HR Wallingford

FLOCCULATION AND SETTLING OF COHESIVE SEDIMENTS

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ABSTRACT

This report describes the development of a video imaging system to measure floc size and settling velocity in the field and laboratory. In the field the system has been used on the River Tees, the Thames and Mersey Estuaries and in Dover Harbour. The concentration range for these measurements has been from 10-1100ppm. In the laboratory the HR carousel was modified to allow a sample of the suspension to be withdrawn through the base of the carousel. A series of experiments were undertaken using the HR carousel to generate flocs, with concentrations in the range 15-1400ppm and bed shear stresses in the range 0.04-0.40N/m^2.

The video imaging system is fairly well automated and easy to use. An advantage over other methods is the visual record of settling on tape. This allows for subsequent reappraisal of a set of measurements.

In the field and laboratory the settling velocity of flocs has been found to increase with floc size. The largest flocs are present at the higher concentrations. In the laboratory for concentrations in the range 0-300ppm there was good agreement beteen the results of the video imaging system and those previously obtained in the field using the Owen tube. However, for higher concentrations in the range 600-1400ppm the settling velocities in the laboratory were much lower than those measured in the field. This is attributed to either inhibited floc growth within the carousel or because the sampling method destroyed large, rapidly settling, fragile flocs.

CONTENTS

CONTENTS (CONTD)

TABLES

FIGURES

FIGURES (CONTD)

PLATES

1. INTRODUCTION

Flocculation is the process by which fine particles of cohesive sediment aggregate together to form larger particles which then have a higher settling velocity than the constituent particles. The conditions under which this takes place are prevalent in many estuaries in the UK and overseas. Work was funded by DTp and DoE under Contract DGR/465/36 and carried out by HR between 1982 and 1985 to find out why measurements made under laboratory conditions gave values for the settling velocity an order of magnitude lower than those measured in the field. This showed flocculation to be a dominant process in real sediment systems. The field measurements showed settling velocities and degrees of flocculation to be highly dependent on the concentrations of solids in suspension but unexplained large differences occurred between estuaries (Refs 1 and 2).

As part of the same contract a laboratory facility was commissioned to study deposition of flocculated cohesive sediment from flowing water (Ref 3). Results from both the field work and laboratory tests have been published and discussed at a number of symposia and conferences (Refs 4 and 5). This study arises from the questions asked by academics and engineers concerned with this subject, in particular concerning the applicability of the results of the earlier work to the successful modelling and prediction of siltation for practical engineering projects.

1.1 Objectives

The primary objective of this research is to produce a definitive statement of the factors affecting the settling velocity of mud under field conditions. The aim is to provide a practical guide to the application of this research to the engineering prediction of siltation.

1.2 Programme

A brief outline for the programme of this research is given below:-

i) Investigate instruments for measuring flocs.

ii) Modify the HR mud carousel to incorporate a settling column in its base.

iii) Choose a field site and obtain a quantity of standard reference mud for use in tests.

iv) Carry out experiments in the carousel covering a range of initial shear stresses.

v) Carry out field measurements to provide data for direct correlation with laboratory results.

1.3 Methodology

The behaviour of natural sediments can be reproduced in the HR Carousel flume. The processes of flocculation, settling and erosion have all been observed and reported previously (for example Refs 3 and 6). The aim of this study is to develop a system for measuring the properties of individual flocs in both the laboratory and the field.

Using this system a series of controlled experiments can be carried out in the laboratory and the relationships between shear stress and concentration and floc size, settling velocity and density investigated. In the field the same system can be used to determine the properties of flocs formed in a natural environment. A comparison can then be made between the behaviour of flocs in the laboratory and the field.

1.4 Video imaging technique

The system adopted for measuring the size and settling velocity of individual flocs (and then inferring floc density) is described in detail in Chapter 5. A high magnification video camera is used to record flocs settling. Subsequently pairs of images from the tape are digitised and analysed using an image processing system to determine size and settling velocity. The uniqueness of this system is that the method is fairly well automated and easy to use and as far as we are aware the first such analysis system to be used operationally.

1.5 Report structure

The basic theory behind the interactions of particles and fluids in a gravitational field are discussed in Chapter 2 along with the concept of floc formation and break up. In Chapter 3 the various instruments for measuring flocs in marine and estuarine environments are described that led to the development of the video imaging technique for this study. In Chapter 4 the HR carousel flume and the modifications made to incorporate a settling column into its base are described. In Chapter 5 the operation of the video imaging technique is described and the analysis procedure leading to the determination of floc settling velocity and effective density presented. In Chapter 6 the results of the laboratory experiments are presented. In Chapter 7 four cases where the video imaging technique has been employed in the field are presented. A discussion and conclusions are given in Chapter 8.

2. PARTICLES AND FLUIDS IN A GRAVITATIONAL FIELD

2.1 Stoke's Law

For a non flocculating suspension of small near spherical particles, the terminal settling velocity can be directly related to the particle size by Stoke's Law if the particle density is known. Stoke's Law applies to spherical particles having a Reynold's number less than 0.1 (The Reynold's number is the ratio of inertial forces to viscous forces in a system). For quartz spheres this would correspond to particles smaller than about 50 microns at normal temperatures. Terminal velocities calculated for larger particles will be overestimates.

$$w = 2g(p_s - p_l) r^2 / 9v$$

where w is the terminal settling velocity
p_s is the sediment specific gravity
p_l is the liquid specific gravity
r is the particle radius
and v is the kinematic viscosity

In sedimentation tests it is assumed that terminal velocity is reached instantaneously, it has been shown that this assumption introduces negligible error (Ref 7).

2.2 Cohesive sediment

The settling of cohesive particles cannot yet be calculated from any theoretically derived expression. These particles are usually in the fine silt and clay size ranges (<63 microns), where Brownian motion is significant compared with gravitational motion. For the finest particles (<1 micron), the Brownian motion would be sufficiently strong to maintain the particles in suspension for a very long time.

Flocculation is the mechanism that causes these particles to settle out. As the particles collide with each other, for instance by Brownian motion, cohesive forces which are large compared with the gravity forces cause them to adhere to each other, forming aggregates of particles or flocs. These flocs can be large enough to overcome Brownian motion and settle out.

The basic unit of settling for cohesive sediment is thus a floc. The size and form of the floc depends on the frequency of collision of particles, and on the strength of the cohesive forces. These forces are complex functions of the particle mineralogy, the nature of the suspending medium; electro-chemical and bio-chemical, and the frequency of collision due to turbulence, Brownian motion or differential settling. The latter depends on the volume concentration of the particles/flocs in suspension. For this reason, the settling velocity of a cohesive material has to be measured experimentally, under conditions resembling as closely as possible the natural environment of the material.

2.2.1 Collision

Collision can occur due to either of the three previously mentioned processes; Brownian motion, internal motion (turbulence) or differential settling.

The probability of a single collision due to Brownian motion is calculated from the expression (Ref 8)

$$I = 4kTn/3u$$

where I is the number of collisions per unit time, k is Boltzmann's constant, T is the absolute temperature, n is the number of particles per unit volume and u is the dynamic viscosity. For the estuarine environment there are two important parameters; the viscosity, u, is almost halved as the temperature increases from 4°C to 24°C and the number of particles per unit volume which is related to the concentration by weight of the material in suspension, which can vary from 10mg/l to about 10g/l. Flocs formed by Brownian motion have a ragged structure, are weak and easily dispersed by shearing or easily crushed in a deposit (Ref 9).

For collision due to internal shearing the expression is

$$J = (4/3)nR^3du/dz$$

where J is the number of collisions per unit time, n is the number of flocs or particles per unit volume, R is the effective floc or particle radius and du/dz is the local velocity gradient. The product nR^3 is a measure of the volume occupied by the particles in suspension, as flocs are formed the inclusion of interstitial water reduces their density and hence the volume concentration, and nR^3 can increase even though the weight concentration remains constant. Flocs formed by velocity gradients tend to be spherical (Ref 10) and are stronger than those formed by other collision mechanisms.

The effect of differential settling velocities on the collision of particles or flocs is more difficult to determine because, as well as depending on the particle radius, and on the concentration, the frequency of collision also depends on the distribution of particle sizes, which itself varies as collision and flocculation proceed. It has been reported that there are minimum radii associated with settling particles and caught particles (Ref 7); for primary particles of a typical clay these would be 5.0 and 2.1 microns respectively.

The process of differential settling contributes to the rapid clarification of water during near-slack periods in mixing zones where the concentration is high (Ref 11).

2.2.2 Cohesion

The cohesive forces exerted between two clay particles depend on the mineralogy of the clay, the electro-chemical nature of the suspending medium and the presence of any organic material. The mutual forces experienced by two or more clay particles in close proximity are the result of the relative strengths of the attractive and repulsive forces. The attractive forces are due to the interaction of the electrical fields formed by dipoles in the individual molecules. These forces vary inversely with the seventh power of distance between particles.

The surface of clay particles is usually negatively charged. The charge on each clay particle is neutralized by ions from the suspending medium, which swarm around the clay particle. When two clay particles, with their accompanying ion clouds, approach each other the repulsive forces are due to the ion clouds, of like charge, repelling each other. The repulsive energy between the particles depends on the ion concentration and the ion valency, generally decreasing as these increase.

The resultant forces can be either attractive or repulsive. In suspensions with a low ion concentration, the ion cloud is large, and the repulsive forces keep the particles too far apart for the attractive forces to have effect. As the ion concentration or ion valency is increased, the ion cloud is reduced in size, accordingly the particles can come closer together. Eventually the ion cloud size is such that the attractive forces prevail and the particles then join together as flocs.

The presence of organic matter in the suspension has been reported to act as a 'glue' increasing the growth and formation of flocs (Ref 9). Micro organisms resident on some clay minerals or flocs also exude this 'glue'. In estuarine waters the 'glue' is generally found to be polysaccharides produced by microorganisms. This phenomena has been observed during the spring-neap cycle where the activity of such organisms is responsible for increasing the resistance of the surface layer of inter tidal flats to subsequent reerosion.

2.2.3 Floc break up

Turbulence influences the floc size in two different ways. As shown in Section 2.2.1, an increase in turbulence results in an increase in the number of collisions per unit time and thus in larger flocs. However an increase in turbulence also results in an increase in the turbulent shear stresses in the flow. When these are larger than the strength of the flocs, the flocs will be broken down, thus turbulence can also result in a limitation of the floc size.

2.2.4 Limiting Floc size

It might seem that even with the mechanisms of floc break up described above that flocs may grow indefinitely in size under certain conditions. However, the floc size is limited by the fluid shear the particle bonds can withstand. As uninhibited flocculation proceeds the flocs get larger until the fluid shear exerted on them by the settling velocity equals the inter-particle bond strength. The flocs will then have reached a terminal size and settling velocity.

2.3 Settling within a column

When particles settle through a fluid of finite extent there are two effects; the fluid pulled along by the particle must produce a return flow since it cannot pass through the walls of the containing vessel, and since the fluid is stationary at a finite distance from the particle, there is distortion of the flow pattern which reacts back on the particle (reviewed in Ref 7). The larger particles within the column are more affected by the finite extent of the column.

The effect of the bottom of the column has also been investigated (Ref 7) and a theoretical correction term determined. The correction term is negligible if the sampling is carried out at a distance greater than 1000 particle diameters from the ends of the suspension and is very small for distances as small as 50 particle diameters.

2.4 Hindered settling

If two particles separated by only a few diameters move through a viscous fluid, the fluid flows around the particles in such a way that the resulting viscous force is greater than that acting on a single particle. Hence the terminal settling velocity is smaller than would otherwise be experienced. It is suggested that volume concentrations below which this effect is negligible are in the range 0.05% to 3% (Ref 7). In the Severn Estuary hindered settling occurs above about 2,000ppm (Ref 1).

2.5 Distribution of flocs throughout water column

Puls (Ref 12) makes a distinction between 'fast' and 'slow' flocs. The 'fast' flocs are those obtained in the first sample withdrawn from the Owen tube (see Section 3.2). Analysis of 'fast' flocs shows that they contain less organic matter and are composed of larger mineral particles. Relatively more 'fast' flocs were found at the surface than the bed and relatively more 'slow' flocs were found at the bed than the surface. In reality there are more flocs at the bed than the surface because of the high concentration of suspended solids near the bed.

The region of high shear stress at the bed prevents flocs settling to the bed. Only those flocs that are strong enough to resist the bottom shear stresses will settle onto the bed and be attached to the bed by cohesive bonds. Flocs in which the strength is too low will break up into smaller flocs which will then be re-entrained into the suspension by hydrodynamic lift forces. These smaller flocs will then again participate in the flocculation process in the water column.

2.6 Procedure for estimating settling velocities

The best method for determining the settling velocity for use in engineering problems is to measure settling velocities in the field. If the location is one where these measurements have previously been made then it is reasonable to use previous results provided there have been no major works to change the hydraulic regime of the site. If this is the case than further measurements should be made.

If no data is available for the site then the procedure adopted at HR (Ref 1) is to estimate the median settling velocity by

$$w_{50} = 0.001C \qquad (0.05<C<2.0)$$

where C is the suspended sediment concentration (kgm^{-3}). This relation is based upon field measurements made at a number of locations (Ref 1). However, between these locations the measured settling velocities vary by an order of magnitude and in estimating siltation rates the range of possible values should be stated.

The HR Mud Manual (Ref 1) recommends the use of the median settling velocity, w_{50}, for use in engineering problems. However in some circumstances it is more appropriate to use a higher value, say w_{70}, because half the material settles faster than w_{50} leading to low estimates of siltation during short periods of settling such as slack water. If there is continual settling such as in a sheltered harbour then w_{50} is more appropriate.

3. INSTRUMENTATION

3.1 Introduction

Most measurements of fall velocity in the field and laboratory are made indirectly and generally do not measure both the settling velocity and size of a given particle (which leads to the determination of an effective floc density). In most cases the particle size distribution is inferred through the settling velocity distribution and some assumed density distribution. There have been some recent applications of photographic techniques to determine the settling velocities and size of marine snow. However with respect to observations made in an estuarine environment, where concentrations are much higher, no instrumentation is currently available to determine both size and settling velocity distributions. The present use of the Owen tube (Ref 13) or a derivative of this design has not been improved upon for the last 20 years.

3.2 Marine Instrumentation

The first in situ measurements of settling velocity and particle size were made in 1980 (Ref 14). A holographic particle velocimeter (HPV) was developed at the University of South Florida that measures size, shape and settling velocity of individual particles. The device, originally developed in the laboratory, has been used in a free floating sediment trap for in situ studies. The holograms were reconstructed on a screen and size and settling velocities were determined from a comparison of two successive holograms. Particle sizes in the range 15-250 microns and settling velocities between 0.19 and 2.30 mm/s were measured.

The concept of using optical measurements to assess particle size has been put into practice in the form of the remote optical settling tube (ROST) (Ref 15). The instrument is able to measure the time series change in transmission of collimated light perpendicular to a column of water as particles in the column settle out of suspension. It is then possible to infer the settling velocity distribution of the suspension. By assuming a Stoke's type settling velocity, and for specific particle densities, the distributions of settling velocity can be converted into particle size distributions (in the same way as particle size is inferred from the Owen tube results). The diameter of the light beam in the ROST was 15mm and the sampling interval was 32 seconds.

3.3 Estuarine Instrumentation

Owen tube

The Owen tube designed at HR (Ref 13) or a derivative of this design, has long been the main instrument for determining settling velocities of estuarine suspensions (Plate 1). The tube is essentially a sampling device which doubles as a bottom withdrawal column. The tube is lowered into the water and held at the required depth, aligning itself with the flow. A trigger is operated which causes the tube to trap a sample of the estuarine water. It is assumed that since the tube aligns itself with the flow, and because there is flow through the tube, the sample obtained in this manner is representative of the flocs within the estuary. The tube is retrieved and as it is brought above surface the column returns to the vertical. A clock is started and samples withdrawn at given times, typically 3, 6, 10, 15, 25, 40, 60 and 61 minutes. Subsequent analysis of these samples produces a settling velocity distribution from which it is possible to infer a median size from Stoke's Law. With the method used (1 hour settling time, eight samples), all solid matter with settling velocities between about 0.05mm/s and 5mm/s is recorded. If the median settling velocity, w_{50}, is smaller than 0.05mm/s the cumulative frequency curve is extrapolated, the smallest w_{50} that is still determinable is of the order of 0.001mm/s.

There are a number of limitations with the Owen tube technique;

1) In low concentrations (less than 50ppm) the mass of material in the 8 samples

is very small and standard analysis techniques are not able to determine these small masses accurately.

2) As the column is retrieved from the sampling depth to the surface settling can occur so that as the column returns to the vertical a density current is formed within the column causing substantial mixing. This is a particular problem at higher concentrations. Delft Hydraulics have developed a modified field instrument based on a side withdrawal system which returns to the vertical immediately the sample is obtained (Ref 9).

3) The sampling by bottom withdrawal typically takes over one hour to complete. This means that reflocculation can occur within the Owen tube after the sample has been retrieved. Puls (Ref 12) concluded that floc formation as a consequence of differential settling within the column increases the measured settling velocities appreciably and that a reduction factor needs to be applied. For Owen tubes results from the Elbe the application of the correction factor led to a reduction factor of 4.4 in the median settling velocity. However since differential settling is a phenomena that may be important in some engineering problems it is possible that in some cases the

settling velocity determined by the Owen tube is appropriate to use without any reduction factor. Similarly hindered settling also occurs in the Owen tube and this can be an important mechanism in the field. Kirby and Parker (Ref 16) present field observations of sharp interfaces in concentration profiles in the Severn Estuary which are caused by hindered settling.

4) It is also possible that during the sampling period external influences such as air temperature may become important causing changes in viscosity and setting up convection currents within the column.

5) The Owen tube itself and the method of capturing the sample will affect the sample which is obtained. The method of trapping the sample is likely to cause significant turbulence within the column and corresponding floc break up and reflocculation. It is thus possible that to a certain extent the flocs in the samples retrieved are not representative of those in the estuary from which they were taken. However this is a problem inherent in all sampling devices and for most purposes the samples obtained by the Owen tube (or similar device) are adequate for making engineering predictions.

Laser particle sizer

Field measurements using a Laser particle sizer have shown that floc size varies with depth and current velocity (Ref 17). The main advantage of this in situ system is the very rapid rate of analysis. It is not possible to determine settling velocities using this technique. Strong evidence was found showing that pumped samples obtained concurrently and analysed using the same method contained fewer large flocs. A problem with the laser particle sizer is the way in which the ranges of particle sizes incorporated in each size band are not linear. For example (Ref 17), of 15 bands recording particle sizes over the range 6 - 564 microns, 10 bands will be in the range 6 - 65 microns and the top band will cover the range 262 - 564 microns. Thus although the method can accurately determine the size of very small particles (less than 10 microns) the resolution of flocs in the size range greater than 20 microns is not very good. However this is the only automated size analysis system that has undergone field trials that we are aware of at the time of writing.

Coulter Counter

The Coulter technique is a method of determining the number and size of particles suspended in an electrolyte by causing them to pass through a small orifice on either side of which is immersed an electrode. The changes in resistance as particles pass through the orifice generate voltage pulses whose amplitudes are proportional to the volumes of the particles. The pulses are amplified, sized and counted and from the derived data the size distribution of the suspended material may be determined.

Kranck has used the Coulter Counter on numerous occasions as a means to investigate the size of floc distributions compared to single inorganic grains after oxidation of organic matter and deflocculation (eg. Ref 18).

3.4 Video imaging technique

As a result of the investigation into available instrumentation packages it was decided that no apparatus currently existed that would allow for rapid analysis of data to measure both the size and settling velocity of cohesive sediments.

A doppler method is useful for analysing the properties of small, fast moving objects (ie. particles moving under the action of horizontal currents). However to determine the properties of small, slowly moving objects requires a different form of analysis.

A photographic technique is appropriate except that using film there is no readily available technique for analysing pairs of images to detect movement and to measure size other than displaying them on a screen and manually measuring movement and object sizes. An image processing system could be employed at this stage to carry out the analysis but even still the analysis would require manually displaying pairs of images and rerecording them. It was decided that without automation the system would be impractical as a field technique, although as a research tool the photographic technique was very promising.

A short series of experiments showed that using a standard CCD video camera with c-mount to Nikon mount adaptor, 200mm bellows and standard 135mm Nikon lens images of 3 x 4mm could be obtained with a resolution of 20 microns. Using a reversed 35mm lens gave an image size of approximately 1mm square and correspondingly increased resolution.

It was also found that a narrow beam of light from a slide projector gave sufficient illumination to film settling within an Owen tube. Tests showed that this form of illumination caused no thermally induced circulation within the settling column. Typically the slide projector was about 0.8 - 1.0m from the settling column (see Fig 1).

