Hydraulics Research
Wallingford

THE CAROUSEL

Commissioning of a Circular Flume
for Sediment Transport Research

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CONTRACT

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ABSTRACT

Studies of the erosion transport and deposition of fine sediment are very relevant to a wide range of engineering problems. Understanding the physical mechanisms of erosion and deposition forms a key step in the predictive modelling of fine sediment transport. For many years scientists and engineers have been aware of the difficulty of achieving this and have undertaken extensive programmes of laboratory experiments.

Early experiments were carried out in conventional recirculating flumes and were found to have shortcomings. In particular the recirculation pumps tended to destroy the natural floc structure which fine cohesive sediments have in estuaries. As a result annular flumes were developed where the flow is driven by rotation of a roof, or floor, or both. While this avoids the floc damage problem, these flumes give rise to secondary flow because they represent, in effect, a continuous bend.

A major facility of this type, known as "The Carousel", has been developed at Hydraulics Research Limited. It is the largest of its type in the world and offers advantages over other systems in terms of its ability to model natural conditions.

A large number of tests have been carried out in the carousel in order to calibrate its performance. The results of these tests form the basis of this report which concludes that the apparatus is consistant, and reliable in its performance and that it will provide an extremely useful tool for further research. Some exploratory tests using sediment in the carousel are presented by way of illustration. They led to a suggestion for a first series of tests using the facility to study the deposition of fine sediment from flowing water and in particular the dependence on concentration of suspended solids. This work is reported separately in HR Report No SR 27.

These tests led to some recommendations for modifications to the Carousel and instrumentation which would enhance its range of applications, in particular to allow studies of the complex sedimentation processes involved during continually varying flow, as occurs in tidal estuaries. Proposals have been submitted for further research on these lines.

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1 INTRODUCTION

1.1 The need for research

The erosion, transport and deposition of fine sediment creates a wide range of design, maintenance and management problems in ports and harbours, docks, estuaries, coastal waters and inland water courses. These problems can be split into three main categories:

(i) <u>Easy navigation</u>: of waterways is essential for ship and boat transportation. Fine sediment can hinder navigation, by deposits building up in channels reducing water depth. These deposits have to be dredged, which is an expensive process: accurate predictions of amounts of dredging and frequency are essential for good economic planning. When new engineering structures are planned, eg a new jetty and berth, the design should take into account potential sediment scour and deposition.

(ii) <u>Pollution transfer</u>: Many polluting chemical species are preferentially sorbed onto fine sediment particles and travel with them. Thus to predict the fates of these pollutants and their relative effects on natural systems the prediction of fine sediment behaviour is essential.

(iii) <u>Ecology</u>: Considerable damage can be done to benthic habitats and recreational amenities by fine sediment entering or depositing in an area where previously it was absent. Such changes can occur as a result of major engineering works.

All of these problems highlight the need to be able to predict and quantify fine sediment movement so that the problems can be avoided, alleviated or economically controlled.

At present, numerical models exist which can predict transport of fine cohesive sediments. However, the physical processes are still not fully understood which obviously limits the accuracy of predictions and clearly points to the need to refine the relevant equations. Field observations have shown that the processes involved are very complex and difficult to measure. The carousel offers the ability to study these complex processes under precisely controlled conditions so that the relative importance of each parameter can be measured. The relevant parameters are now discussed briefly.

1.2 Properties and behaviour of fine sediment

Fine cohesive sediment consists basically of an assemblage of mineral and organic particles, mainly less than 0.063mm diameter, of various shapes. Because of the particles' very small size and chemistry, they develop electrical surface charges (the majority being negative). This is a very important factor in fine sediment behaviour, as these negative charges lead to interactions between the particles themselves and the fluid they are suspended in. The parameters governing these interactions are collectively called physicochemical parameters.

Physicochemical Parameters

1. Particle size, and number of particles (concentration).

2. Particle mineralogy, and its distribution through the particle population.

3. Ph, ionic strength, chemical composition and temperature of the fluid the particles are immersed in, and of the fluid collected between particles (pore fluid).

Hydrodynamic parameters may also affect fine sediment behaviour. These relate to the energy of the fluid in which the sediment particles are immersed.

