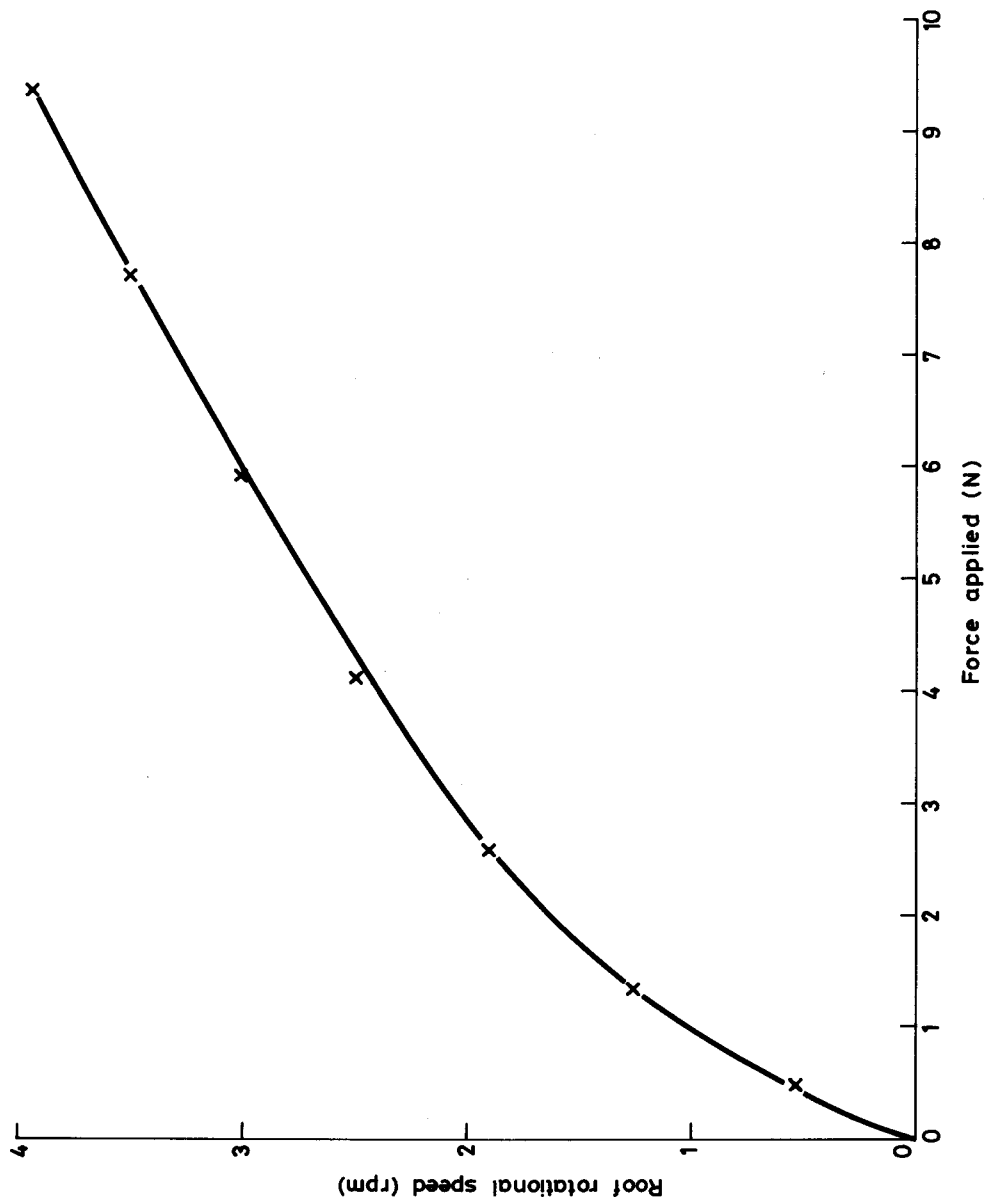
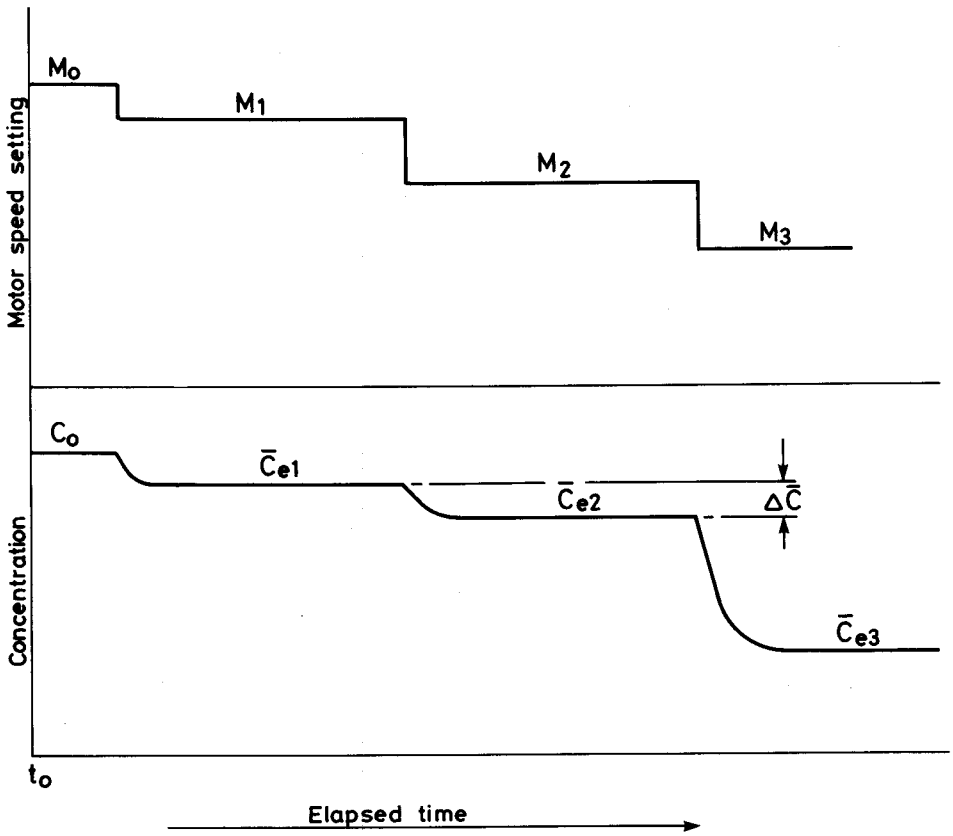