An appraisal of different commercially available image processing systems showed that there were many systems available for determining object size, shape, position etc. (most of these systems were aimed at the medical and biological sciences for cell counts etc.). No systems were available to automatically carry out an analysis between two successive images to determine object movement. All these systems were able to operate from a live image produced by a video camera.

Only one system, available from Digithurst, was found that could satisfactorily operate from a recorded video image. This system was obtained on the understanding that the standard image processing facilities be extended by Digithurst to include a method for grabbing two successive images from a video tape at a prescribed time interval. This additional modification was carried out in due course.

The video camera, bellows and lens combined with either a VHS or U-matic recorder and the image processing system thus formed the hardware of the video imaging system. The operation of this hardware is described in Section 5.1 and the analysis technique is described briefly in Section 5.2.

4. HR CAROUSEL

4.1 Description of Carousel

The carousel flume (Fig 2) is an annular flume, with an outer diameter of 6m, a channel width of 0.4m and depth of 0.35m, and has a detachable roof 0.09m thick. The flume stands approximately 1.1m off the ground, supported by 12 brick pillars. The channel and roof are constructed of fibre glass, with a 0.12m long perspex section in the channel for viewing. The roof fits into the channel, and floats on the fluid. Fluid motion in the carousel is induced and continued by the drag between the roof and the fluid surface as the roof rotates.

The driving mechanism for the roof consists of a DC torque motor with a drive wheel, which turns a horizontal plate around the central spindle. The drive arm is attached to this horizontal plate at one end and to the roof at the other end.

A strain gauge is used to measure the force applied to the roof of the carousel flume as it rotates. Mean strain gauge readings were converted to applied force using a best fit calibration line and the results related to the roof rotation rate (see Fig 3).

The speed of the motor, and hence roof speed, is controlled by a micro computer. The motor speed can be set to an accuracy of

0.1% of the maximum speed. A tachometer voltage was recorded for various motor speed control settings. The relationship between the two was found to be linear. A linear relationship was also obtained between the motor speed and the roof speed. The relationship obtained (see Fig 4) demonstrates a slight non-linearity of the control system. Figure 5 shows schematically the filling and emptying process involved with the carousel.

4.2 Flow velocities in the carousel

Flow velocities within the carousel have been measured using a direct Laser doppler anemometry technique in pure water (Refs 3 and 19). The measurements were very accurate (±1mm/s) and can be made at any point in the cross section of the flume, through the perspex measuring section. These measurements show evidence of a secondary flow system at right angles to the horizonal component of the flow. This secondary circulation is induced by the centrifugal force produced when the roof is rotated. The motion is helical because of the longitudinal component of the flow. The velocity fields within the carousel have been numerically modelled at the Polytechnic South West (PSW) and the predictions show good agreement with the observations (Ref 19).

4.3 Bed Shear stress measurements in the carousel

Four methods have been employed for measuring the shear stress exerted by the fluid on the bed. The first method was simple and involved direct measurement of the energy input to the roof through the calibrated strain gauge. A number of different speeds of rotation of the roof were used ('input' in Fig 6). This method can only predict a mean bed shear stress.

The second and more complex way of determining the bed shear stress was by measurement of the near bed velocity profiles in the flume. The friction velocity at the bed was determined from a log-linear plot of height above bed and horizontal velocity. Velocities were determined at three sections across the width of the flume for different speeds of rotation of the roof. The bed shear stresses were then computed from the logarithmic portion of the velocity-depth profiles ('average 1' in Fig 6).

Thirdly flush mounted shear stress probes designed at PSW were deployed to measure shear stress along the base and side walls of the flume (Ref 13). The results of this work are shown as 'average 2' in Figure 6. Shear stresses determined from the numerical model are shown as 'predicted' in Figure 6.

It is also possible to infer the qualitative distribution of shear stress across the flume from eroded profiles of mud beds. It is assumed that the shear strengths of a mud bed increase with depth but are consistent across the width of the flume. A strong relation was found between the depth of erosion and the bed shear stress predicted by the PSW numerical model except within 0.05m of the outer wall of the flume. However the shear stress probe measurements illustrate a similar trend to the erosion profiles. This effect may be due to incomplete resolution of the secondary circulation in the numerical model.

4.4 Modification to carousel

It is possible to measure approximate floc size distributions through the perspex window of the carousel using the video imaging technique. The speed of rotation influences the clarity of the images and analysis can only be approximate (see also Section 5.3). However, to determine settling velocities it is necessary to observe flocs in an environment where there is minimal horizontal fluid motion (typical settling velocities are in the range 0.05 - 2.0mm/s whilst horizontal velocities and turbulence may be up to 0.5m/s). It was thus necessary to install a device in the base of the carousel into which a sample of the suspended sediment generated in the carousel could be withdrawn and then filmed.

Initially a plug and settling column as shown in Figure 7 was installed. The basis of the design was to minimise disturbance to the flocs formed within the carousel. The settling column was filled with filtered water at the same temperature and salinity as that in the carousel and a sample of the suspended sediment withdrawn into the settling column by pushing up the plug and running off a volume of the clear water from the bottom of the settling column. The settling process was then filmed. Subsequently by a system of flushing, the settling column can be refilled with clean filtered water.

5. VIDEO IMAGING TECHNIQUE

5.1 Operation

The system is operated in the same manner whether imaging is being carried out in the field or in the laboratory. Once a sample has been obtained filming should commence almost immediately, in order that the flocs are analysed in as close to their in situ state as possible. In practice filming can typically start within one minute of retrieving the sample. Turbulence caused by the retrieval method within the sample is usually damped out after a few minutes.

The camera and light source (typically a slide projector) are set up perpendicular to one another and focused on the settling column (see Figure 1). An adjustable slit is placed in front of the slide projector to control the amount of light on the settling column. The position of the camera relative to the illuminated portion of the settling column and the bellows extension are finely adjusted until the correct focus is established. This is very sensitive since at the high magnifications used the depth of field is very small. The aperture on the lens can be adjusted to provide the best image, however for the analysis purposes it is best to maintain the largest aperture possible so as to keep the depth of field to a minimum.

Once the correct focus and light level has been established a record of the bellows extension is made. Because the depth of focus is so small it is then possible to back calibrate the image during the analysis stage. There is a unique magnification associated with every bellows extension for a given lens. The output from the camera is then recorded on video tape. The output from a time date generator can also be added to the recording for analysis purposes. The format of the camera and recorder should be either PAL or RGB compatible.

5.2 Analysis

There are various methods of selecting consecutive images from the video tape. In this section the analysis of a single pair of images is described.

The output from the video recorder is used as input to an image processing card installed in an IBM compatible PC. This card then converts the analogue input into a digital output which is displayed on a monitor (this occurs in real time for either monochrome or colour images). The brightness and contrast of the digital image can be adjusted to enhance the recorded image. The analysis is more straightforward and faster if all analysis is carried out in monochrome mode.

The image is calibrated using the recorded bellows extension and then the system is set up to capture two frames. Video frames are comprised of two interlaced fields which are 0.02 seconds apart, thus successive frames are 0.04 seconds apart. The image processing card has a minimum capture interval of 0.25 seconds (since one image is up to 1Mb in size a finite time is required to write this data to the on card store). The required interval between the two frames is selected (typically 0.28 seconds) and then, with the tape playing, the images are grabbed.

Once a pair of images are grabbed the analysis is automatic. A grey scale level (0-255) is chosen at which to form a cut off, this thresholding results in the monochrome image being converted to a binary image (see upper photo in Plate 2). The binary image is then analysed using various in built features of the image processing card. Parameters such as detected object size, intensity, position (x,y co-ordinates in pixels) orientation, perimeter, area, etc can be automatically determined. From these records it is possible to immediately produce a size distribution for detected objects in the image. Providing that an appropriate thresholding level has been chosen this then converts to a floc size distribution.

5.3 Determination of settling velocity

Given that the time between the two consecutive images is known, all that remains is to determine the relative movement between the two frames (shown in the two photos in Plate 2).

The movement can be manually determined by using routines of the image processing card (Ref 20) or an automatic analysis routine external to the card can be run. This software was developed at HR and is described below.

The method consists of comparing the recorded parameters of one detected object in one image with those of all detected objects in the other image. If a pair of detected objects have similar size, shape, intensity (grey scale value) and position they are deemed to be the same object in successive images and the settling velocity can be inferred. In order that a level of confidence in such automatic analysis can be achieved the two data sets are compared in four different orders. Only if the same pair of objects are matched in each sweep through the data is it inferred that the data refers to the same object in each image.

A comparison between manual and automatic determination of floc size and settling velocity was made. It was found that the automatic system worked well but was not able to match up as many pairs of objects in the two images as the human eye/brain combination. However since the automatic system typically identified 50-60% of the objects identified manually it was deemed to be satisfactory on the basis that it was a method considerably faster than the manual system (possibly as much as 10 times faster) and it was independent of the operator.

5.4 Determination of floc density

If the size and settling velocity of a floc are known it is possible to use Stoke's Law to determine an effective floc density. In the simplest case it is assumed that the floc is spherical (Ref 9).

$$p_s = 9vw_{50} - p_l$$

Having assumed spherical flocs it is possible to determine the mass of the individual settling flocs and hence produce a plot of cumulative mass against settling velocity as is carried out in the standard Owen tube analysis.

6. LABORATORY EXPERIMENTS

The programme of laboratory tests is outlined below:-

i) Investigation of sampling mechanism.

ii) Calibration of analysis technique.

iii) Size distribution of flocs in the carousel.

iv) Effect of time on settling within column.

v) Effect of concentration on floc size and settling velocity.

vi) Effect of shear history on floc size and settling velocity.

vii) Investigation of other phenomena observed during above tests.

6.1 Sampling mechanism

The sampling system is shown in Figure 7 and described in Section 3.4. During the course of early experiments it became apparent that it was almost impossible to generate a perfect seal between the settling column and the carousel using the simple plug mechanism and that although leakage did not occur, a significant circulation was set up within the settling column due to the flow over the top of the plug. There were also practical problems encountered in the flushing and refilling of the settling column whilst the carousel was full. It was also noted that the actual withdrawal method produced secondary circulation within the settling column.

Because of the problems initially encountered it was necessary to adopt a different sampling system. The same plug and settling column below the carousel was used, however, a large bore tap was installed at the top of the settling column (see Fig 8). It was now possible to open the plug, open the tap and run off a sample of the suspended sediment into a second settling column, filled with filtered water at the same temperature and salinity as that in the carousel. This column was independent of the carousel and could be properly cleaned and refilled between sampling events. Initially on opening the plug and tap the suspended sediment was run off into a bucket and filtered to use for the next sample. Not until the flow was deemed to be representative of the suspension within the carousel was the settling column inserted below the tap and a small sample (approximately 50ml) run into the column.

Using this new method strong circulations were initially set up in the upper part of the 0.6m long settling column. However, if filming was carried out between 0.1-0.2m above the base of the column by the time the flocs were passing through the field of view of the camera the circulations set up were damped out.

Problems with this system are listed below:-

1) Flow through the tap; during this passage the flocs could experience and react to shear stresses higher than those in the carousel.

2) Initial circulation in the settling column; a period of swirling at this stage enables reflocculation and growth/destruction of flocs.

3) Time lag between first observations and time sample was withdrawn; during this period the properties of the flocs may alter owing to either 1) or 2) above or some other process.

It is possible to minimise these problems by the experimental technique, it was considered that overall the method was adequate for the series of experiments intended. An important feature of this laboratory method was that it would be very easy to repeat the entire process in the field, obtaining a sample of suspended sediment using either an Owen tube or Casella water sampler or some other device.

6.2 Accuracy of analysis technique

Prior to undertaking the series of experiments and as part of the process of assessing different commercially available image processing systems, film was made of different size particles settling within the settling column. This provided a means of assessing the likely accuracy of the system and the subsequent analysis techniques employed.

Sand grains were obtained from the HR Sedimentation Laboratory in the following sizes; <38um, <63um, 150-180um, 180-210um, 300-355um, 355-425um. The results of the subsequent analysis are shown in Table 1.

It can be seen that the best agreement between the observed settling velocities and the velocity predicted from Stoke's Law is obtained for the grain sizes 150-210um. For the finer particles flocculation is beginning to occur, and this combined with the way in which these fine grains behave in the settling column (settling as swirling clouds) means that the particles settle faster than would otherwise be expected. The coarser grains, although observed to settle at close to their predicted speeds, are a little slow. This is to be expected since Stoke's Law overestimates the settling velocity of larger particles since it discounts the inertial effects (Section 2.1). The larger particles will also be affected by the diameter of the settling column (Section 2.3).

6.3 Size distribution of flocs within carousel

During the course of trials with the high magnification camera film was taken through the window of the carousel. Later analysis of this film using the image processing system could provide no more than a visual appraisal of floc size since the horizontal motion was generally too fast and the quality of the images obtained not sufficient to carry out standard analysis procedures. However with the highly magnified image it was possible to estimate maximum floc size.

Film was made of the erosion process. This showed that the erosion mechanism was a process where large flocs, up to 2.0mm in size, were dislodged from the bed and lifted up into the flow. These large flocs were then rapidly broken up into smaller flocs with maximum size typically less than 0.2mm. This process of large floc break up in the high shear layer close to the bed is in agreement with the mechanism discussed in Section 2.5. The interesting observation is the actual erosion process, where large flocs are removed from the bed rather than individual particles or small flocs. However since the flocs have to be relatively strong to settle onto the bed

(Section 2.5) it is perhaps not surprising that they are sometimes apparently removed as complete entities.

These observations provide evidence of the size of flocs within the carousel. It should be noted that in the field using the Owen tube floc sizes of 1mm or more (estimated by eye) have been reported.

6.4 Effect of time on settling velocity distribution

Once a sample has been obtained in a settling column the settling process takes a considerable time to complete. The finest particles in the suspension may not have completely settled even if left overnight. However, considerable changes in the size and settling velocity distributions at one point in the column occur during the first 30 minutes of settling.

Throughout any one experiment the position of the camera remains fixed. Initially (typically the first minute) the fastest travelling particles/flocs are recorded, these may be individual sand grains or large flocs. With time (from 2 minutes onwards), a steady rain of flocs fall through the field of view. The size and settling velocity distributions of these flocs changes with time. Initially there are larger more rapidly settling flocs present (2-10 minutes), eventually the flocs appear to be of nearly the same size and settling velocity (20 minutes onwards). This latter phenomena seems to be due to processes within the settling column. The process eventually reaching a quasi steady state, with a balance achieved between flocculation and disintegration of small particles.

Figures 9 and 10 show the size and settling velocity distributions respectively of a sample obtained from the carousel with a concentration of 263ppm. Figures 9a and 10a show data obtained in the first 10 minutes whilst figures 9b and 10b show data obtained between 10 and 35 minutes after settling commenced. It can be seen that there are more large flocs present at the start of the settling process (Fig 9a) and that the mean settling velocity is greater at the start of the settling period (Fig 10a). It can also be noted that settling velocities are seen to increase with floc size.

Figure 11 shows the floc size against calculated effective density (Section 5.4). Density is found to decrease with increasing floc size as expected.

Figures 12 and 13 show the mean size and settling velocity determined from each pair of grabbed images during the first 35 minutes of the settling period. Although there is some variability in the first 15-20 minutes of settling there is a very clear trend of reducing floc size and settling velocity with time. Both parameters appear to asymptote towards the quasi-steady state referred to above. Figure 14 shows the average effective floc density with time. A trend for increasing density with time can be seen.

From these observations it was deemed that in order to obtain the size and settling distributions of the flocs in a state as close to the conditions inside the carousel it was necessary to analyse only images obtained during the first 5-10 minutes of settling. It is assumed that after the sample has been within the settling column for more than 10 minutes processes occurring within the column have significantly affected the physical properties of the flocs in the column.

6.5 Effect of concentration.

A quantity of mud was obtained from the Thames Estuary at Tilbury. This site was chosen because of the large data sets that already exist for the Thames at HR. Over 200 Owen tubes have been obtained from the Thames in recent years (Ref 2) and a well established silt monitoring program has been in existence for the last 20 years.

In the laboratory quantities of Tilbury mud were sieved (to remove stones, coal, etc) and then mixed in the mixing tank (Figure 5) with a quantity of salt to produce a salinity of approximately 20ppt. This suspension was then pumped into the carousel to a depth of about 150mm.

A number of tests were carried out in the carousel using different concentrations and different shear stresses (roof rotation speeds). The test programme is given in Table 2 with the sample concentrations that were subsequently measured in the HR Sedimentation Laboratory. To a large extent the concentration of a suspension in the carousel is governed by the shear stress since below a critical stress settling occurs.

Taking all the experiments that were carried out irrespective of the shear stresses applied it can be seen that for the lower concentration suspensions generated in the carousel there is good agreement between the laboratory results and those obtained in the Thames over a number of years (Figure 13). For the higher concentrations the settling velocities measured in the laboratory are about half those measured in the field. This may be because there is a limit on the size of flocs that can be generated within the carousel. Flocs up to 0.5mm were seen in Section 6.3, although these were formed during erosion of the bed, subsequent break up of these flocs by shear forces experienced within the carousel reduced the floc size to a maximum of about 0.2mm. Another possible factor is the sampling technique, the size of flocs may be limited by the sampling method. The largest flocs produced in the carousel may break up on passage through the plug and tap system where shear forces may be higher than those experienced within the carousel. It can be seen that settling velocity increases with suspended solids concentration for samples in both concentration ranges.

6.6 Effect of shear history

One of the aims of the experiments was to investigate the effect of shear history on the flocs generated within the carousel. Thus the test programme shown in Table 3 was devised. For every speed of roof rotation used an experiment was carried out over a period of 2-3 hours, with samples being withdrawn and filmed every 30 minutes or so. It was envisaged that if at given concentrations and shear stresses floc growth was occurring then there would be corresponding changes in the measured size and settling velocity distributions.

The result of the whole series of experiments was that there was no conclusive proof for such a phenomena occurring within the carousel. It is possible that the speed of such changes was so rapid that the sampling interval was too short. The first sample was taken after the suspension had been remixed by hand, gradually spun up to the chosen speed and then maintained at that speed for a number of minutes. Subsequent samples were taken at 30-35 minute intervals.

There was some evidence that flocs generated during the hand mixing period were of a different nature to those formed after 5-10 minutes of rotation. This is likely to be due to different collision mechanisms occurring during these periods.

6.7 Other laboratory observations

During the settling column experiments it became apparent that towards the end of the settling period (after approximately 25 minutes) sometimes a sharp interface was observed within the carousel dividing a region of high particle concentration from the lower part of the column where a small amount of settling continued. This is shown schematically in Figure 16. A plume of settling flocs was seen extending from the interface towards the base of the settling column. To either side of the flume observations with the camera showed particles ascending and it was deduced that a circulation cell had been set up and become quasi stable.

There was no measurable temperature difference across the interface and no apparent salinity difference. The only density difference being due to the number of flocs in suspension. As described in Section 2.3 settling particles cause a return flow of fluid. It is possible that the circulation cell set up is due to return flow associated with the settling within the plume in the central part of the column. It also seems likely that there is a significant effect due to hindered settling in the region above the interface.

No explanation for this phenomenon is given here, the purpose of noting this observation is to support the hypothesis that the nature of flocs and the flocculation process as observed in a settling column may be quite different to that occurring in the field or within the carousel. It is thus of utmost importance that size and settling velocity distributions are measured in an environment as close to the in situ case as possible.

7. FIELD EXPERIMENTS

In the field for practical purposes, and in order to minimise the disturbance to the sampled flocs, film was made of the settling process that occurred in a homogeneous sample rather than one where a small sample of a suspension was introduced into the top of a column of clear water.

A brief description of fieldwork carried out at four UK sites is given in this Chapter. the reader is referred to the appropriate references for further details.

7.1 Thames Estuary

The first field trial of the video imaging system was carried out on the Thames at Crossness. The aim was to make a direct comparison between settling velocities determined using the Owen tube and those obtained by filming the settling within an Owen tube.

The results of the standard Owen tube survey are presented in Table 4. Filming was carried out concurrently in a second Owen tube, both samples being obtained from the same location within a few minutes of each other.

The internal settling column of the Owen tube is approximately 1m in length with an internal diameter of 50mm. Filming was carried out either 0.3m above the bottom of the tube or 0.3m below the top of the tube. In the two cases where filming in the upper half of the tube was carried out no net settling was apparent with nearly all the material moving upwards. Observation of the whole tube with the naked eye showed that circulation cells were set up inside the column resulting in hindered settling and suspension of the flocs in the upper part of the column. The same observation had been made in the laboratory (see Section 6.7). It is possible that the withdrawal of samples at different time intervals overwhelms this circulation during the standard operation of the Owen tube. However it is worth noting that every time a sample is removed a large scale circulation will occur within the column causing further mixing, floc break up and reflocculation.