Hydrodynamic Parameters

1. Fluid velocity.

2. Fluid turbulence.

3. Internal fluid shear.

4. Bed shear stress.

5. Stress history of fluid.

It is the combined effect of these two sets of parameters which control the state(s) of the sediment at a particular time. Fig 1 shows the various states of sediment that are believed to occur.

(a) Mobile suspended sediment Particles of sediment are supported by a balance of momentum, buoyancy and drag.

(b) Floc settling Under certain fluid flow conditions particles aggregate to form larger particles known a flocs which, because of their large size, have a higher settling velocity than the individual particles. The result is that the flocs fall towards the bed. Some are redispersed as they settle: some stay in the fluid mud zone.

(c) Fluid mud Flocs settling from suspension collect near to the bed. It is difficult to define this phase precisely as its characteristics are to some extent transitionary. Some of its characteristics are as follows:-

(i) high concentration
(ii) behaves as a fluid of some description (but not Newtonian)
(iii) has some small cohesion which maintains its integrity
(iv) when stationary it rapidly tends towards the next phase of a consolidating bed due to continued settling of flocs.

(d) Consolidating bed Water is squeezed out as the self weight of the flocs deforms the flocs at the lowest level and a soil skeleton begins to exist (ie forces can be transmitted through inter particle contact whereas in a suspension they cannot). In this phase the material can no longer be considered as a fluid.

(e) Settled bed This is properly defined as a fully consolidated bed, ie when all the excess pore pressure has been dissipated. In practice this takes a long time but a pragmatic definition would be a bed which has consolidated to a degree where further detectable consolidation would take months rather than days.

Deposited material (d or e) can be resuspended by erosion if the currents are strong enough. In this event material is returned to the first state (a).

1.3 Previous studies

Early experiments to study erosion and deposition processes were undertaken in recirculating flumes with centrifugal recirculating pumps and return pipes [1,2]. Both of these are regions of high shear, and were noticed by many workers, eg Partheniades, to cause floc breakage. This was thought to have a more significant effect on deposition experiments than erosion experiments. Partheniades attempted to solve this problem by developing an annular flume.

The principle advantage of the annular flume is that it effectively represents an infinitely long flume with uniform conditions throughout, although the degree of uniformity around the annulus may be open to question. Because of the absence of pumps it has great advantages in studies of deposition in that it allows flocs to grow and settle without passing through a short section of high shear.

One of the problems encountered by Partheniades in the annular flume was that of secondary flow induced by the curvature of the flume. It was argued that this could artificially maintain sediment in suspension which would otherwise settle out. To overcome this he designed the apparatus so that the flume could rotate in the opposite direction to the roof. By careful adjustment of the relative velocities he was able to produce circumferential flow at the floor with no radial component.

Some criticisms of the experiments conducted by Partheniades in this apparatus may be made without detracting from the progress they allow. These include the facts that:

(i) the stresses in the suspensions are derived from false floor calibrations and not from actual flow velocity measurements.

(ii) the suspended solids were monitored by taking samples only at the wall, at discrete points in the vertical. The bottom 40mm was not monitored at all.

(iii) the turbulence characteristics of the flow are unknown.

(iv) there was no control of the physicochemical conditions.

Other experimental facilities which have been planned for deposition and erosion studies include racetrack flumes, of which several are under construction in USA. These are an attempt to use the advantages of the circular flume while avoiding the insuperable hydrodynamic problems of radial velocity components associated with them by having straight drive and test sections, and low curvature connections. They are large, expensive and at present very difficult to drive.

2 THE CAROUSEL

2.1 Design criteria

The annular flume (Fig 2) was designed to take advantage of the benefits of eliminating floc disrupting pumps and return pipes, found in recirculating flumes.

Its large size was designed to minimise channel curvature and therefore radial flow. In this way it was hoped that it would not be necessary to have a contra-rotating roof and channel.

The stationary channel and perspex test section allow direct measurement of the velocity field using laser anemometry, which is a major advantage over previous circular flume studies.

The continuously variable drive allows gentle acceleration or deceleration of the roof, which also gives the capability to follow the stress history of, for example, a tidal cycle.