Fig 6 Energy input calibration



M_o = Initial motor speed setting

C_o = Initial concentration

$\bar{C}$ = Cross sectional mean concentration

M_n = Motor speed setting

$\bar{C}_{en}$ = Equilibrium concentration at motor speed M_n

$\Delta\bar{C}$ = Change in concentration due to reduction in motor speed to a lower value

Fig 7 Schematised test results and notation

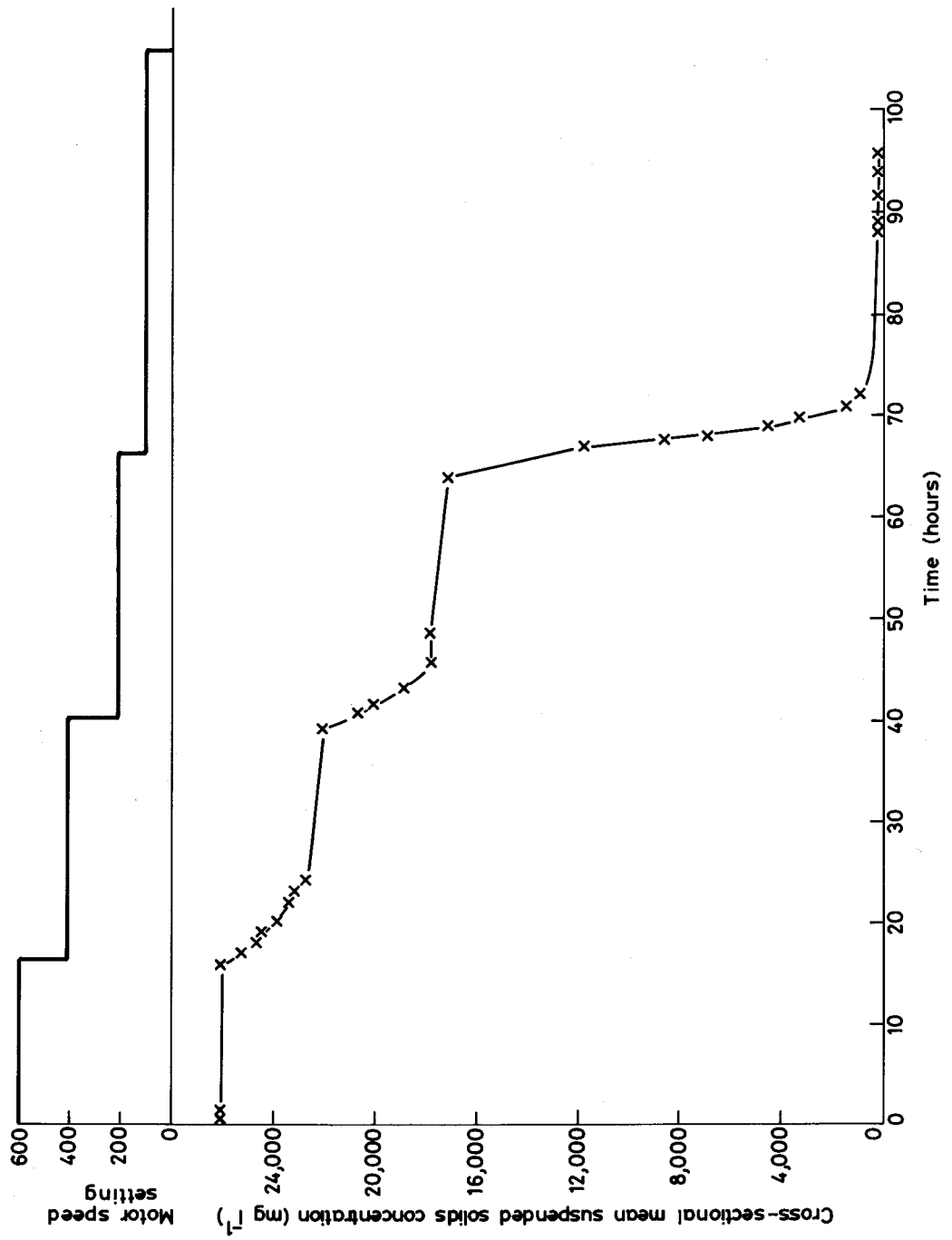


Fig 8 Example of concentration - time plot

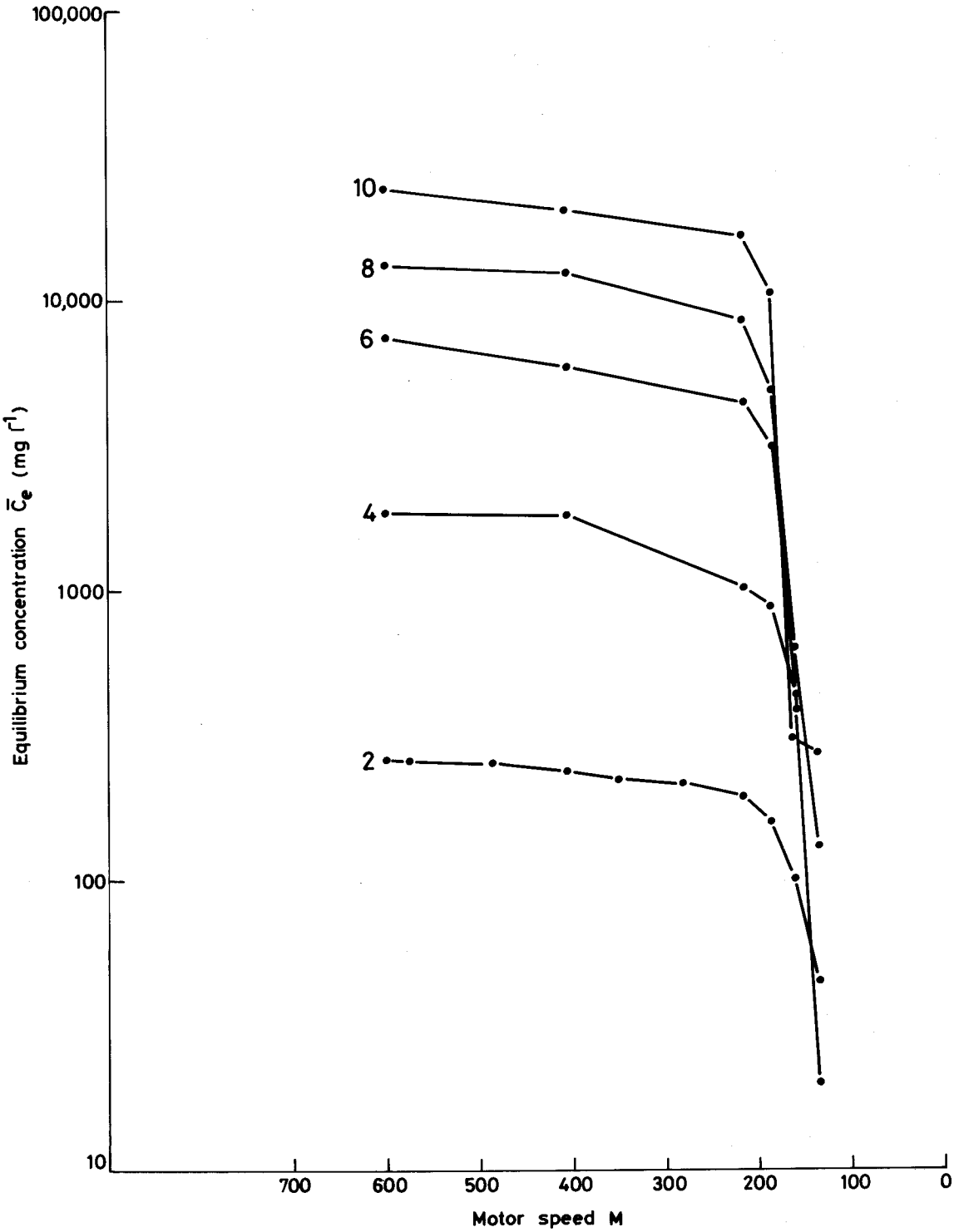


Fig 9 Equilibrium concentration vs motor speed