Irrespective of the motion of the flocs inside the column if analysis is carried out on images grabbed from the tape close to the start of each settling period it is possible to establish the in situ floc size distribution. These size distributions are shown in Figure 17. As observed in the laboratory an increase in the proportion of large flocs is found with increased concentration. There is however, little difference between the size distribution of flocs in the samples at 420 and 470ppm.

In one of the columns where settling was filmed analysis was carried out to determine settling velocity distributions based on data obtained from images after 5, 10, 15, 20 and 25 minutes of filming. The results are presented in Figure 18 as a comparison with the Owen tube results obtained at the same time. It can be seen that initially the video imaging technique gives significantly higher settling velocities. However after 15-20 minutes of settling the settling velocity distribution measured is similar to that obtained with the Owen tube. It must be noted that the video imaging technique does not resolve the finest flocs, hence the settling velocity distribution measured will be a slight over estimate. However results obtained at the beginning of the filming are likely to be a much better representation of floc size and settling velocity distribution than those obtained from the Owen tube because the flocs have had less time to be altered by their new environment within the settling column. This result shows the same effect as observed in the laboratory (see Fig 12).

One important observation of this study was the inhomogeneous nature of the settling processes throughout the Owen tube similar to that observed in the laboratory (Section 6.7). Steady settling was not observed throughout the column, settling was apparent in discrete regions and regions of upwards flow were also apparent. Thus what is inferred to be a gross settling in the Owen tube is not simply gravitational settling of a sample of flocs generated in the field but a more complex process which includes to some extent the effects of the Owen tube on the settling flocs.

7.2 River Tees

Tees and Hartlepool Port Authority (THPA) are in the process of carrying out a general study of the physical regime of the River Tees. As part of this study HR was commissioned to assist with the measuring of in situ settling velocities of suspended solids (Ref 21). Typical suspended solids concentrations are less than 10ppm, thus the standard Owen tube analysis technique could not be employed and the video imaging technique was adopted.

The results of this work are shown in Figures 19 to 21. It can be seen that even at these very low concentrations the video imaging system operates well. The results suggested that compared with Owen tube results for concentrations greater than 100ppm settling velocities associated with the low concentrations in the Tees were relatively high compared to other estuaries (see Figure 22).

This short study emphasised the practical application of this technique. Once a video tape has been made of a period of settling it is possible to reanalyse the data and to very easily establish an approximate settling velocity. Thus, even though the analysis gave high settling velocities reappraisal of the video tape supported the measurements. This quality assurance would not be possible with the standard Owen tube technique where if necessary a second survey might have had to be made.

7.3 Dover Harbour

In July 1990 Dover Harbour Board (DHB) commissioned HR to establish if dredged material dumped in the approved spoil ground was returning to the Harbour, and, if so, to what extent. As part of this study it was necessary to measure settling velocities within the Harbour (Ref 22). Concentrations are generally low and in the range 0-50ppm.

In total 19 samples were filmed over one ebb tide and one flood tide. As on the Thames it was found that the largest flocs were found at the highest concentrations (Fig 23). However, no relation between settling velocity and suspended sediment concentration was established (see Figure 24). It was suggested that a settling velocity of 0.3mm/s be applied for concentrations in the observed range 10-180ppm (see Figure 22).

7.4 Mersey Estuary

An Owen tube survey was carried out in the Mersey for the Mersey Barrage Company as part of a feasibility study. The results of this survey showed no correlation between settling velocity and concentration. Subsequently HR offered to undertake a short survey using the Video Imaging System.

Samples were obtained on spring and neap tides close to the Manchester Ship Canal approach channel. Over the two periods six samples were obtained covering the concentration range 50 - 400 ppm.

For each retrieved sample 10 pairs of images were obtained from the tape within five minutes of the sample being retrieved. The results thus relate to flocs in their in situ state. As found elsewhere larger flocs are found at the higher concentrations (Figure 25). Particle size vs settling velocity distributions show similar features to those obtained elsewhere with settling velocity generally increasing with floc size (Figure 26). As found at Dover there is no correlation of median settling velocity with concentration and it appears that a constant settling velocity of 0.2 +/- 0.15mm/s is appropriate in the concentration range 50-400ppm.

A comparison of the Mersey settling velocities with those of other sites (Fig 22) shows that settling velocities in the Mersey are low. Comparison of the results of the Owen tube survey with those obtained using the Video Imaging System showed that settling velocities obtained using the imaging technique were approximately half those obtained from the earlier Owen tube survey.

8. DISCUSSION

A system has been developed that allows the determination of individual floc size and settling velocity. There are also possibilities for determining other parameters such as shape, orientation and density. The main problem with this system is filming a sample in an in situ state. Irrespective of sampling technique there will be some disruption of the flow field and this may influence such parameters as the size, shape and density of the flocs sampled. At low concentrations, where generally the flocs are small, the sampling technique is less likely to alter the physical properties of the flocs. At higher concentrations the fragile nature of the largest flocs present is very easily disrupted.

The best method available at present is to film the flocs in a suspension within a few minutes of the sample being obtained. After 20 minutes or so of settling within a column the nature of the floc distribution has been influenced by the column and is not representative of flocs within their natural environment. Within the column small scale circulations are set up as larger flocs settle through a field of smaller flocs and on some occasions larger scale circulations are set up that create structure in the floc field. This observation suggests that a field settling column such as the Owen tube will be influenced by processes occurring within the column and that since the settling occurs typically for one hour the results may be questionable.

Observations of the suspension within an Owen tube showed that all flocs in the top half of the upright tube had upwards movement. This observation was made throughout a 30 minute period during which no samples were withdrawn from the Owen tube. It should be noted that every time a sample is withdrawn from the tube a large scale circulation will be set up that may well cause disruption of the flocs.

In the Owen tube differential settling will take place and is likely to lead to an over estimate of the settling velocity (see Ref 12). On the other hand towards the end of the settling when there are longer intervals between sampling, hindered settling could well occur leading to an underestimate of the settling velocity. The effects of differential settling are likely to occur throughout the entire settling period whilst the effects of hindered settling will probably only occur towards the end of the settling period when most of the material has already settled. Both these processes are important in nature and although there occurrence in the Owen tube may be different to that in the natural environment in certain cases it may be necessary to account for on or other of the processes. The basis for this will be related to the period of settling and the concentrations involved.

The obvious step forward in terms of sampling is to devise a system that does not disrupt the natural floc field. In order to determine settling velocities it will still be necessary to film the flocs as they settle through a column to remove any horizontal component of motion. Devising a mechanism for obtaining a sample underwater without generating secondary circulations due to the horizontal currents is in itself a major project and is currently being carried out at Polytechnic South West (personal communication K. Dyer).

The sampling technique used in the laboratory was found to work well for low concentration samples where the floc size was limited and apparently less influenced by the shear stresses experienced on passage through the tap. It is possible that further laboratory experiments could be carried out in the low concentration range (50-300ppm) looking at the effects of salinity and different sources of cohesive material. However it is felt that samples obtained from the natural environment are a truer representation of natural flocs and that further research should be carried out on field samples.

In the field, samples have been obtained using an Owen tube, a Casella water sampler, a perspex settling column and a bucket. In most cases the samples obtained are then transferred to a settling column where filming occurs. In some cases it is possible to film settling within the Owen tube directly, this is obviously the method which causes least disruption to the flocs. However at low concentrations the other methods appear to be equally suitable. The Casella sampler is the simplest method to use and it would be possible to adapt this sampler to allow direct filming into the sampler. However, in terms of causing the least disruption to the flocs it is felt that the Owen tube would still be the best sampler available because it aligns itself with the flow and there is never any great inrush of water, with associated high shear stresses, into the tube.

9. CONCLUSIONS

1) A system has been developed that can measure the size and settling velocity of individual flocs in the field and laboratory. The effective floc density can be determined from these measurements.

2) The system is fairly well automated and easy to use. An advantage over other methods is the visual record of settling on tape. This also allows for subsequent reappraisal of a set of measurements.

3) Both in the field and the laboratory it has been found that the flocs are affected by the column in which the settling occurs. In order to determine in situ size and settling velocity distributions images should be taken during the first 10 minutes of settling.

4) In the field and laboratory the settling velocity of flocs has been found to increase with floc size.

5) In the field and laboratory larger flocs are present at higher concentrations.

6) In the laboratory it was found that settling velocity increased with concentration and that for

concentrations in the range 50 - 300ppm there was good agreement with previously made Owen tube measurements.

7) For higher concentrations in the range 600 - 1400ppm the settling velocities in the laboratory were much lower than those observed in the field. This is probably because floc growth is inhibited in the HR Carousel and because the sampling method may destroy large flocs.

8) No correlation between bed shear stress in the range 0.04-0.40 N/m^2 in the HR Carousel and the measured settling velocity or size of flocs was found.

9) No correlation with shear history was observed in the laboratory. It appears that in the carousel the distribution of flocs is established very quickly once flow has commenced. There are however significant differences between flocs formed during a period of hand mixing and those formed once the flow in the carousel has been established.

10) Within the carousel flocs formed during erosion of the bed have been found to be up to 2.0mm in size, however the largest flocs observed in the settling column were only 0.2mm. In the field flocs up to 1.0mm have been reported in Owen tubes.

11) During laboratory experiments sharp interfaces developed within the settling column between regions of high and low floc density (by number). These interfaces and the circulation associated with them were not due to convection currents set up by the light source, nor were they due to salinity differences between the water within the carousel and that within the settling column.

12) During the course of any filming flocs are found to move both upwards and downwards within the column. There is no clear case of continual settling throughout the column.

10. ACKNOWLEDGEMENTS

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TABLES.

Table 1

Measured and Predicted Particle Settling Velocity and Size

Sieved Grain Size (microns)	Video Imaging System		Stoke's Law Settling Velocity** (mm/s)
	Size (microns)	Settling Velocity (mm/s)	
355-425	480±20	74±5	81.4-115.5
300-355	370±60	48±2	57.8-81.4
180-210	320±10	26±1	20.8-28.3
150-180	255±10	18±1	14.5-20.8
<63	80±5	4.5±1	<2.6
<38	65±5	5.5±1	<0.9

** The following parameters were used in the prediction;

viscosity assumed to be 0.0000014m/kgs (10°C)
specific gravity of sediment taken as 2.65g/l
specific gravity of liquid taken as 1.0g/l

Table 2

Carousel test program

Concentration (ppm)	Roof Rotation Speed (rpm)	Bed Shear Stress (N/m^2)
15	1.80	0.126
76	1.80	0.126
84	2.29	0.221
93	2.29	0.221
55	2.66	0.311
77	2.66	0.311
101	2.66	0.311
109	2.66	0.311
128	1.12	0.042
112	1.12	0.042
103	1.12	0.042
96	1.12	0.042
75	1.80	0.126
58	1.80	0.126
83	2.29	0.221
100	2.29	0.221
104	2.29	0.221
180	2.66	0.311
134	2.66	0.311
135	2.66	0.311
136	2.66	0.311
137	2.66	0.311
263	3.00	0.426
210	3.00	0.426
236	3.00	0.426
236	3.00	0.426
238	3.00	0.426
188	1.12	0.042
162	1.80	0.126
217	2.29	0.221
297	2.66	0.311
741	3.00	0.426
1383	3.00	0.426
1113	2.66	0.311
863	2.29	0.221
587	1.80	0.126
175	1.12	0.042

Table 3

Effect of shear history test program

Bed Shear Stress (N/m^2)	Time at Shear Stress (mins)	Concentration (ppm)
Constant Shear Stress Program		
0.042	5 35 65 94	128 112 103 96
0.126	20 52 84 160	75 58 54 53
0.221	7 37 69 98	83 100 102 104
0.311	18 55 90 130 160	180 134 135 136 137
0.426	9 44 80 118 166	263 210 236 236 238
Cumulative Shear Stress Program		
0.042 0.126 0.221 0.311 0.426	13 13+36 13+36+35 13+36+35+34 13+36+35+34+37	188 162 217 297 741
0.426 0.311 0.221 0.126 0.042	9 9+32 9+32+34 9+32+34+34 9+32+34+34+35	1383 1113 863 587 175

Table 4

Results of Owen tube survey Crossness (Thames Estuary 3/4/90)

Time	Concentration (ppm)	w^{30} ** (mm/s)	w_{50} ** (mm/s)	w_{70} ** (mm/s)
13:08	536	0.30	1.35	4.85
13:42	455	0.17	0.47	0.85
14:35	412	0.26	1.15	2.90
15:10	337	0.05	0.19	0.51
16:10	232	0.10	0.34	0.74
16:35	130	0.07	0.19	0.41

** Fall velocities are determined at 20°C a reduction of 23% should be made to give appropriate fall velocities at 10°C, the temperature at which the Video Imaging System recorded settling.

FIGURES.

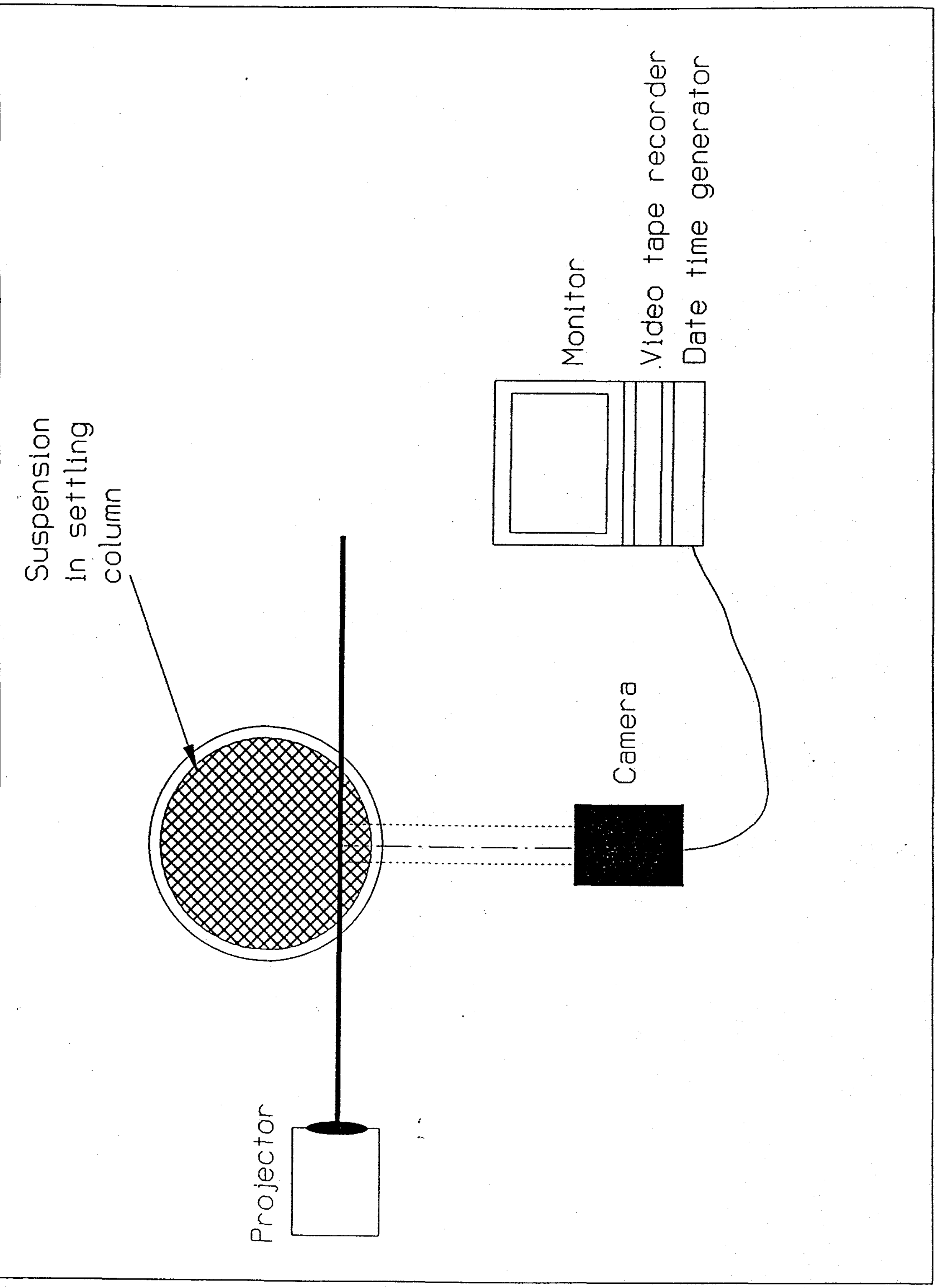


Fig 1 Apparatus for filming settling flocs.