2.2 Operation

The carousel (Fig 2) consists of an annular flume, with an outer diameter of 6m, a channel width 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 the 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. It is to this plate that the drive arm is attached at one end (via the strain gauge) and to the roof at the other.

The speed of the motor, and hence roof speed, can be altered by a dial control, situated on one of the flume support pillars. The motor speed can be set to an accuracy of 4 digits, between 0000 and 9999, 0.1% of the maximum speed. This produces a mean water velocity range in the flume from zero to approximately $0.7ms^{-1}$.

Fig 3 shows schematically the filling and emptying processes involved with the carousel. Before a suspension is put into the carousel, it is first mixed up homogeneously. This is achieved by putting the mud and fluid into the mixing tank and pumping them through it's recirculatory system.

The suspension is then pumped into the flume from the tank until the required depth of suspension, in the flume, is reached. The roof is lowered onto the suspension surface and the experiment is ready to start. After experimentation is completed the roof is raised, the drain opened and the suspension can either be pumped to waste, or back to the tank for remixing, or to another tank for storage.

2.3 Instrumentation

Strain gauge (Fig 2 inset)

This is used to measure the force applied to the roof of the carousel as it rotates. It consists of a spring and displacement transducer arrangement attached to the driving arm at the point of contact with the roof.

The magnitude of the applied force is determined by the displacement transducer deflection, which is displayed on a chart recorder. The strain gauge is calibrated by applying known forces via a pulley system.

Tachometer

This is used to measure the speed of the motor which drives the carousel roof. The speed is proportional to the voltage of the motor power - this voltage is displayed via a chart recorder.

Laser velocity meter

This is used to measure the flow velocity in the carousel. The measurements are very accurate ($\pm$ 1mms^{-1}) and can be made at any point in the cross-section of the flume, through the perspex section. These point velocities are used to obtain velocity profiles and cross-sectional mean velocity.

The equipment comprises three parts:-

(a) Laser optical unit (Fig 4a). This consists of a 5 milliwatt helium-neon laser, a beam splitter, a Bragg cell and a Lens.

(b) Photomultiplier optical unit (Fig 4b). This consists of a photomultiplier tube, an achromatic focus lens, a mirror and a viewing eye piece.

(c) Electronic units. These consist of power supplies for the laser and photomultiplier, Bragg cell driver(s) and electronic frequency shift, and circuitry to extract the relevant doppler frequency from the detector output signal.

The laser velocity meter operates by emitting two convergent beams in the same horizontal plane. These beams pass through the perspex window of the flume and intersect at some point in the flow. It is at this intersection point that the velocity component of the flow normal to the beam crossing is measured (see Fig 4c). The photomultiplier unit is focussed on the beams crossing point, and as a particle in the flow passes through the crossing point light is scattered from the two beams, doppler shifted in frequency by equal and opposite amounts. The difference is detected in a signal modulation, which is then converted by one of the electronic units into a voltage output which in turn is fed onto a chart recorder. From this the velocity can easily be calculated.

3 COMMISSIONING TESTS

A series of tests were carried out to examine the performance of the carousel. Each aspect is now reported in detail.

3.1 The drive mechanism

3.1.1 Motor speed control (Fig 5)

The tachometer voltage was recorded for various motor speed control settings. The relationship between the two was found to be linear.

3.1.2 Motor speed stability

At several speed control settings the motor was run for periods up to 24 hours to test stability. The results showed there was no variation at all in the voltage output. Hence, the motor speed is considered to be stable. This means that the long term roof speed is also stable because the two are mechanically linked.

3.1.3 Calibration of roof speed (Fig 6)

A relationship was obtained between the motor speed and the roof speed, by recording the number of revolutions per minute the roof made at various motor speed settings. The relationship obtained demonstrates a slight non-linearity of the control system.

3.1.4 Stability of roof rotation

<u>Speed - long term</u>

The motor speed has been demonstrated to be stable for at least 24 hours. This means that the long term roof speed is also stable because the two are mechanically linked.

Speed - short term

Although the average roof speed is constant it was considered that short term variations could take place for 2 reasons:

(a) unsteady load on the drive motor, (for example if the bearings on the central roof spindle were badly aligned or if the roof itself was catching on the walls of the flume).