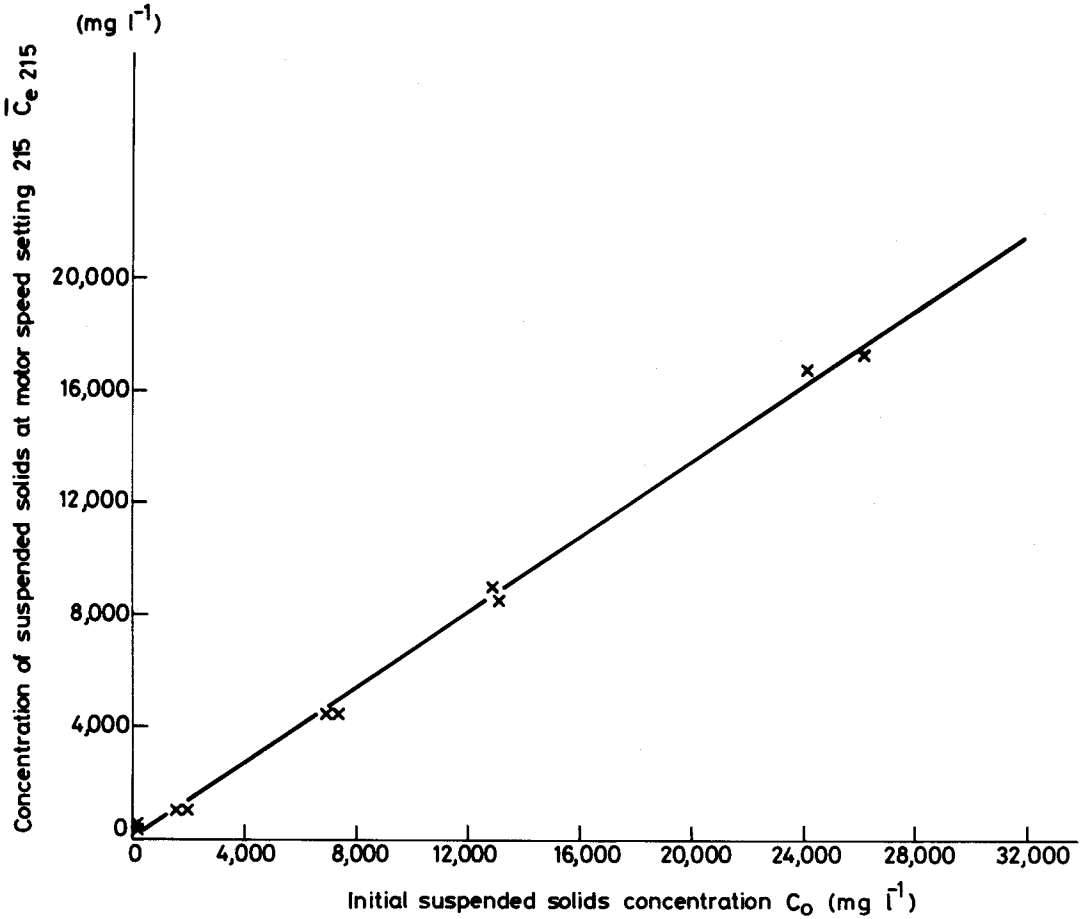


Fig 10 Proportional settling

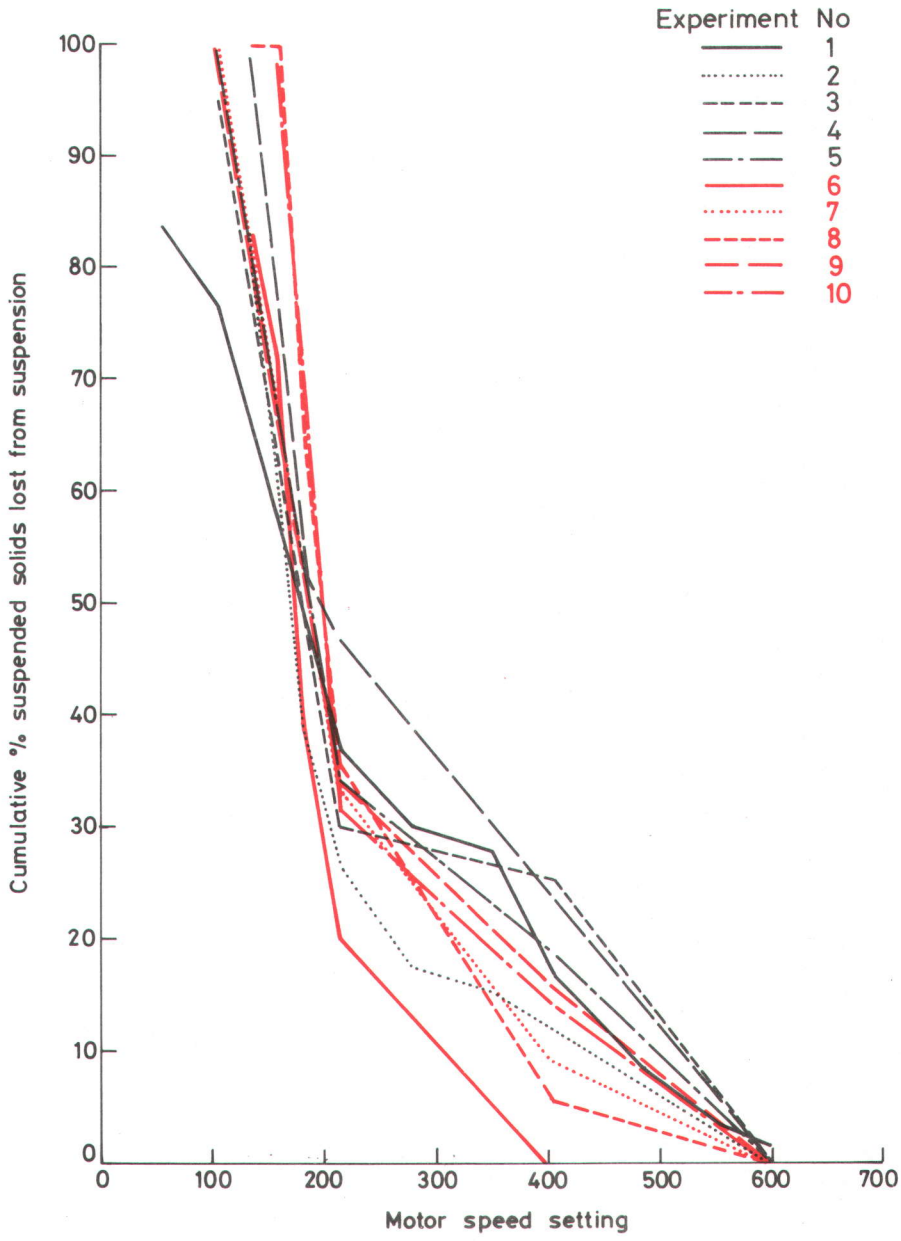


Fig 11 Percentage loss at different speeds