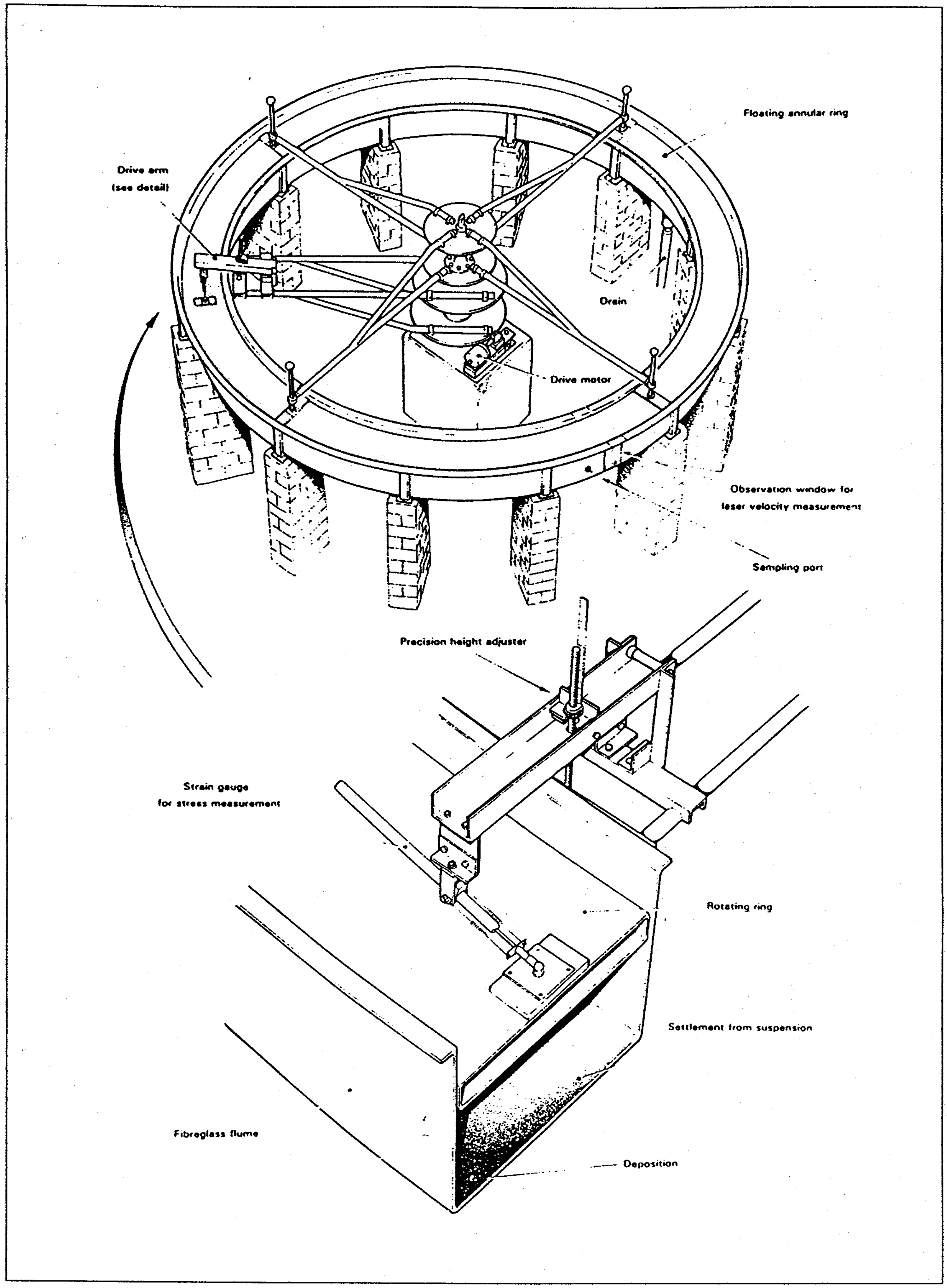


Fig 2 The carousel

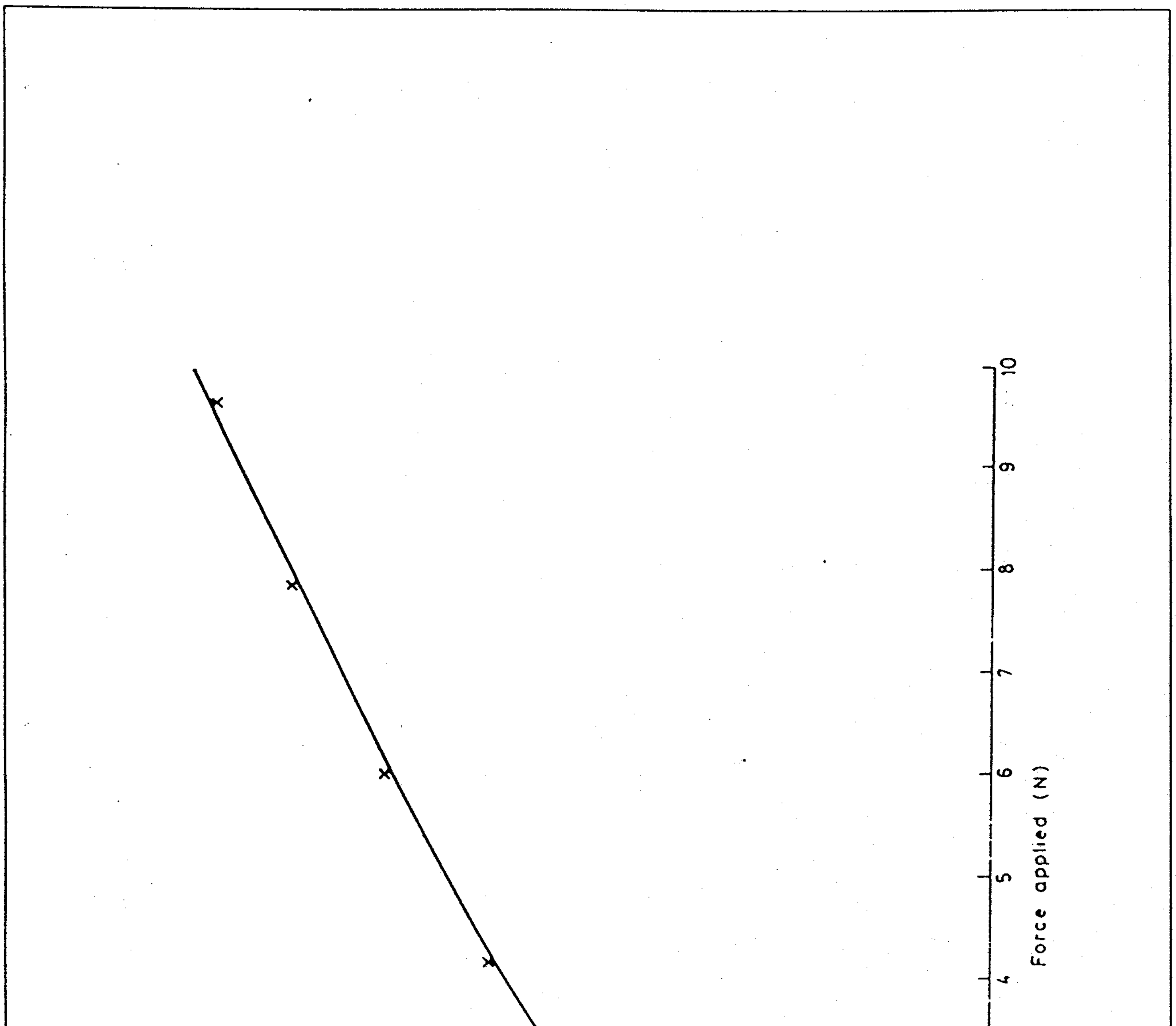


Fig 3   Energy input calibration

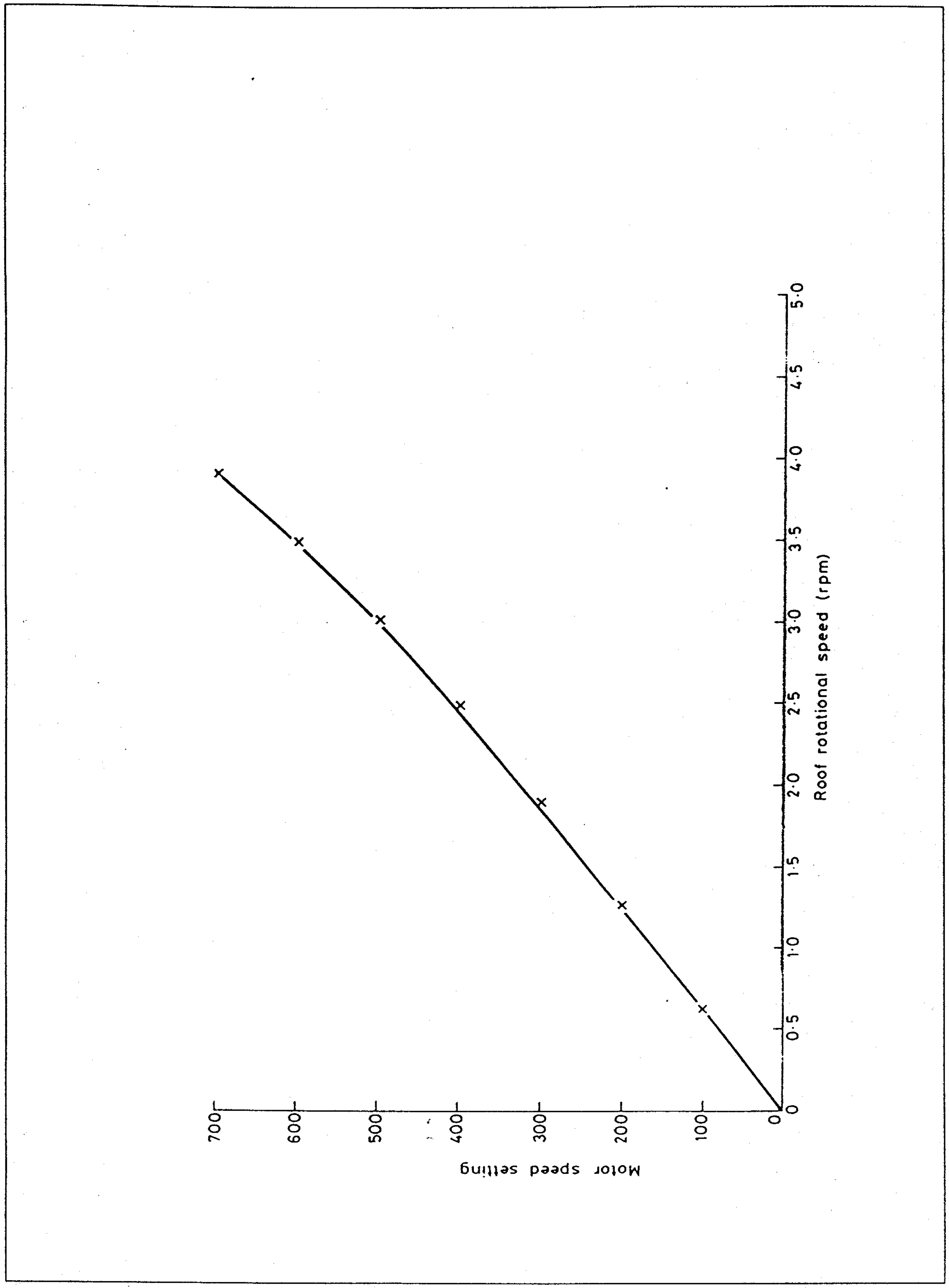


Fig 4 Roof speed calibration

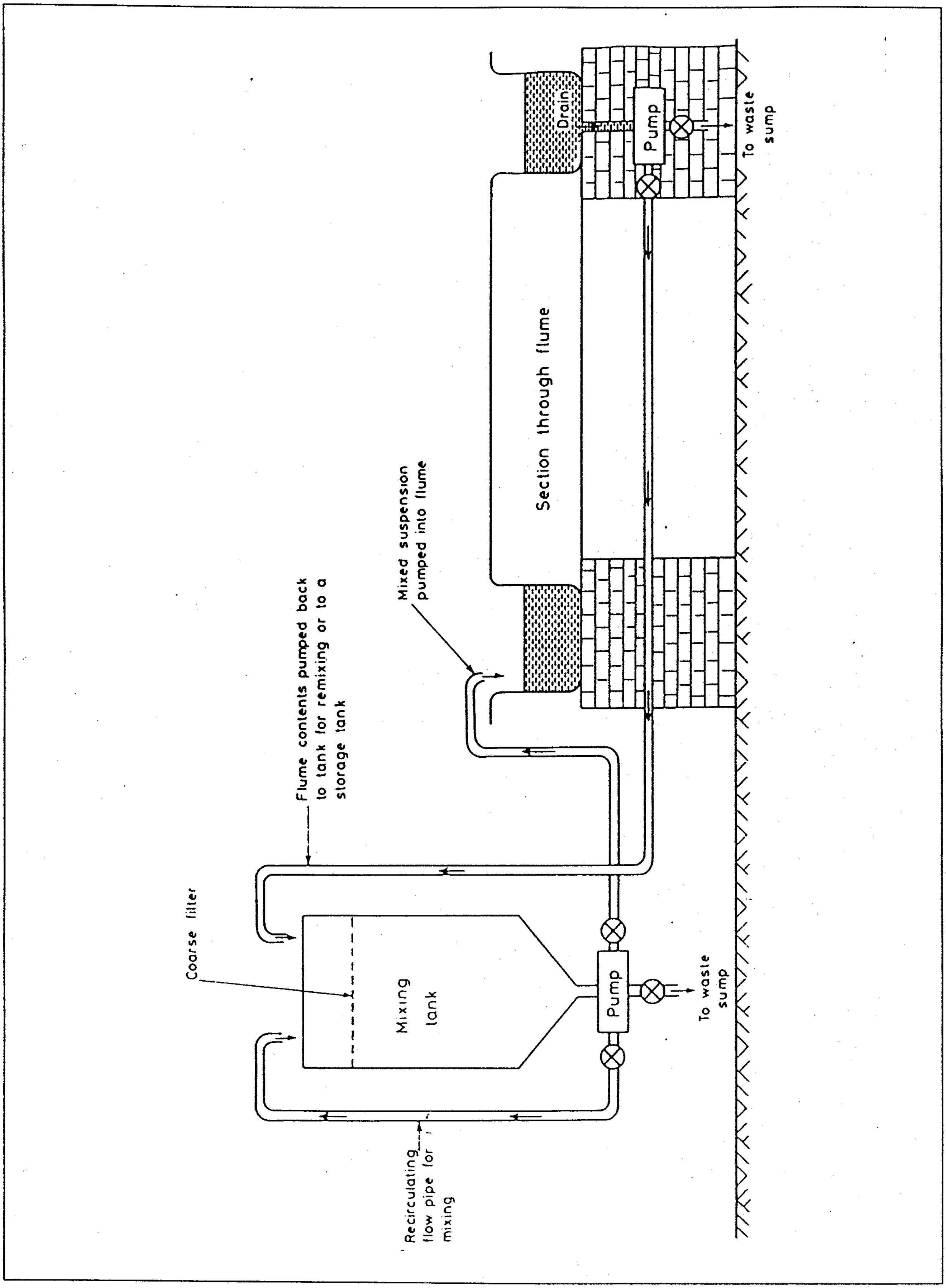


Fig 5   Filling and emptying system

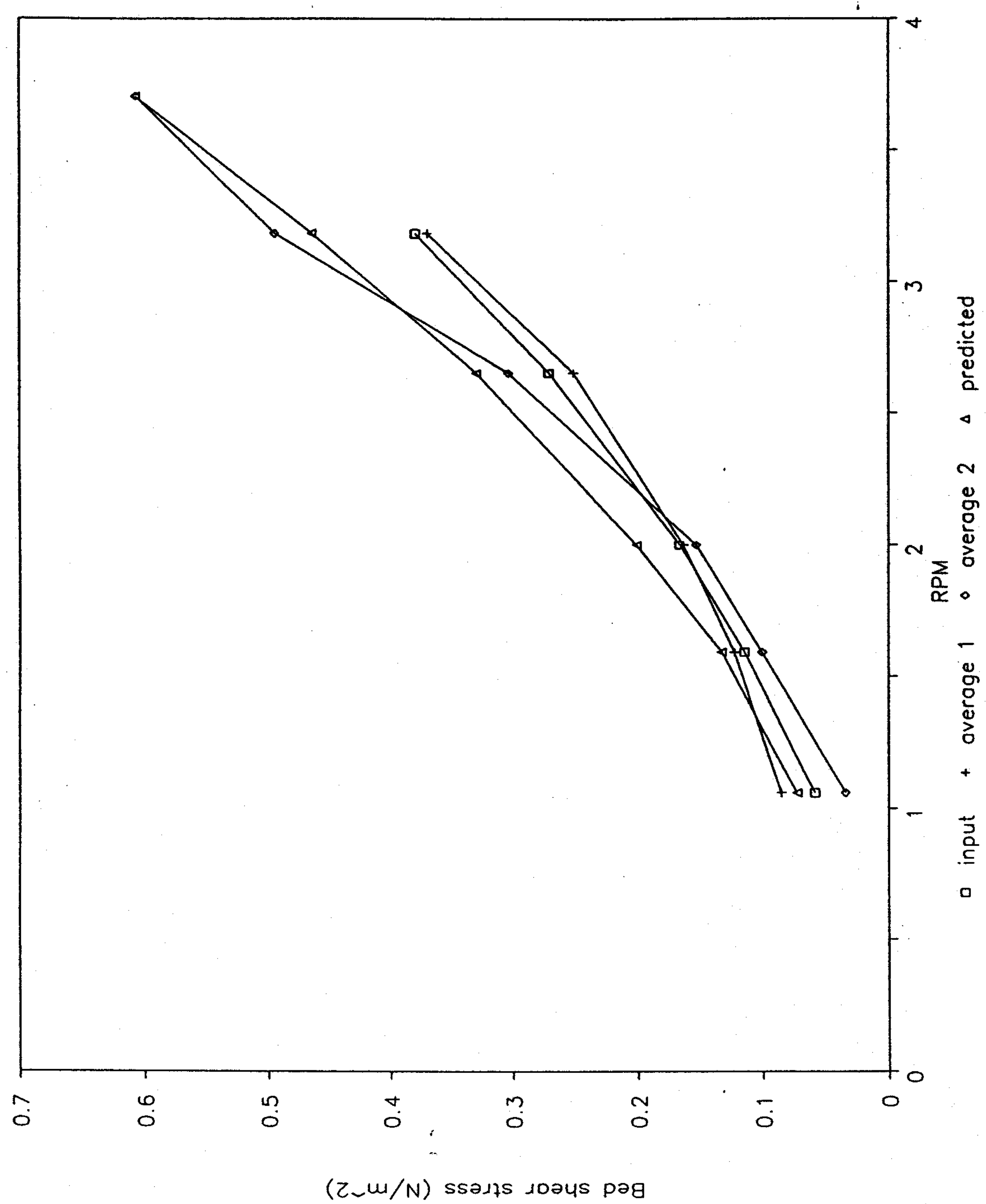


Fig 6 Average bed shear stress values against roof speed

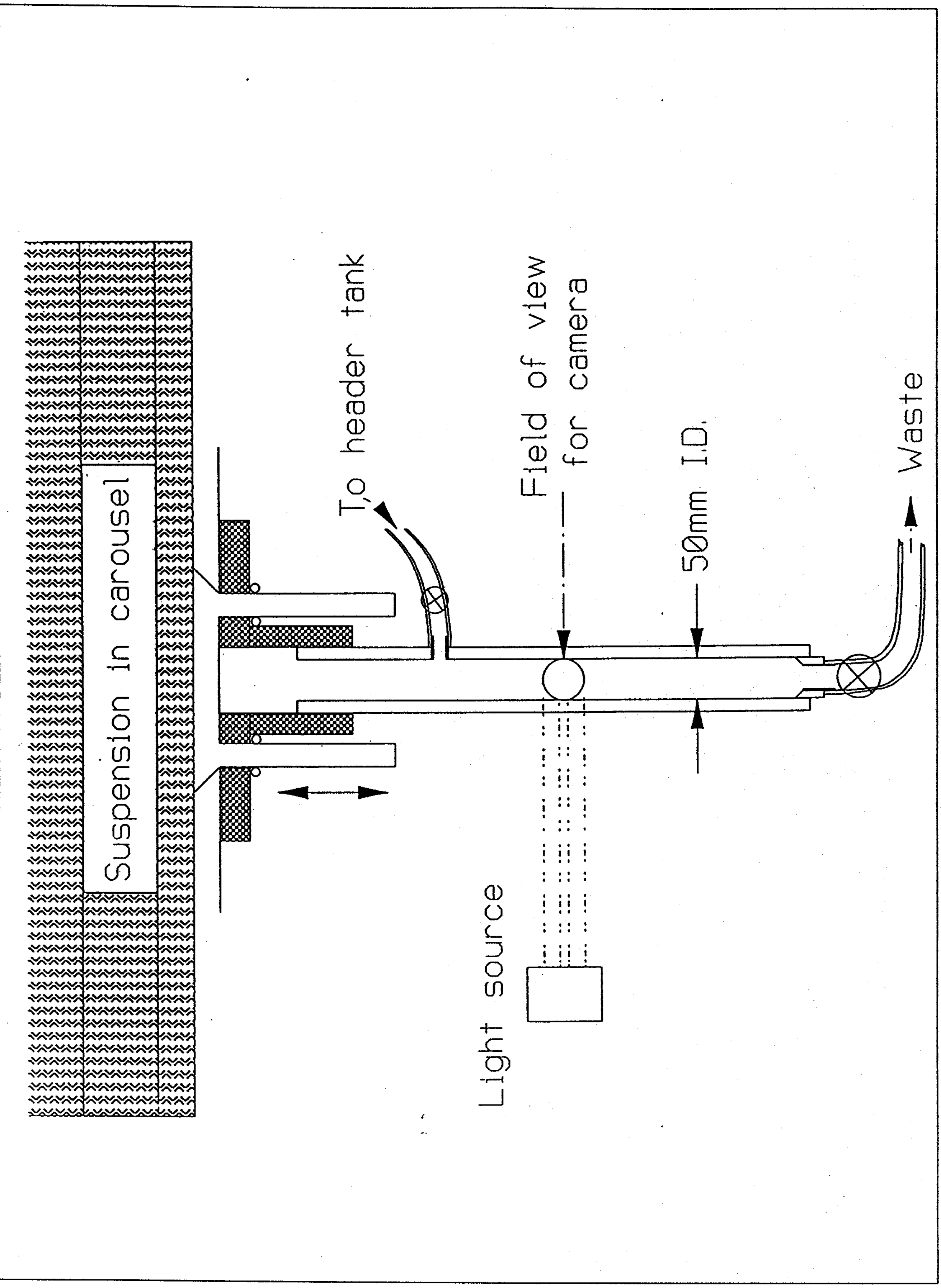


Fig 7   Sampling system for base of carousel

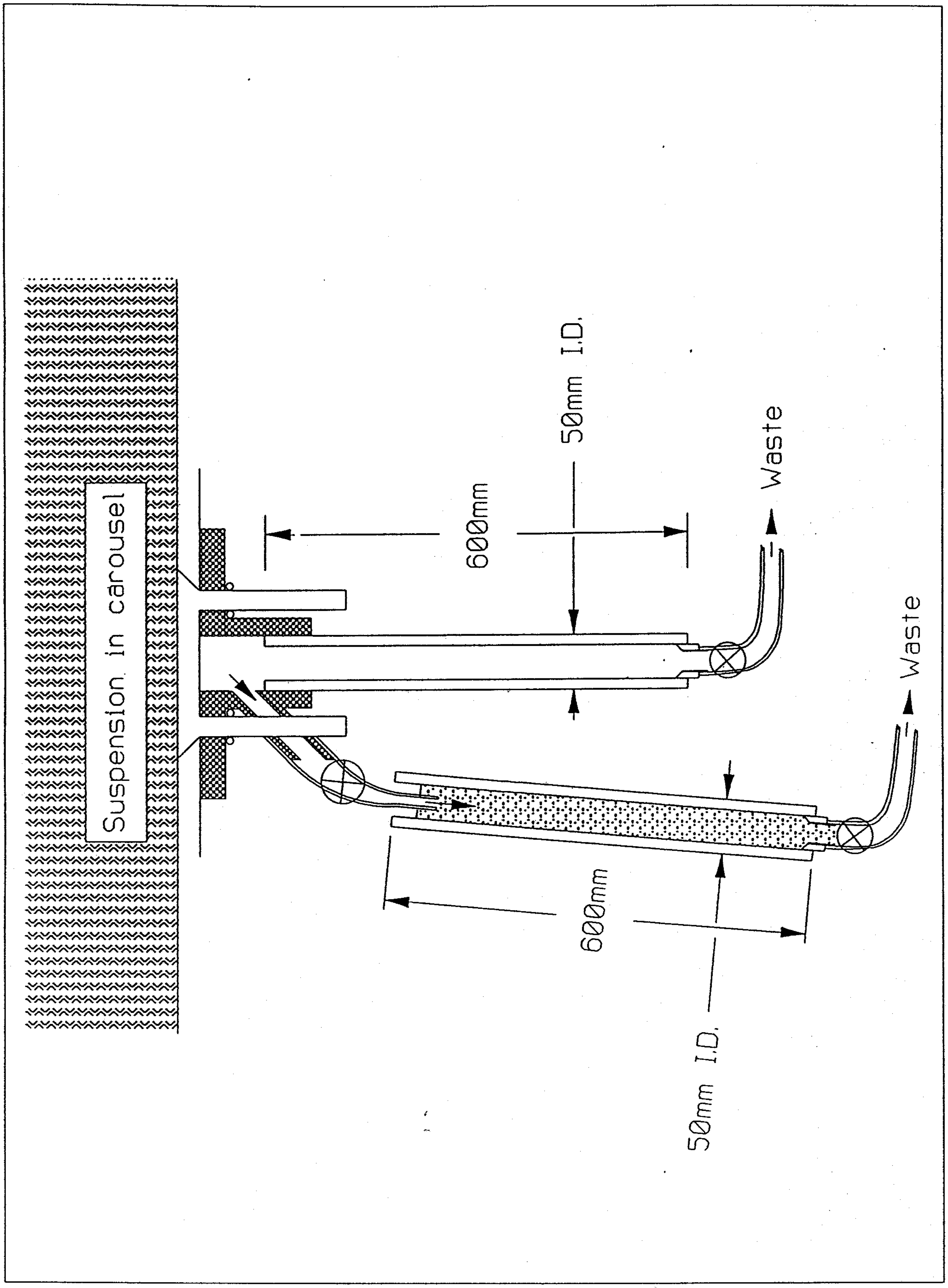