(b) there is some freedom of movement in the linkage between the drive arm and the roof (ie the strain gauge) which could allow a periodic acceleration and deceleration to develop.

The combined affect of these is revealed in the voltage output from the strain gauge.

A number of tests were done, recording the gauge reading for various roof speeds. An example of the record obtained for one roof speed is shown in Fig 7 where it is clearly evident that there are periodic fluctuations in the reading within each revolution of the roof. Varying the roof speed showed that the number of oscillations within a roof cycle was constant and equal to about 9. Investigation of the mechanical drive system showed that this corresponded to the gearing ratio of 9:1 between the friction wheel and the main drive plate where there was also a slight eccentricity. Occasional additional oscillations are caused if the roof binds against the flume. This tends to happen more at the higher speeds.

Returning to consider the effects of these oscillations on the flow field it is evident firstly, that if the link between the drive arm and the roof were to be rigid the amplitude of the oscillations would be very small and secondly, that variations in roof speed are proportional to the displacement of the strain gauge and the period of the oscillation. The variations have been estimated at typically about ±1% of roof speed. Allowing for the inertia of the flow in the flume, this is likely to be damped almost out of existance. [Velocity variations of 1 to 4% of similar period have been observed but cannot be attributed to this mechanism alone.]

Variation in height

The roof floats on the water and any variations in height during rotation could cause unwanted pressure waves through the flume. This was investigated by recording the underside height of the roof, above an arbitrary reference point, during a series of complete rotations, at a motor speed setting 96. Fig 8 shows the averaged results, the largest variation in roof height that occurs is 3.5mm which is 3.5% of the total depth (ie a very small change).

3.2 Energy input

The inertia of the water in the flume is altered only when the force exerted on it by the roof rotating is changed. Force is obtained by the relationship:-

Force = mass x acceleration.

As the mass term stays constant for the water in the flume, the only way that the acceleration, and hence velocity of the water can be changed is by altering the roof force. That is to say if the force is decreased or increased so will the acceleration term decrease or increase and hence velocity of the water. Thus to keep a steady state situation in the flume the force has to be kept constant, by producing a constant torque on the roof.

When the flow velocity in the flume is kept constant the kinetic energy of the water is constant and is equal to the work done by the applied force in overcoming resistance to flow. Thus:

work done = applied force x distance moved.

Thus in unit time:

work done/sec = $F \times \omega r$

where ω = angular velocity of roof, r = radius of flume. This constant energy input to the system is dissipated mainly as heat.

3.2.1 Calibration of strain gauge

Energy input was measured by the strain gauge, between the roof and the drive arm. To convert the strain gauge voltages to applied force it was first necessary to carry out a calibration. This was done by uncoupling the strain gauge from the roof and attaching progressively heavier weights to it via a pulley system. The relationship between voltage and applied force is linear and shown in Fig 9. It should be noted here that strain gauge characteristics change with use and this calibration exercise needs to be repeated regularly. After a certain amount of use the strain gauge springs may become distorted and need replacing.

3.2.2 Relation to roof speed

The flume was filled with water to a depth of 0.10m and the roof driven at various speeds to observe the required energy input. After smoothing the oscillations described in Section 3.1.4 mean strain gauge readings were converted to applied force using the best fit calibration line shown in Fig 9. The results are shown in Fig 10.

3.3 Velocity Field

3.3.1 Measured velocity field

Using the laser velocity meter it is possible to measure precisely the circumferential velocity at any point in the cross-section of the flume visible through the perspex window.

A large number of exploratory tests were carried out varying the water depth and roughness of the roof to find the combination which minimised secondary flow effects and gave as even a shear distribution on the bed of the flume as possible. No purpose is served by recording here the details of all the tests which in essence were simply exploring the fundemental fluid mechanics of the flume. The conclusion was that best results were obtained when the water depth was about 100mm and the roof was smooth. This condition was adopted as standard for all further tests and its flow field was studied in detail.

Point velocity measurements were taken on a grid across the cross-section of the flume and used to plot isovels (lines of equal velocity). Fig 11 shows examples of the velocity profiles obtained for different roof speeds.