Fig 8 Modified sampling system for carousel

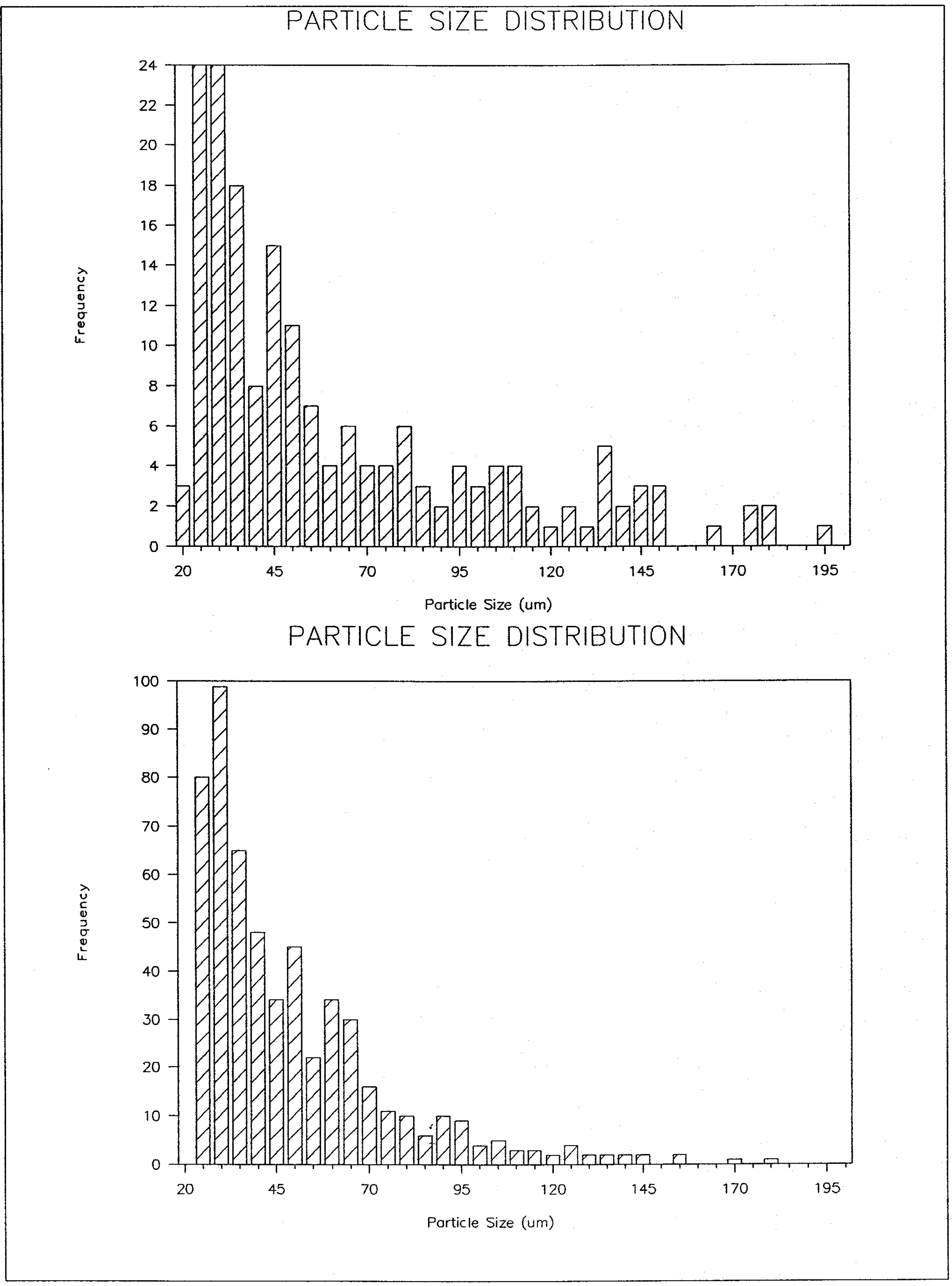


Fig 9 Effect of time on floc size distribution

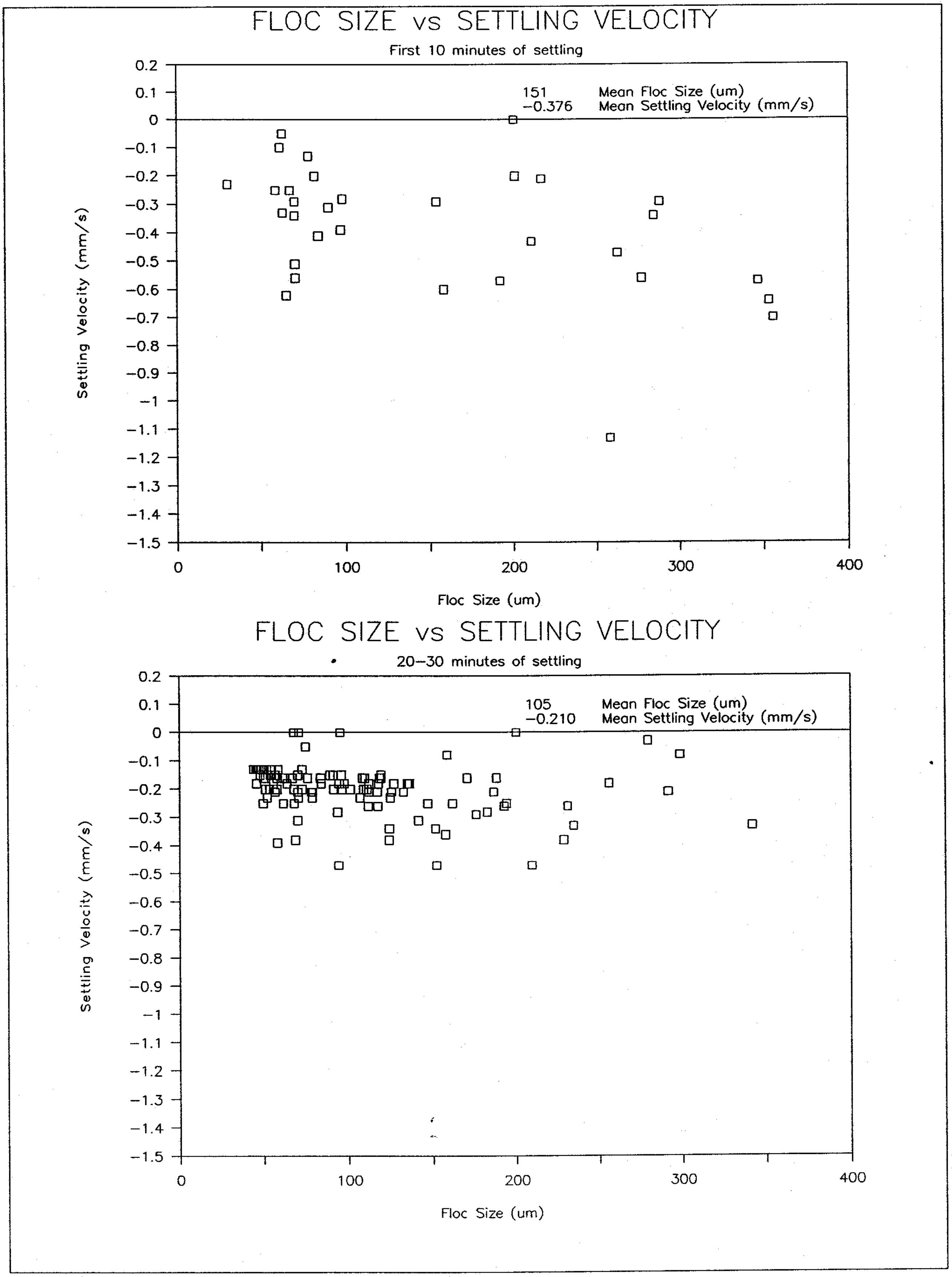


Fig 10 Effect of time on settling velocity distribution

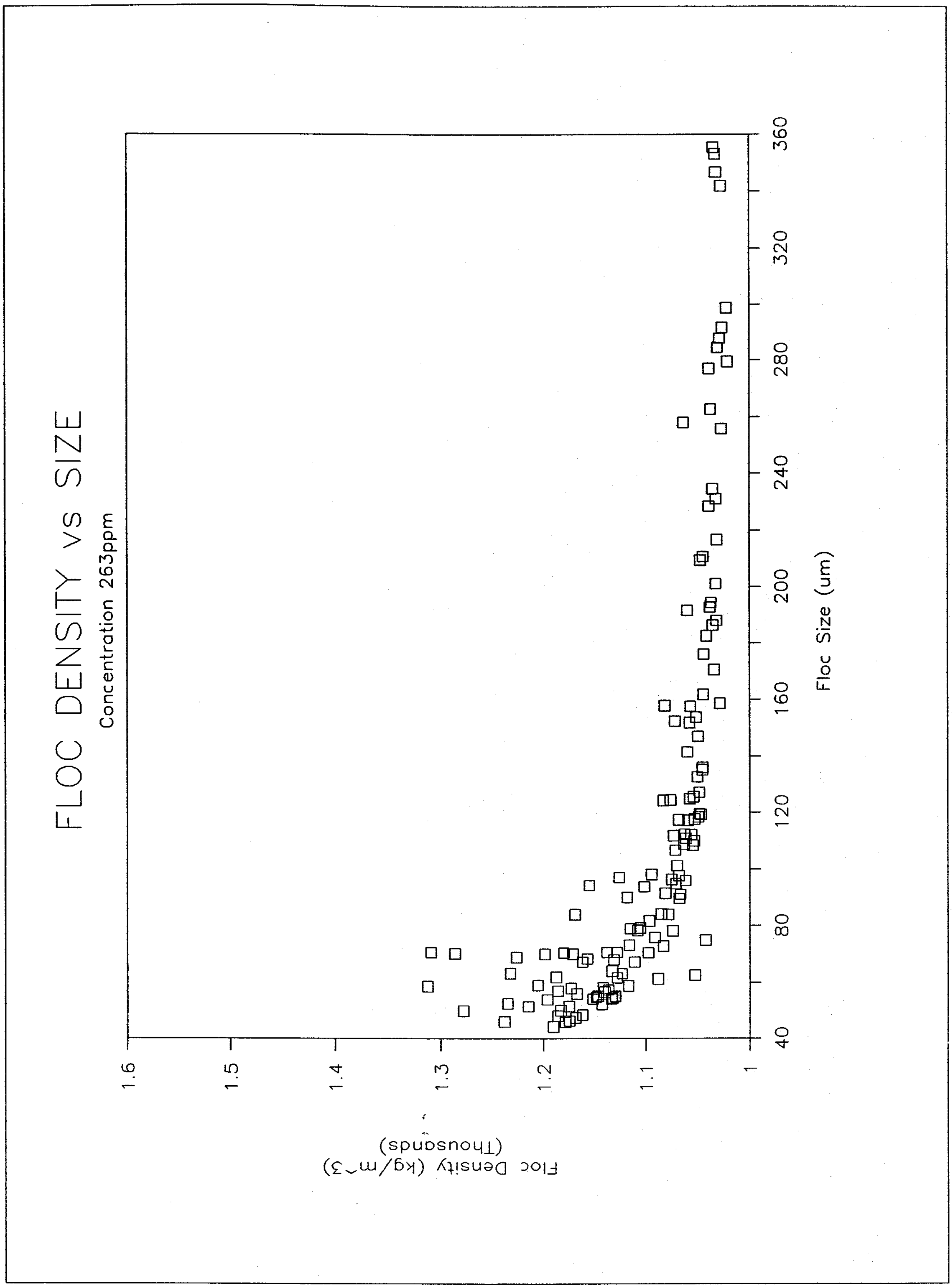


Fig 11 Effective floc density against floc size

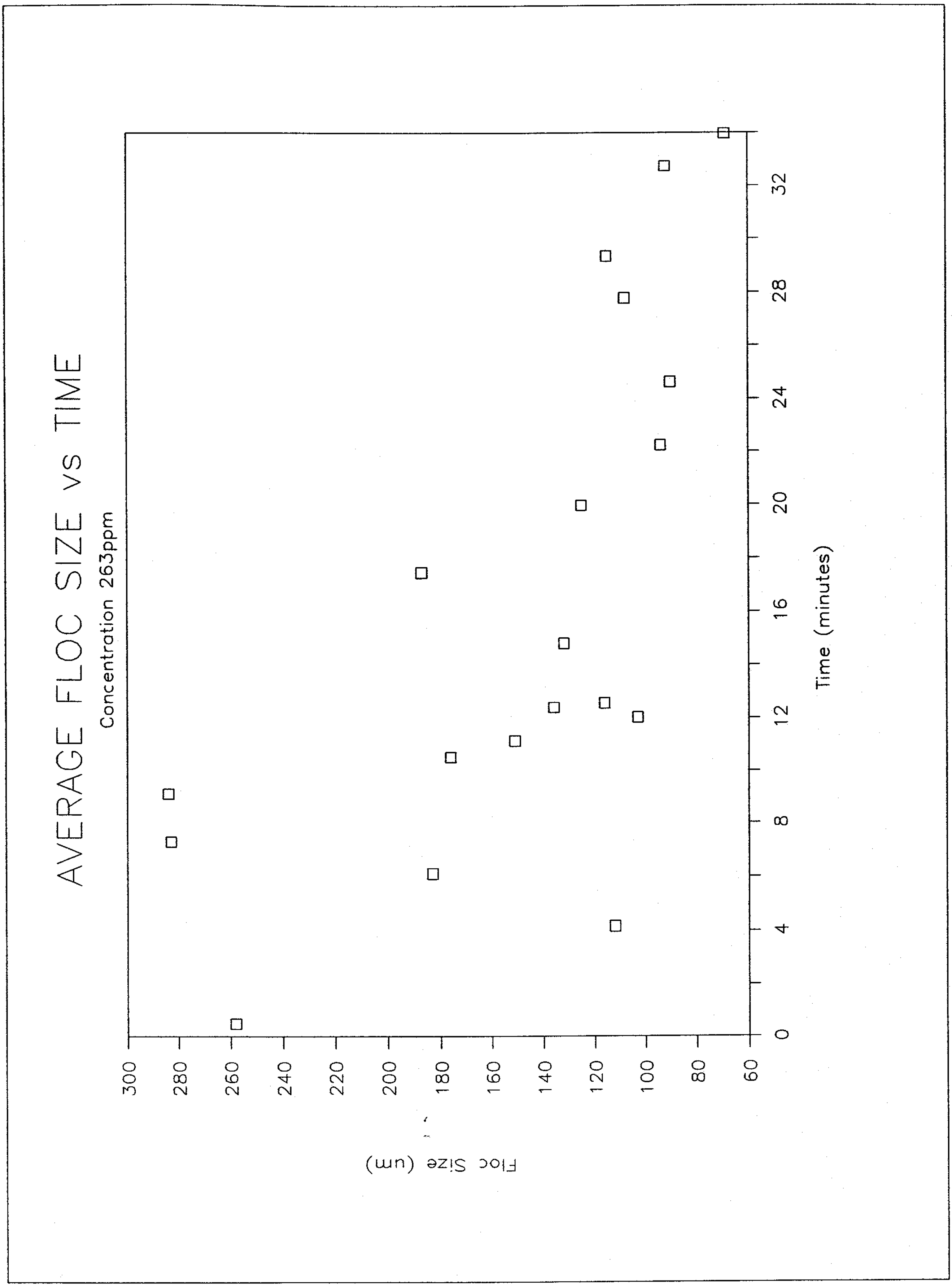


Fig 12 Effect of time on average floc size

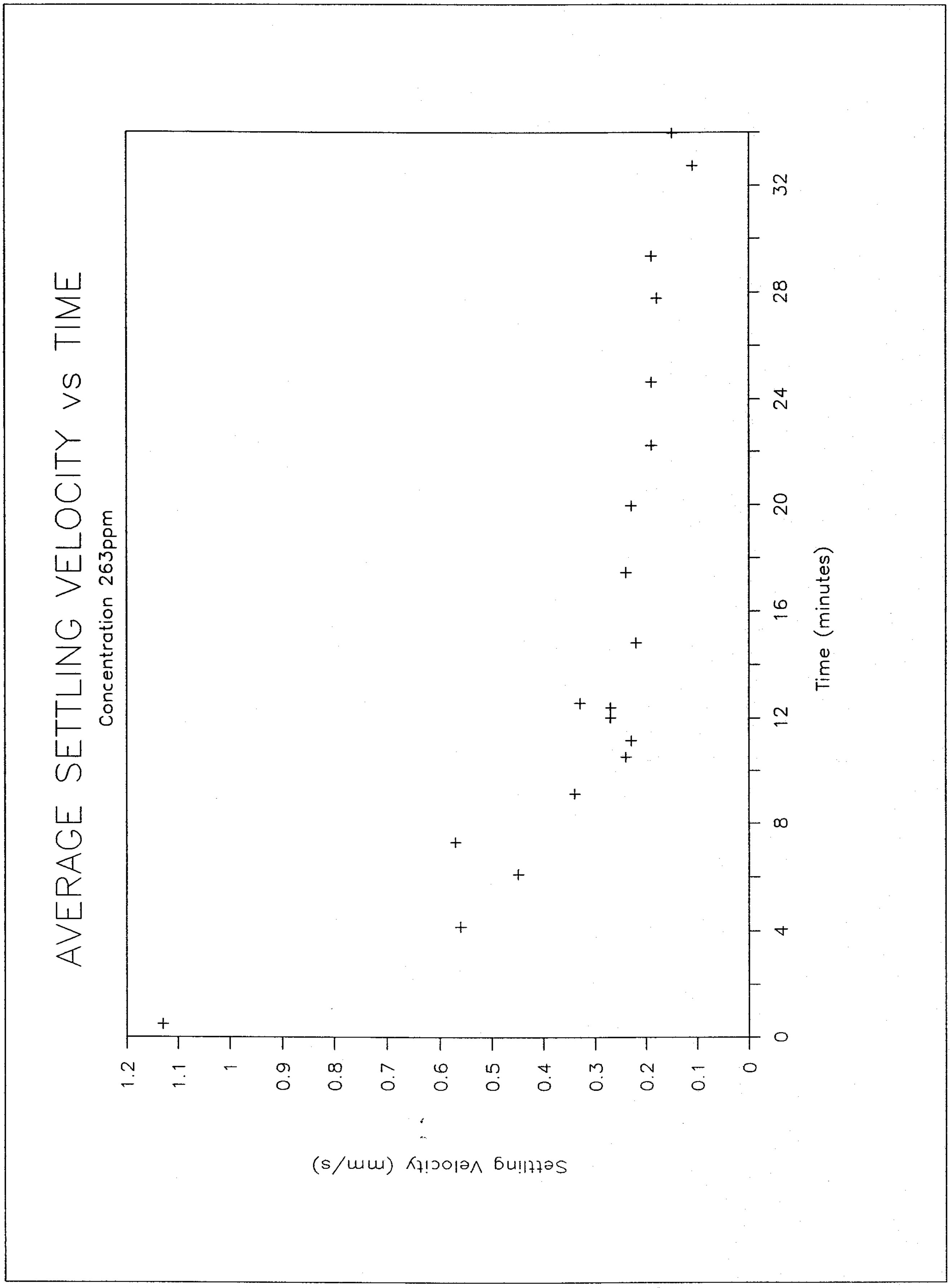


Fig 13 Effect of time on mean settling velocity

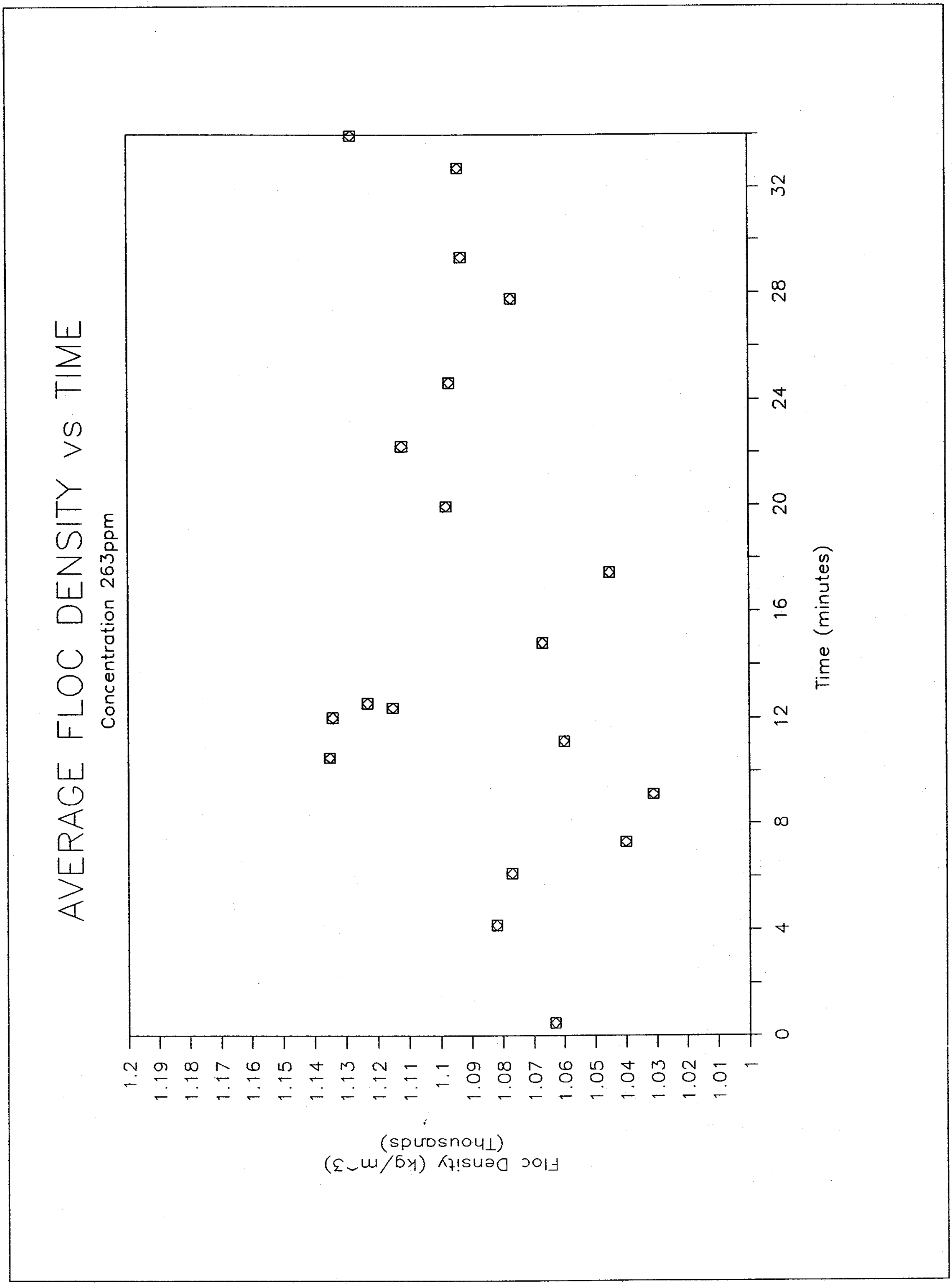