From these figures it can be seen that the isovels patterns are all very similar, displaying a sharp inward bend at a depth of 20mm with the middle sections sloping upwards towards the outside and a gentle bend outwards at an 80mm depth. Because these figures were so similar they were used to construct a generalised section (Fig 12). Each isovel value is displayed as a fraction of the cross-section mean velocity.

3.3.2 Secondary flow

In the cross-section velocity profiles, Figs 11 and 12, there is evidence of a secondary flow system, at right angles to the circumferential component of flow. This has been sketched on Fig 12.

This secondary circulation is induced by the centrifugal force produced when the roof is rotated. The water on the surface is forced outwards, when it reaches the outer wall it is deflected downwards, then when it reaches the outer bottom corner most of the flow passes on towards the inner side and back up to the surface, but some remains in this corner and sets up a smaller circulation cell. From this description and Fig 12 it may appear that the circulation cell is completed, which is not true because the longitudinal component of flow, gives it a resulting helical motion along the flume.

3.3.3 Cross-section mean velocity

The velocity measurements used to produce the isovels in Figs 11 and 12 were also used to calculate cross-sectional mean velocities for each motor speed setting. The relationship is shown in Fig 13 demonstrating that mean water speed is directly proportional to roof speed over most of the operating range. It is interesting but not important that the mean tangential velocity sustained in the flume is approximately half the roof speed.

Thus using the above relationship and Fig 12, it is possible to predict with reasonable accuracy the entire cross-sectional flow field knowing only the roof speed.

3.3.4 Further discussion

The isovels in Figs 11 and 12 give a rather misleading view of the flow field, emphasising the variation across the width. Fig 14 shows the variation across the width at several depths. Also shown is the roof speed normalised to cross-sectional mean velocity. This figure clearly shows that the velocity distribution across the width of the flume is closely related to the variation in tangential roof speed due to radius.

Vertical velocity profiles have also been plotted separately for different positions across the width of the flume in Fig 15. This shows that although the velocity magnitude increases with radius the profiles are very similar in form. It should be possible to derive shear stress distribution on the bed from this data.

3.4 Sediment

3.4.1 Sampling of suspended solids

When performing sediment erosion or deposition experiments in a flume, it is vital that sediment concentration changes, in the fluids involved, are monitored so that any sediment movement occurring can be directly detected. The monitoring processes generally involve a system in which a small portion of the fluid/sediment under investigation is periodically extracted and analysed for sediment concentration.

In the carousel the sampling system consists of two port holes, one on each wall of the flume, 80mm above the floor (See Fig 16). Through each of these port holes protrudes an 'L' shaped stainless steel sampling tube, which has an internal diameter of 2mm. The sampling tube on the inner wall of the carousel is non-movable, with its entrance facing downstream, and is only used for returning analysed samples into the flume. The outer wall sampling tube has its entrance facing upstream, its elevation is adjustable, and it is used for extracting samples. The elevation of the tube's entrance can be altered by rotating the outer portion of this tube across a scale corresponding to 0-100mm above the flume floor.

A sample of the fluid is obtained by inserting a syringe into the silicon rubber tubing, attached to the sampling tube, and extracting a volume of 30ml, which is then analysed for concentration in an absorptiometer, calibrated with frequent gravimetric analyses.

The main advantage of this system is the ability to sample at any height in the fluid, and to return analysed samples back into the flow. However, during some preliminary experiments in the carousel a few problems arose. The first problem was that as the horizontal distance of the sampling tube's entrance is fixed in the middle of the flume, any variation in sediment concentration across the width of the flume could not be monitored. The second problem encountered, was that when the sampling tube entrance was close to the sediment bed, the bed was disturbed.

3.4.2 Bed thickness

This measurement is also essential in determining sediment movement in the carousel. At present bed thickness can only be measured by reading off the apparent surface of the bed on the depth scale which is fixed onto the window on each side of the carousel. The obvious disadvantage of this is that measurements cannot be made in between the two. Hence any bed thickness changes taking place in this region cannot be detected.

4 SUMMARY AND CONCLUSIONS

A large number of tests have been carried out in the carousel in order to calibrate its performance. The results lead to the conclusion that the apparatus is consistent and reliable in its performance with few shortcomings. Each aspect of its performance is summarised below.

The drive mechanism

The performance of this is both consistent and reliable. The only shortcoming observed in the tests was a short term instability of the roof speed, due to an eccentricity in the drive wheel and binding of the roof in a couple of places. Although the effect of this on the flow velocity in the carousel was almost negligible, the drive mechanism was modified, resulting in greater stability of the speed.

The energy input

This comes from the drive mechanism, and as the latter is concluded to be reliable and stable, then so the former is. This can be measured reliably by the strain gauge as long as frequent calibrations of the springs are made.

The velocity field

This has been accurately measured at many points over a cross-section of the flume. The results indicate that there is a higher velocity towards the outer edge of the flume, the velocity variation across the width is very similar at all depths and is directly related to the variation in tangential roof speed due to the radius. The cross-section mean velocity is directly proportional to the roof speed. All the vertical velocity profiles are very similar in form. There is a secondary flow element in the carousel, the magnitude of which is very much smaller than in the 'normal' direction of flow. The disadvantage of slightly distorted flow directions is outweighed by the advantage that the flow generated in this way does not disrupt the flocs.

Sediment

The original suspended solids sampling system worked adequately, however, it had the shortcoming that changes in concentration over the channel width could not be monitored. The system was modified to allow this and is now considered to be satisfactory.

Bed thickness measurements can be made very easily and accurately on either side of the carousel, however, at the moment the bed level in between cannot be observed.

Practical applications and future research

The first experiments to be carried out in the carousel need to investigate and evaluate the circumstances under which sediment starts to deposit and the rate under specified flow conditions.

Understanding these processes would help to increase our accuracy in predicting silt deposition in estuaries.

However, in an estuary the flow is very dynamic and steady state flow conditions do not prevail for long periods of time. Because of this the net siltation depends on the balance of deposition and erosion processes, which depends on the energy paths of the tides. The carousel with a small modification would be ideally suited to studying this phenomena by simulating estuarine tidal cycles. This is anticipated to be the next major step forward in the study of estuarine siltation.

5 RECOMMENDATIONS

There will always be scope for developments and improvements to experimental apparatus, which must be carefully weighed against likely benefits. However, based on observations and conclusions drawn during the commissioning tests there are some modifications to the control system and instrumentation which would enhance the carousel's range of applications in particular for studying the complex sedimentation processes involved in tidal estuaries. These are listed below.

1. A reversible driving system with servo control, to allow simulation of reversing tidal flow and tidal cycles.

2. A system whereby all the existing measured parameters can be displayed clearly and the motor speed control altered, from a central control panel. Allowing more flexibility and easier control of the experiments.

3. A control system based around a small micro computer to facilitate autonomous operation of the carousel and data storage.

4. The existing laser velocity meter is very accurate in low concentration of suspended sediment and clear water, however in higher concentration of suspended solids it is limited, due to beam attenuation. A range gated pulsed acoustic doppler should be investigated, as an alternative. It would be non-intrusive and could be made sufficiently accurate and reliable at all concentrations of suspended solids.

5. Continuous monitoring of suspended solids throughout the cross-section without extracting samples for analysis. At present a co-axial fibre optic system offers the most promising method. However, investigation of an acoustic

doppler scattering technique should be made as this would have the advantage of being non-intrusive.

6. Installation of a system of ultrasonic transducers at several sections around the flume would allow very accurate monitoring of bed thickness in the flume.

Having this system would allow controlled correlation between energy input, suspended solids and bed changes.

6 REFERENCES

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Appendix

APPENDIX

SOME PRELIMINARY EXPERIMENTS

Kaolinite deposition experiment

This was the first deposition test to be carried out in the carousel. It was essentially an observational test, in order to identify the pattern of deposition that would take place in a suspension subjected to a progressively decreasing velocity field.

The particle size distribution of the kaolinite sample is shown in Fig 17. Kaolinite and fresh water were mixed, in the tank, to give a suspension with a concentration of 54,570mgl^{-1}. This was then pumped into the carousel. The roof was initially rotated at the motor's highest speed setting (999), and then gradually reduced in steps at approximately 45-60 minute intervals to zero. 30ml samples of the suspension were extracted from 60mm above the flume's floor at various time interals. Visual observations were made at regular intervals through the perspex windows on the inside and outside of the flume.