Fig 14 Effect of time on floc density

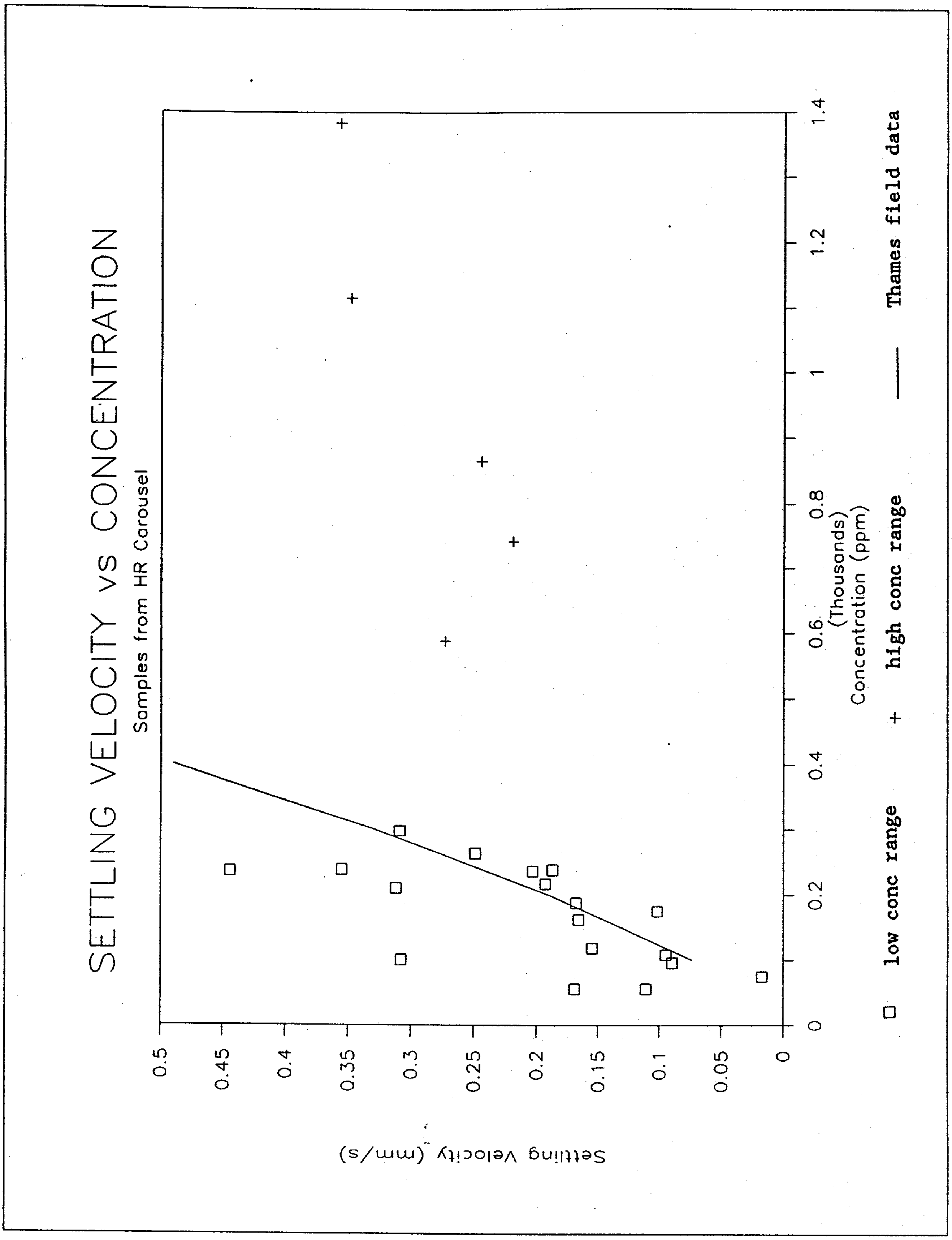


Fig 15 Comparison of laboratory settling velocities with Thames field data from Owen tube measurements

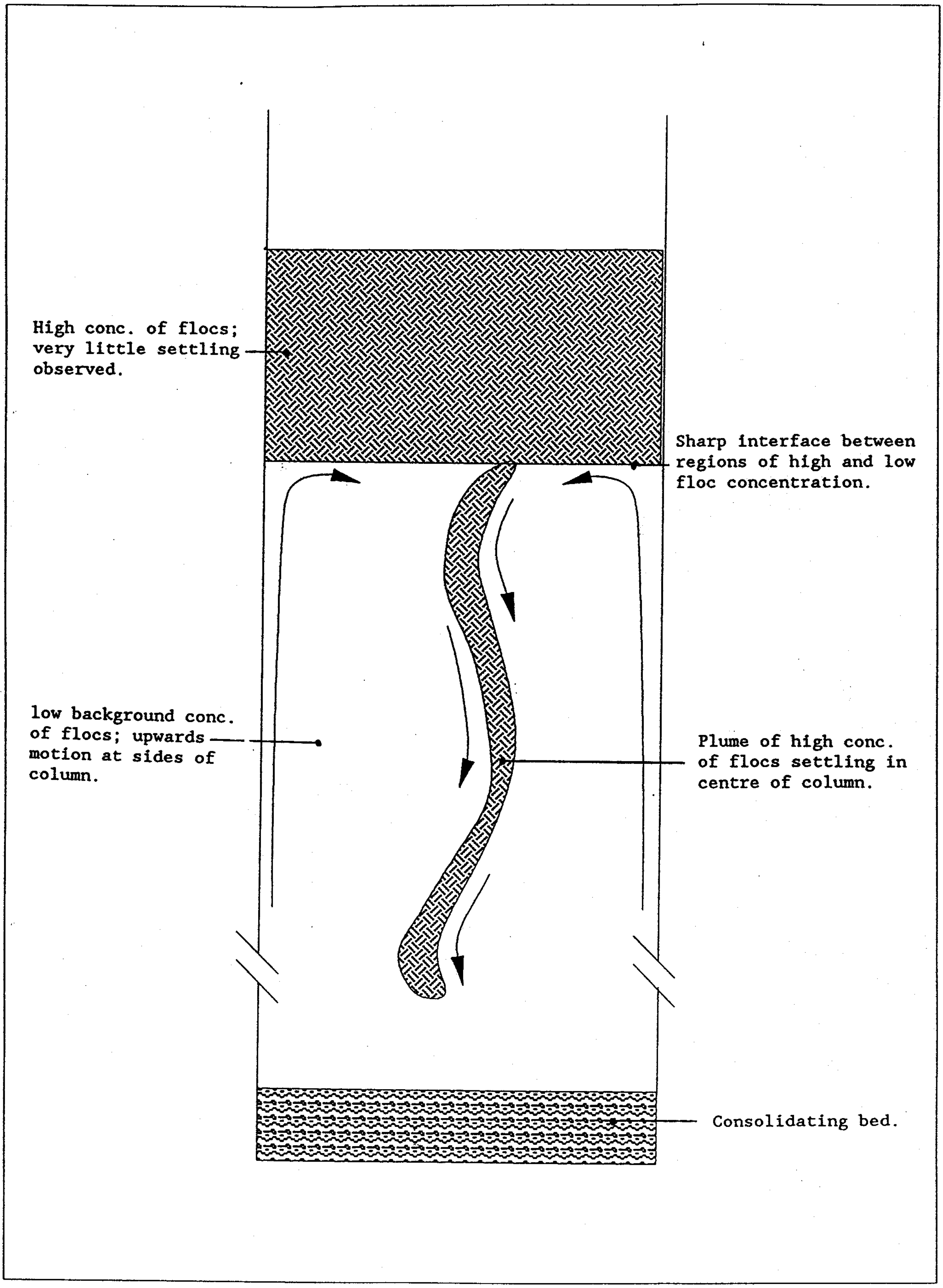


Fig 16 Schematic representation of interface and circulation after 25 minutes of settling

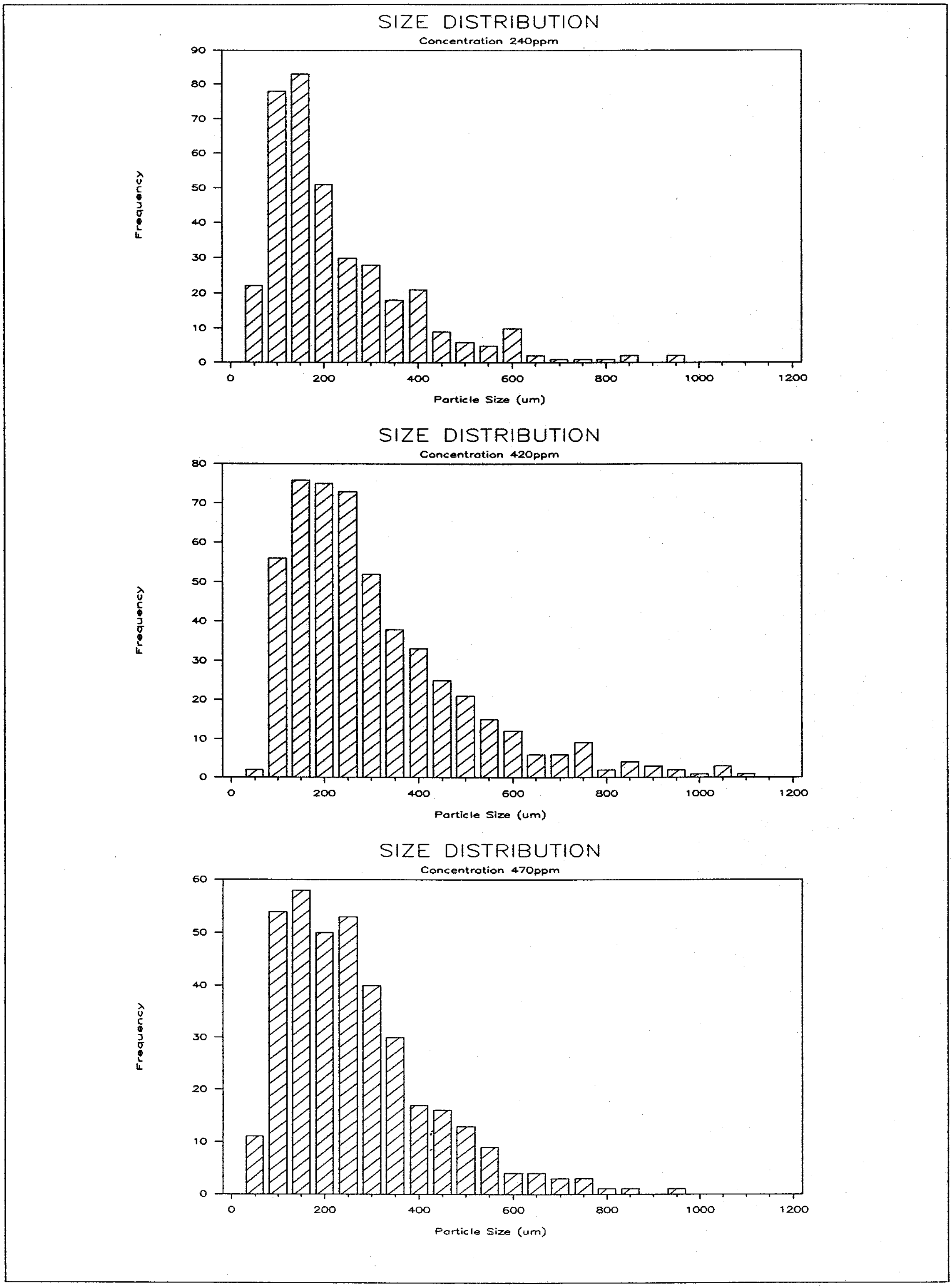


Fig 17 Effect of concentration on floc size distribution for Thames estuary

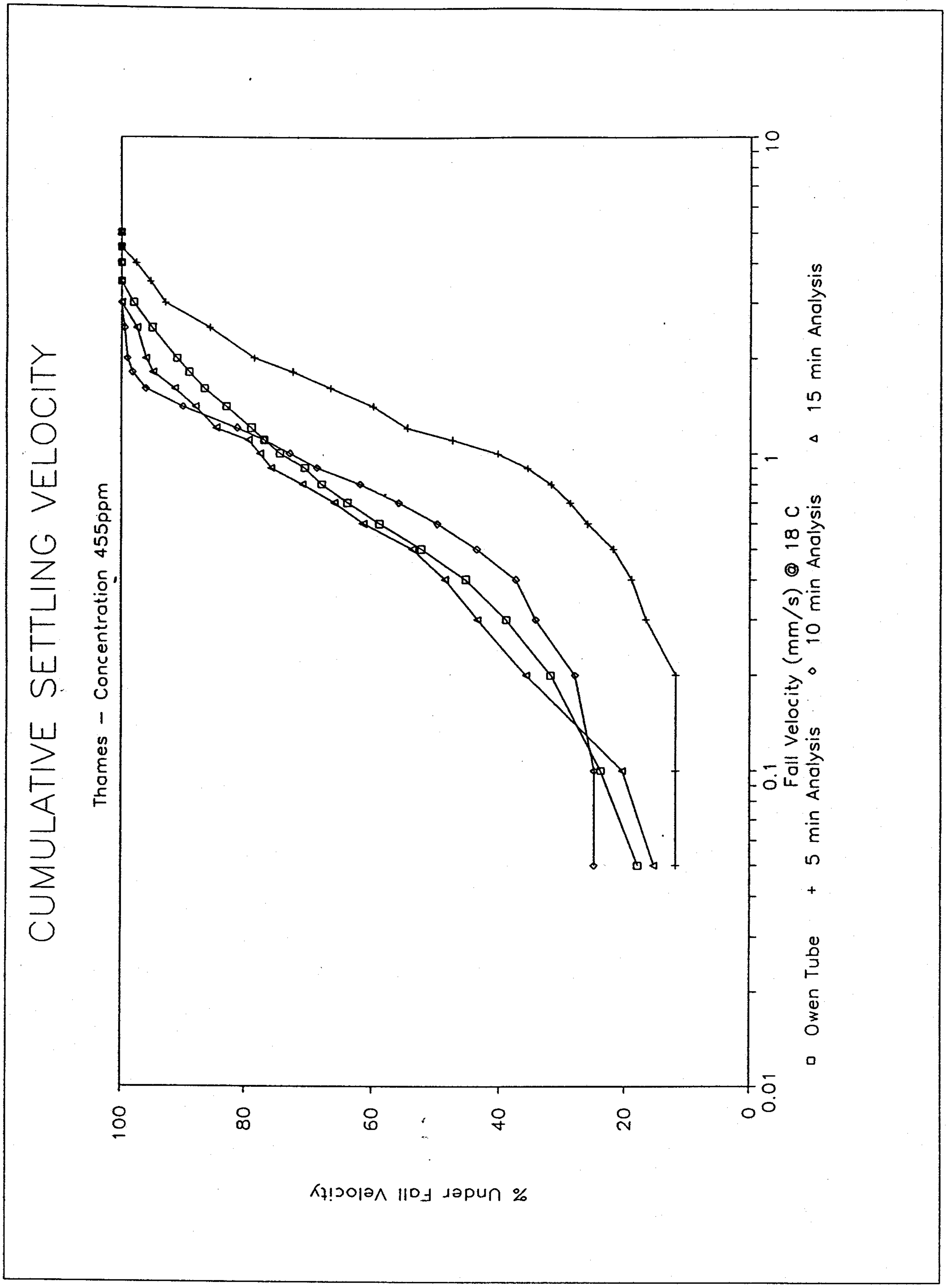
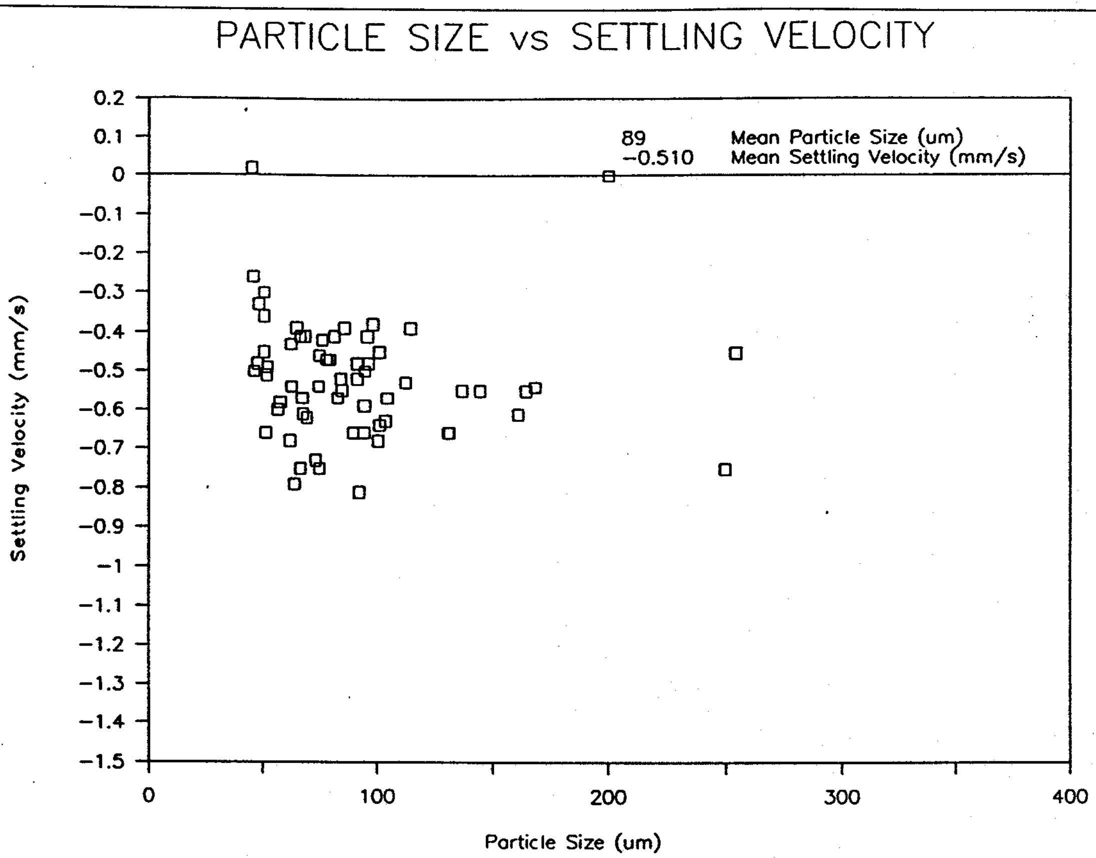