Visual observations

The suspension remained in its initial well mixed state until the flow velocity had been reduced to 0.260ms^{-1}, 11.5 hours after the start of the experiment. At this time there appeared a 'bed' 7.5mm deep, on the inside window, which had the appearance of an elongated ripple with a rough surface. When the velocity was reduced to 0.190ms^{-1} this 'bed' disappeared and flocs formed at the bottom of the suspension while the top of the suspension (5mm) cleared. The suspension at this stage was still moving along, the top moving faster than the bottom. Flocculation, settling and consolidation of the suspended sediment with a corresponding clearing of the upper part continued throughout the rest of the experiment, on the inside window.

On the outside window, the first change to take place in the suspension was 13.3 hours after commencing the experiment with the flow velocity at 0.118ms^{-1}. There was a clearing in the top 20mm of suspension revealing a gently waving suspension/water interface, the suspension still moving throughout the depth.

As the velocity was reduced to 0.081ms^{-1} the flocculated suspension on the inside window ceased to move along.

Meanwhile, on the outside, the interface wave motion had subsided but it was not until there was a reduction in velocity to 0.043ms^{-1} that the first very fine flocs started to form in the bottom 5mm. Substantial floc formation only took place when the velocity had been reduced to zero.

Results

The suspended kaolinite concentration variation with time is shown in Fig 18. Throughout the experiment the suspended kaolinite concentration remained almost constant at $51,000 mgl^{-1}$ until the velocity was reduced to $0.190 ms^{-1}$, 12.5 hours after the experiment had been started. Then the concentration began to drop, but even over the following 2½ hour period where the velocity was reduced to zero from $0.190 ms^{-1}$ in four stages the concentration only dropped from $51,000 mgl^{-1}$ to $38,000 mgl^{-1}$.

Simulated tide experiments

The tidal cycle to be simulated was obtained from near bed tidal velocity profiles available from the Humber estuary. This test was carried out on two suspensions, firstly on kaolinite, then on mud from the same source as the velocity measurements.

Experimental procedure

This was the same for both suspensions used, the only difference being in the initial concentrations, for kaolinite it was $54,570 mgl^{-1}$ and for pyewipe mud $62,000 mgl^{-1}$. The particle size analysis of the Humber mud is given in Fig 19.

The flow velocity pattern followed, can be seen in Figs 20 and 21. During these experiments visual observations were made regularly through the perspex windows, and additionally for the pyewipe mud suspension time lapse photographs were taken (Plates 1-8). 30ml portions of the suspension were extracted, 60mm above the flume floor, at 5 to 10 minute intervals and analysed for suspended solids concentration.

Kaolinite test: visual observations

Velocity decreasing

The first change observed in the suspension took place at the inside window of the carousel 1 hour, 40 minutes after the start of the experiment when the velocity had dropped to $0.198 ms^{-1}$. The bottom 10mm of suspension stopped moving along and flocs began to form. As the velocity continued to decrease the number and size of these flocs increased upwards throughout the depth of the suspension, and correspondingly the depth of non-movement increased. The flocs also began to consolidate at the bottom of the flume. Simultaneously the suspension depth decreased, and a clearer layer of water developed above it.

It was not until about 2 hours, into the experiment, when the velocity was $0.137ms^{-1}$ that anything happend. There was a sudden clearing in the top 10mm of suspension on the outside, exposing a water/suspension interface exhibiting wave motion. This wave motion gradually diminished in magnitude, as the velocity decreased further; it eventually ceased at a velocity of $0.027ms^{-1}$. 10 minutes before this, at a flow velocity of $0.075ms^{-1}$, flocs began forming in the bottom 10mm of suspension. As the velocity continued to decrease the flocs increased in size and number throughout the suspension depth, compacting to give an increasingly deeper clear water layer on top.

Slack water

During the 20 minute period at the lowest velocity ($0.008ms^{-1}$) the suspension behaviour was the same on both sides of the flume. There was continued compaction of the flocs, and an increase in the depth of clear water.