Fig 18 Comparison of settling velocity with Owen tube measurements



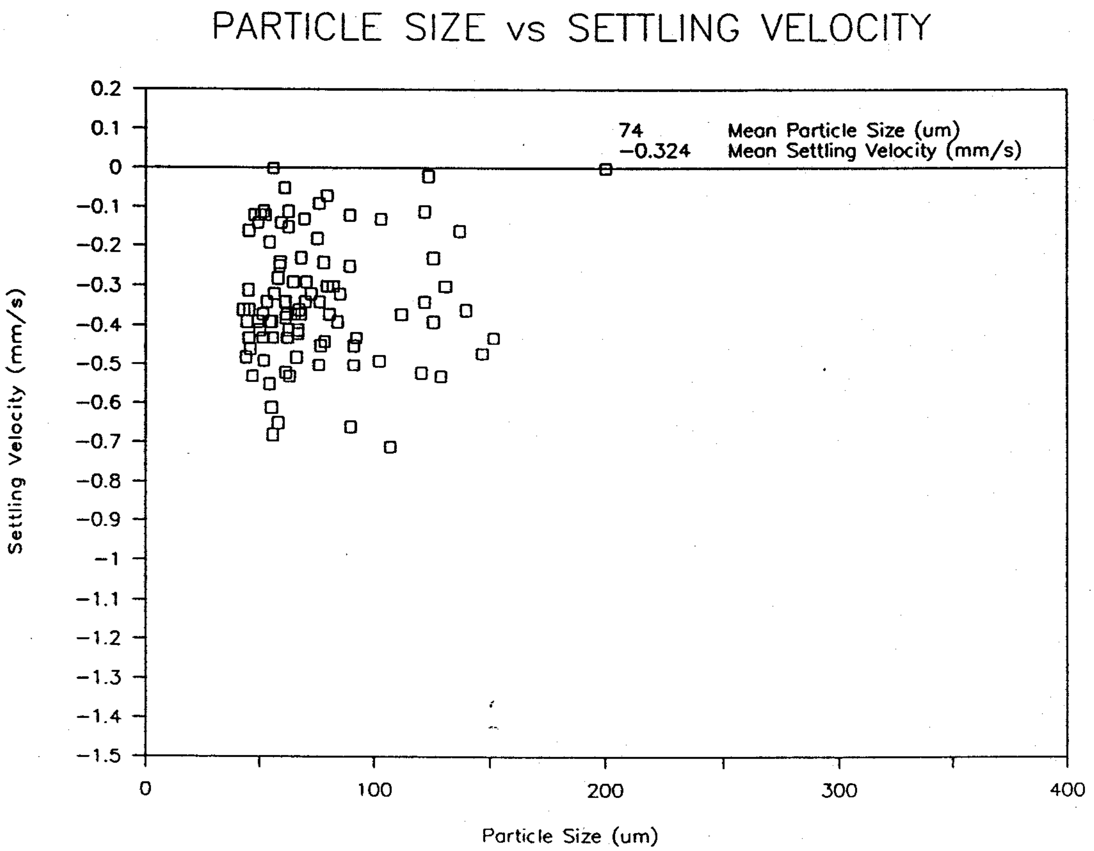


Fig 19 Particle size against settling velocity measurements made on River Tees

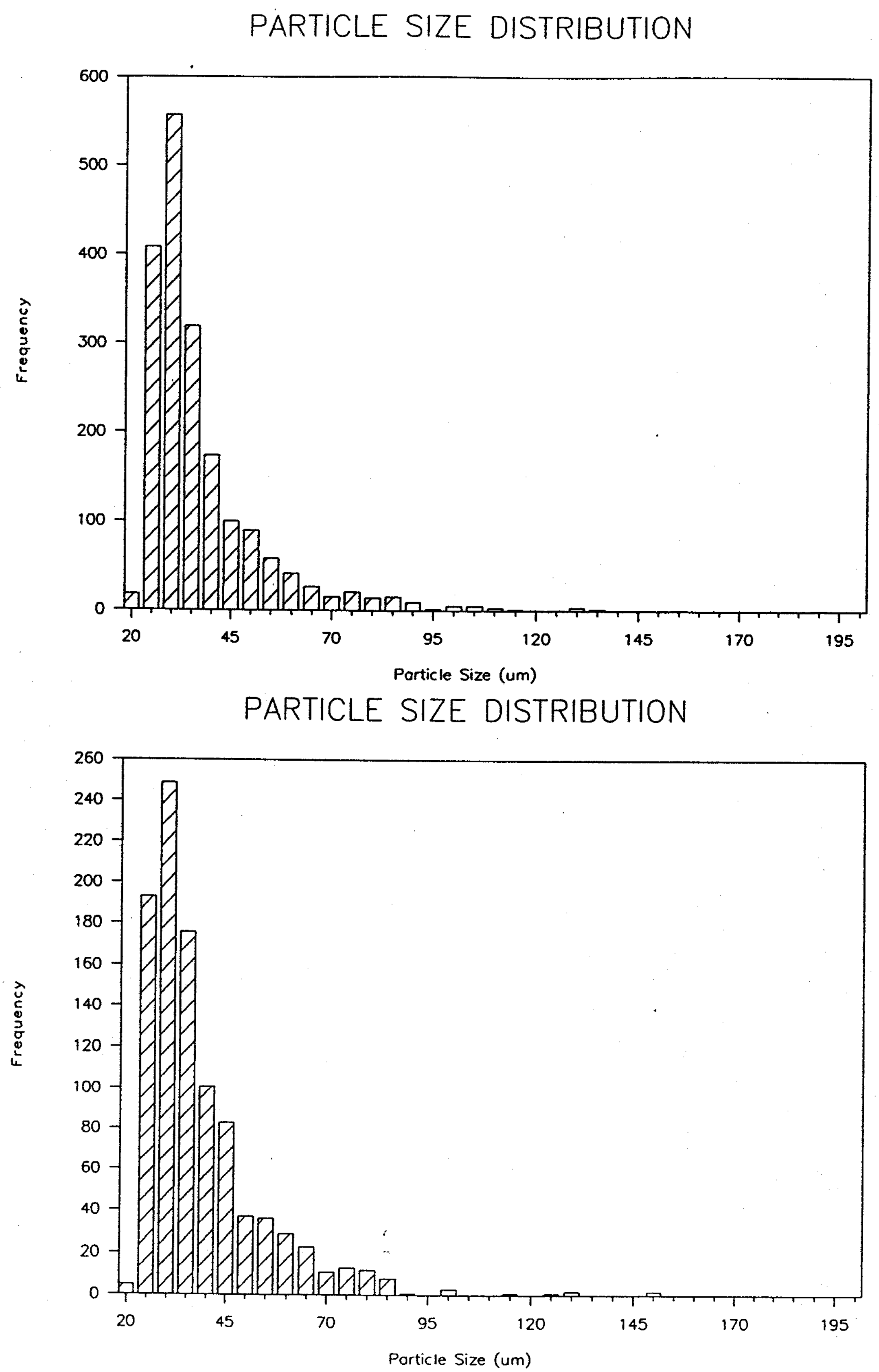


Fig 20 Floc size distributions on River Tees

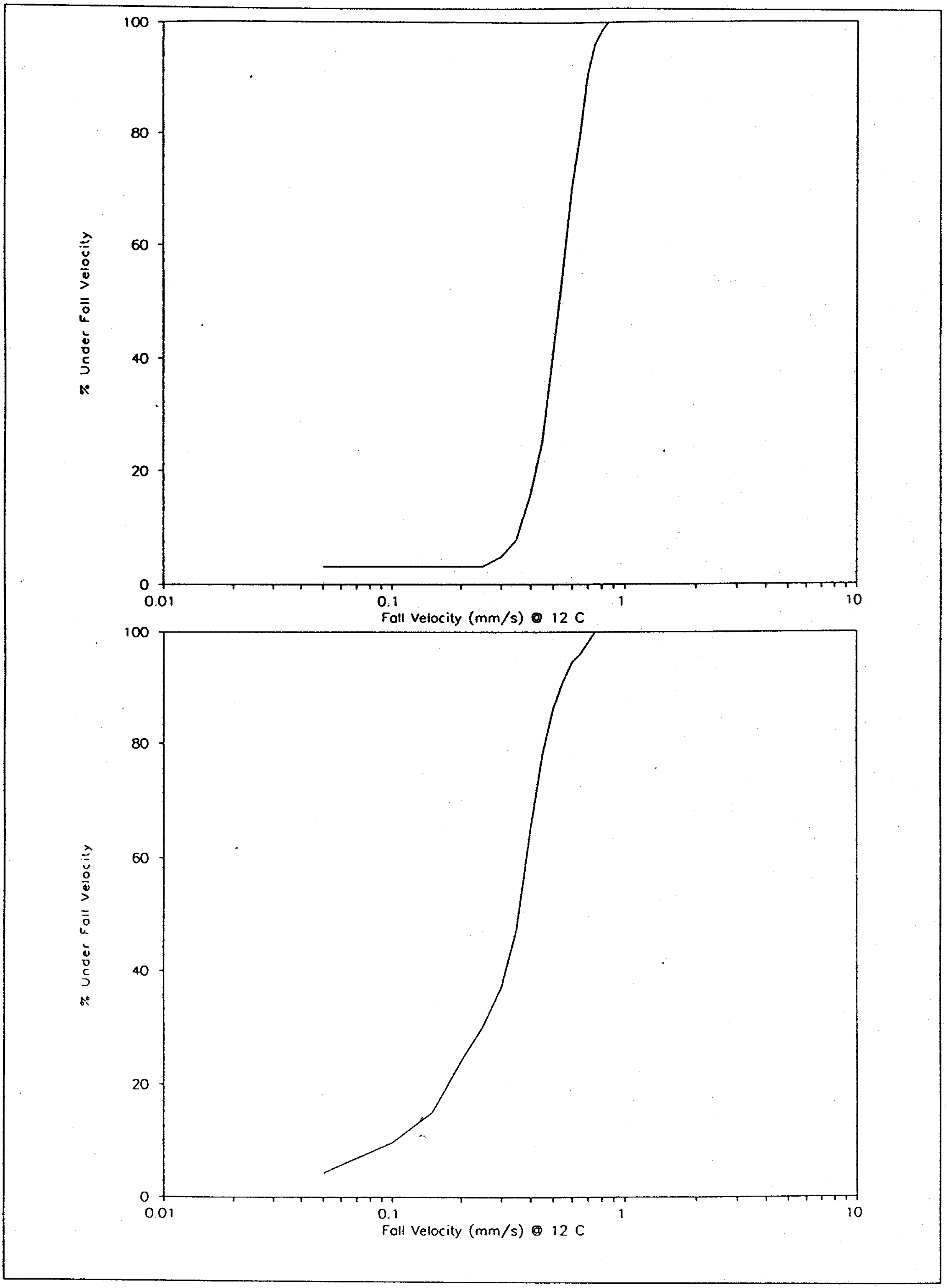


Fig 21 Cumulative settling velocity determined by Video Imaging System

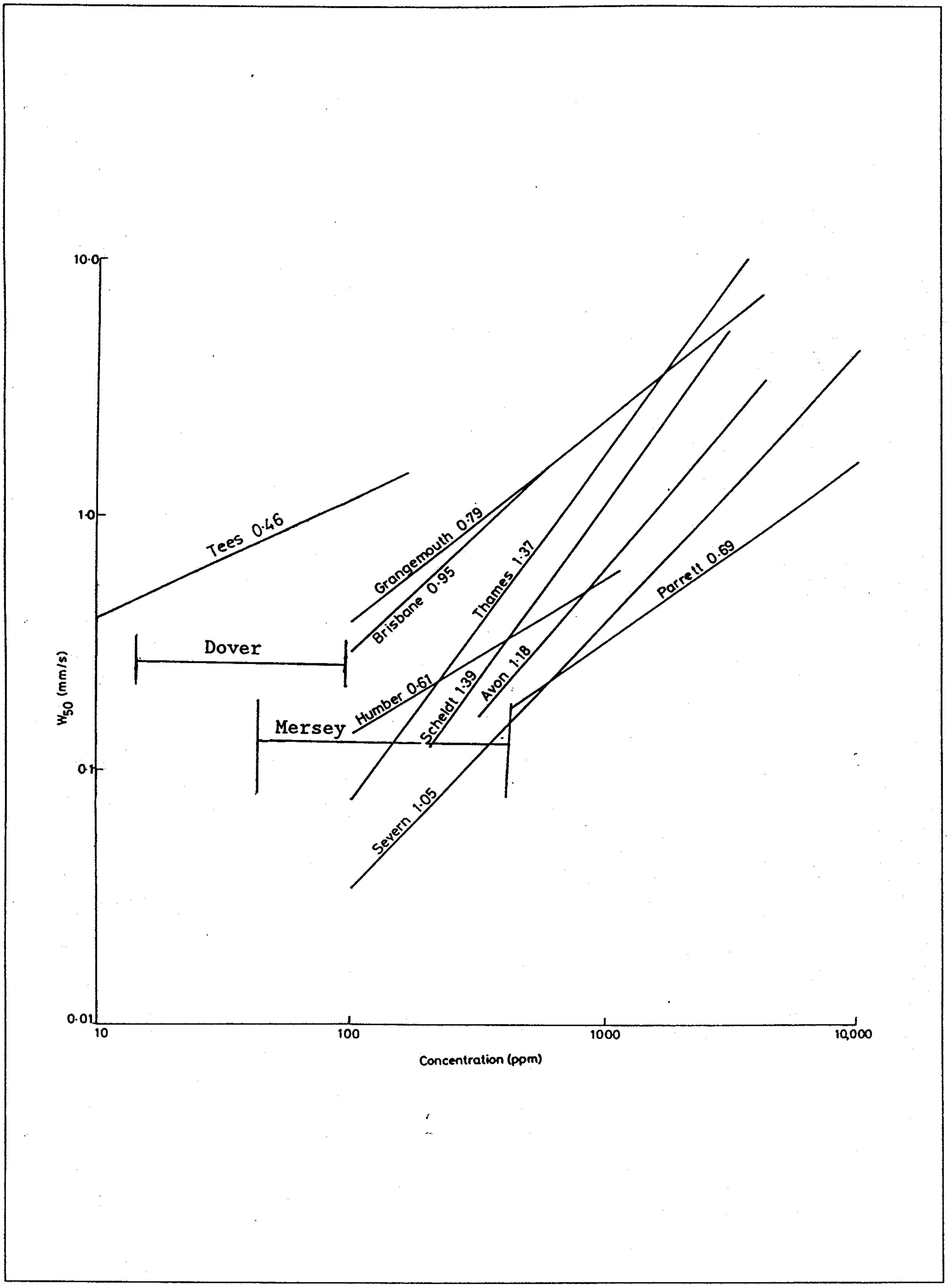


Fig 22 Median settling velocity vs concentration
Comparison of eleven estuaries

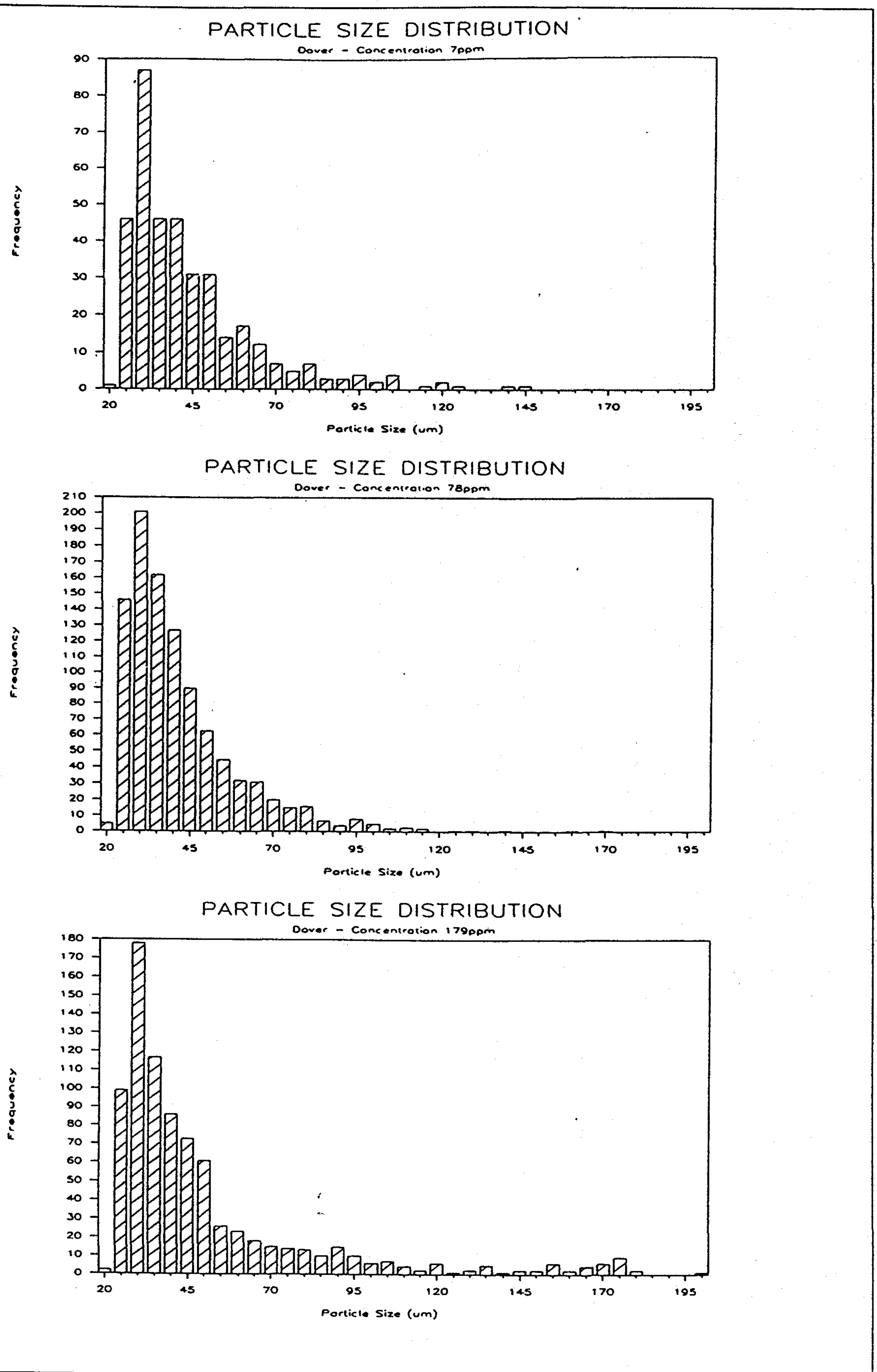
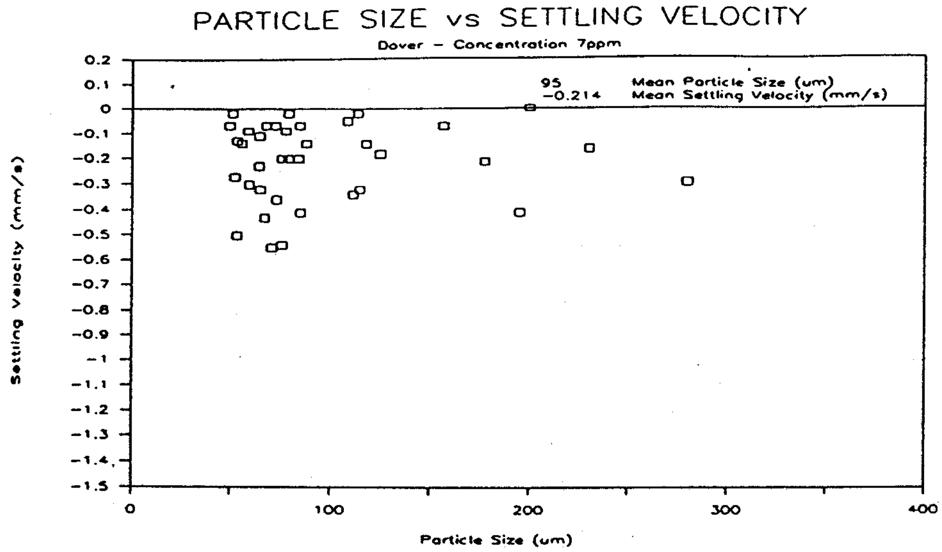
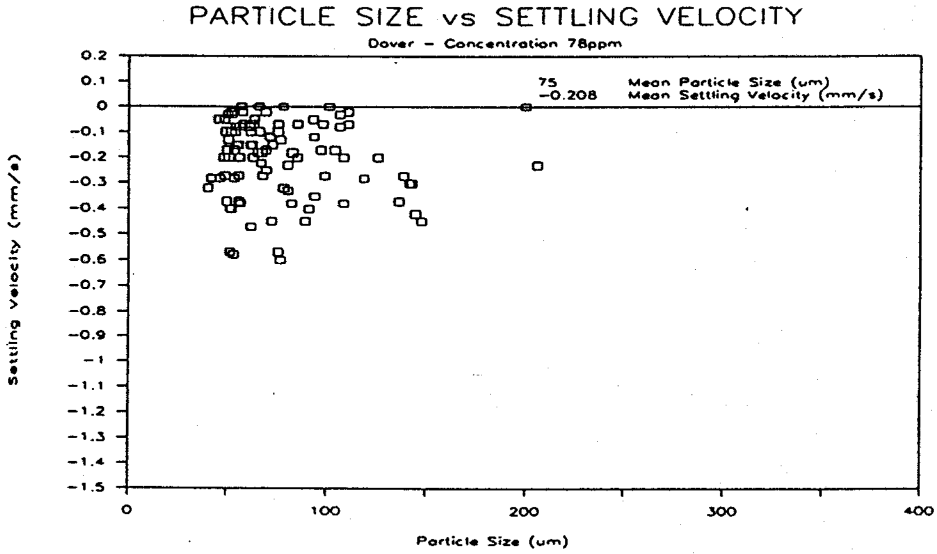


Fig 23 Effect of concentration on floc size distributions for Dover Harbour





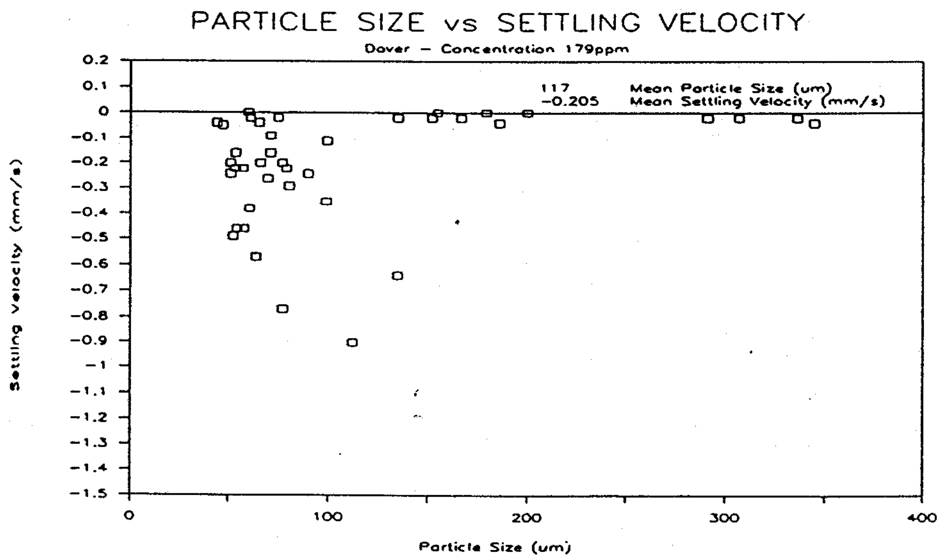


Fig 24 Effect oc concentration on settling velocity vs size distributions for Dover Harbour

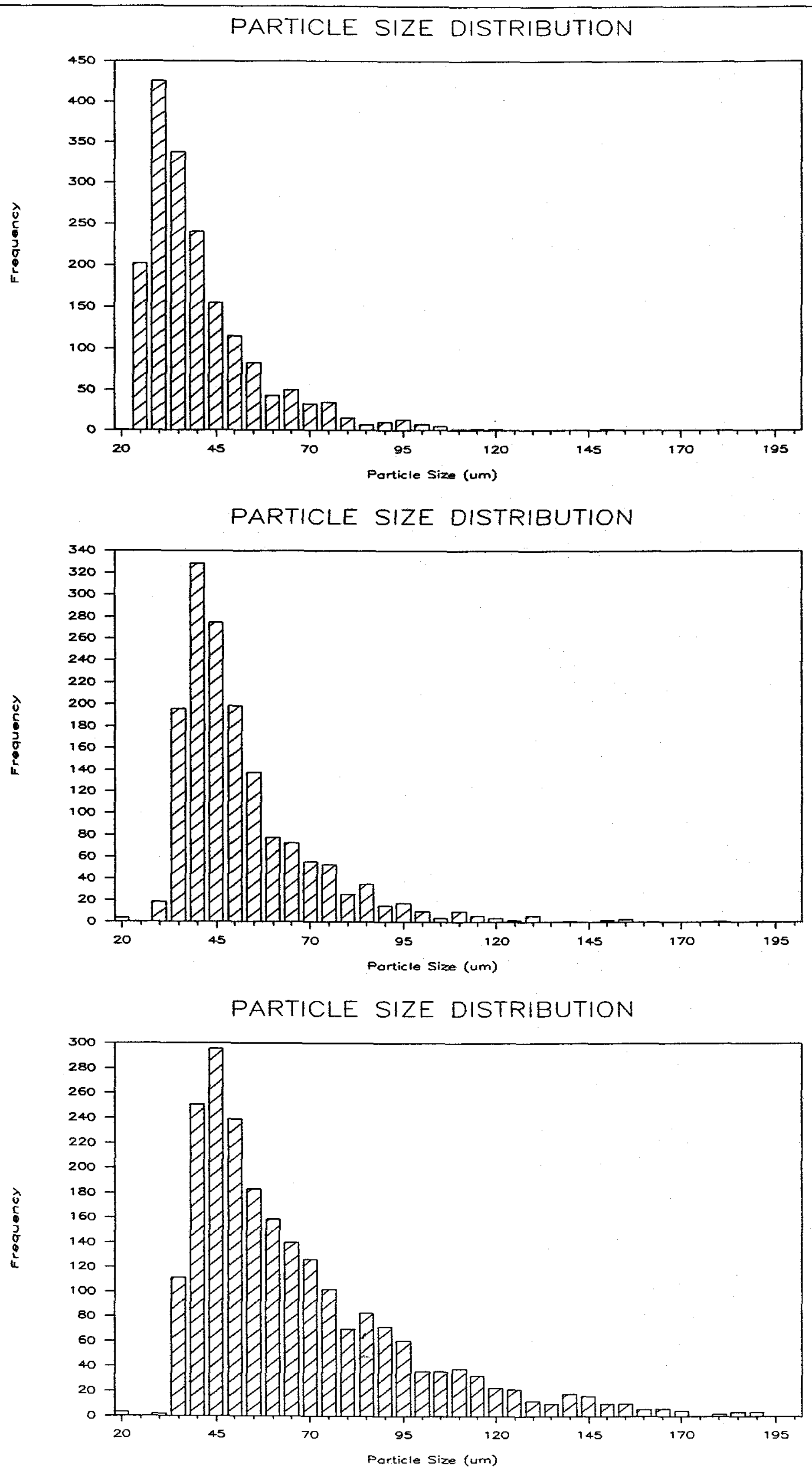


Fig 25 Effect of concentration on floc size distributions for Mersey Estuary

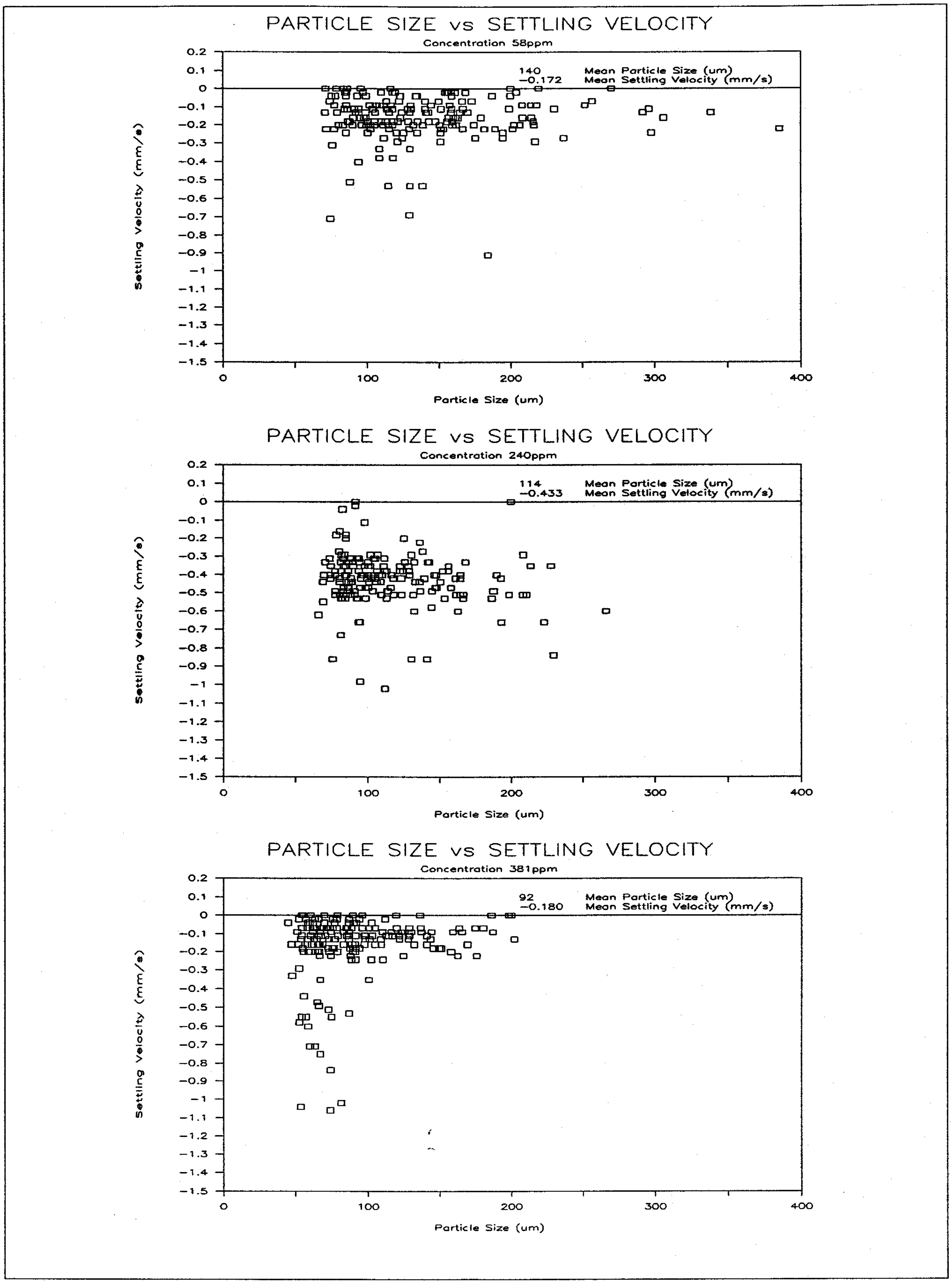


Fig 26 Effect of concentration on settling velocity distributions for Mersey Estuary

PLATES.

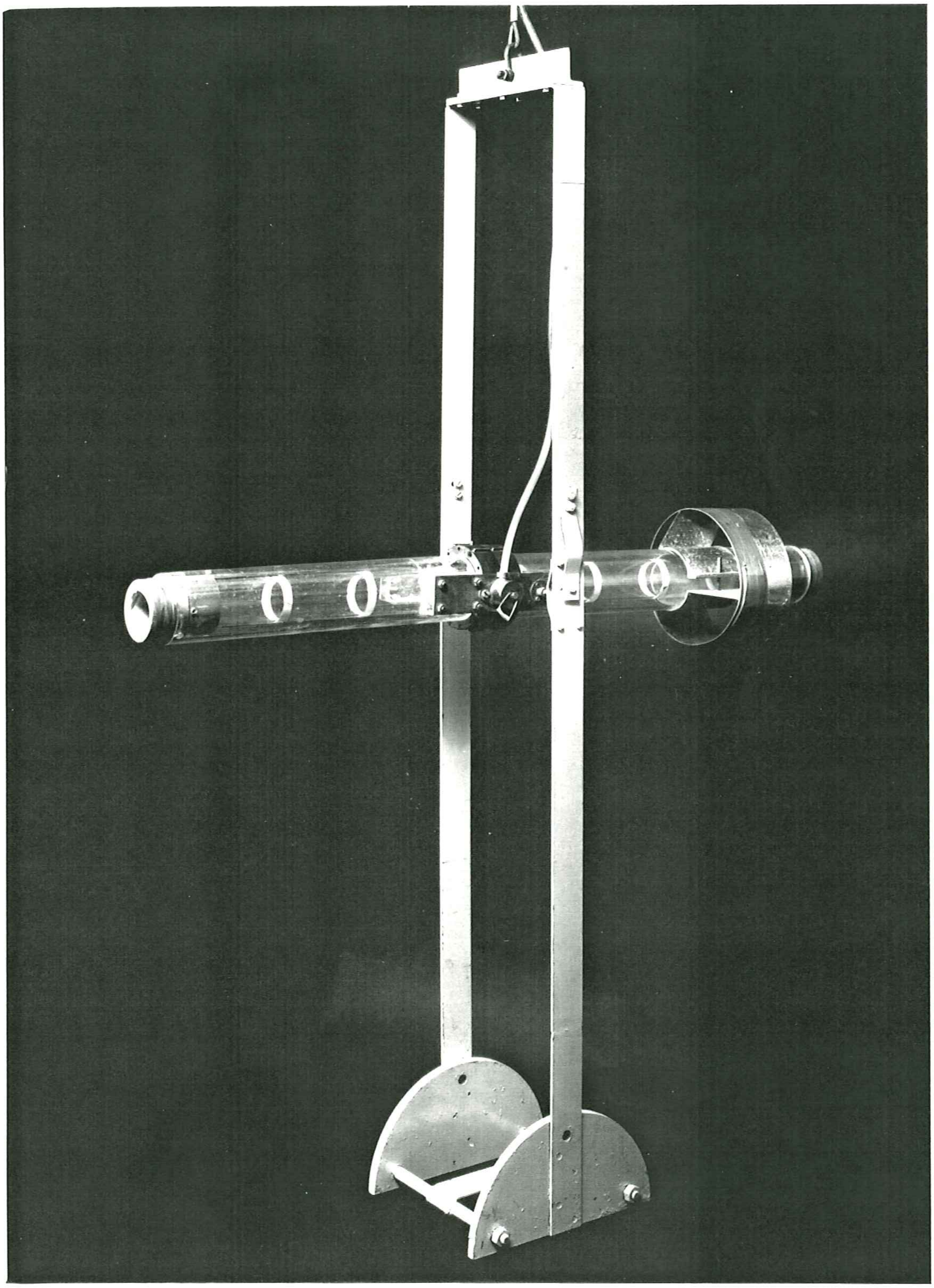


Plate 1 Owen tube in submerged position

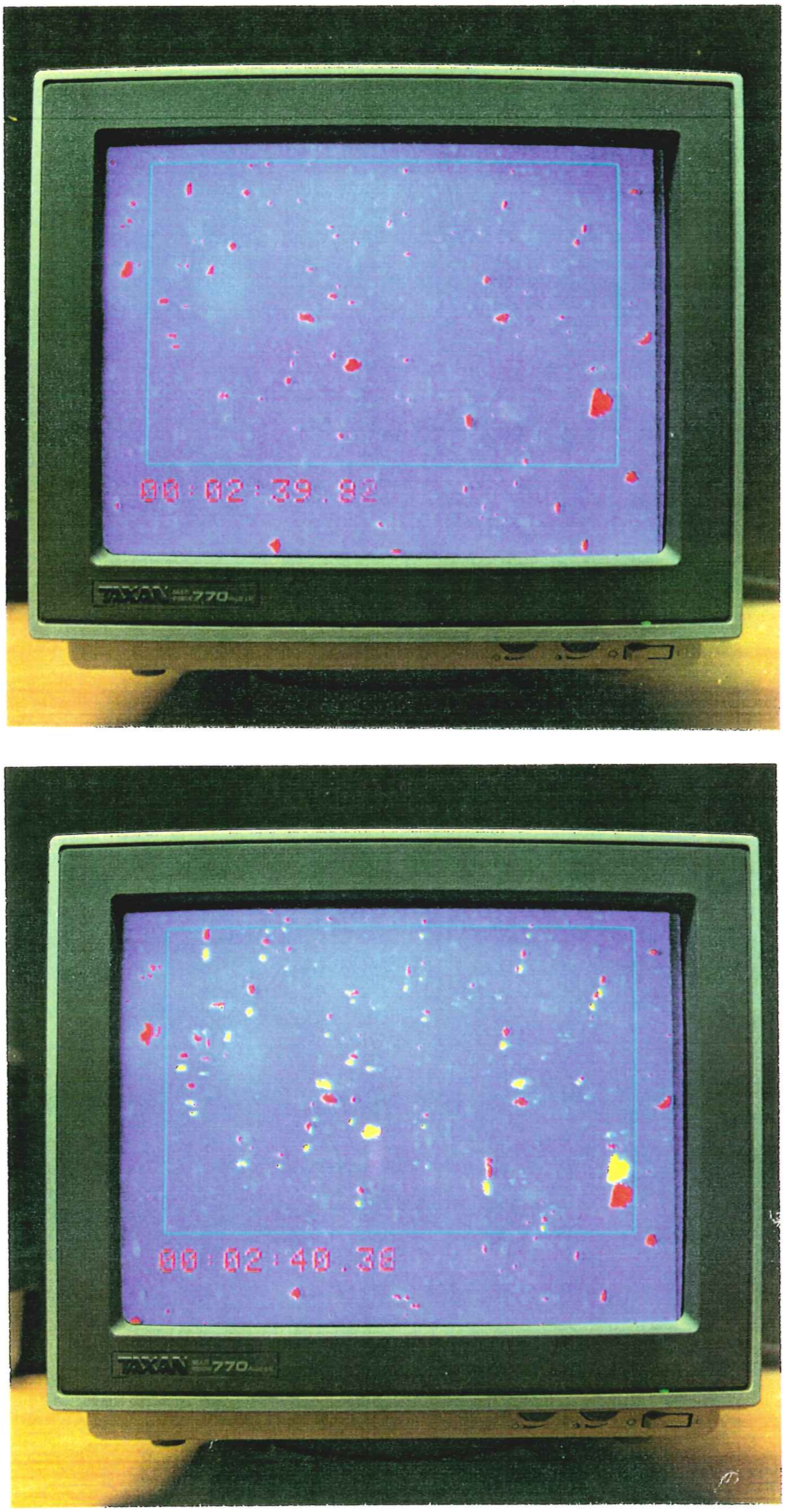


Plate 2 Output from Image Processing System showing relative floc movement