Velocity increasing

During the first 20 minutes of this phase there was an increase in turbidity of the upper layer on both sides. As the velocity increased to $0.047ms^{-1}$ different behaviour was observed on the two sides of the flume. On the outside wave motion began again in the suspension/clear water interface, and in the region 5mm below this the flocs had broken down into smaller aggregates. As the velocity increased further the wave motion became increasingly more vigorous with the waves breaking and dispersing kaolinite particles into the clearer water above. Hence the depth of the high concentration layer decreased and the clearer layer, whilst becoming more turbid, correspondingly increased. However, at a velocity of $0.137ms^{-1}$ the wave motion quite suddenly stopped, leaving a flocculated bed 5mm thick and a 'homogeneous' suspension above it. This situation remained the same till the end of the experiment.

During the same time on the inside of the flume the clearer layer had become progressively more turbid, with the flocs in the top 5mm of the deposited kaolinite breaking down completely. Eventually at a velocity of $0.102ms^{-1}$ they began to move along in a slight undulating fashion. As the velocity increased this moving non-flocculated region increased in depth as more flocs were broken down and taken up into the flow. By the end of the experiment there were three distinct layers, a 25mm large floc bed, a region of moving fine particles above and on top a 5mm clear water layer.

Suspended solids concentration

Fig 20 shows that the suspended solids concentration remained constant (at around $47{,}000 mgl^{-1}$) for all of the velocity reduction phase and slack water. Then it suddenly dropped to about $9{,}000 mgl^{-1}$ in the first part of the velocity increasing phase. The concentration then just as rapidly rose to around $35{,}000 mgl^{-1}$ 15 minutes further into this phase. The concentration level remained approximately at $35{,}000 mgl^{-1}$ till the end of the experiment.

Humber mud test: visual observations

As the general pattern of events that took place in the Humber mud experiment were very similar to those occurring in the kaolinite experiment, a detailed description will not be presented. Descriptions of the time lapse photographs, taken of the outside windows will be given instead.

Plate 1

Initial well mixed suspension of the Humber mud, no deposition or flocculation has taken place.

Plate 2

Initial clearing of the top 10mm of suspension as the velocity had been reduced to $0.137 ms^{-1}$.

Plate 3

Continued clearing of the top of the suspension reveals a suspension/water interface with gentle waves. Floc formation begins in the bottom of the suspension, at a velocity of $0.087 ms^{-1}$.

Plate 4

Wave motion at the interface ceased at a velocity of $0.027 ms^{-1}$, the total depth by now is taken up by flocs grading from large to small upwards.

Plate 5

The mud flocs continuing to compact with the clear layer increasing in depth, at the turning point of the tide.

Plate 6

The deposited mud is re-eroded by gentle waves starting up in the top 3mm of bed at a velocity of $0.047 ms^{-1}$. The top 5mm of flocs being broken down into smaller particles.

Plate 7

Interface waves becoming more vigorous, their crests breaking, dispersing mud particles into the clearer layer above. The clearer layer becoming more turbid.

Plate 8

The end of the experiment, the interface waves have ceased, 15mm of bed is left on the flume floor uneroded.

Figure 22 is a diagram of the mud layers observed on the inside window at a flow velocity of $0.096ms^{-1}$, in the velocity reduction phase of the tide.

Suspended solids concentration

The suspended solids concentration remained constant during the velocity reduction phase, approximately $40{,}000mgl^{-1}$. This dropped rapidly during the initial increase in velocity after slack water to about $220mgl^{-1}$, but gradually rose again in the rest of the velocity increasing phase to about 45% of the initial concentration.

Comparison of results for the tide simulation experiments

The two materials displayed similar overall behaviour in suspended solids concentration changes during the experiments, however, there were a few notable differences (see Figs 20 and 21):

(i) for the Humber mud the lowest suspended solids concentration coincides with the lowest flow velocity in the tide. However, with the kaolinite the lowest suspended solids concentration lagged behind the lowest velocity point.

(ii) the period of rapid suspended solids concentration change was twice as long for the Humber mud than for the kaolinite.

(iii) the minimum concentration of suspended solids was much smaller for Humber mud (approximately $220mgl^{-1}$) than for the kaolinite (approximately $9000mgl^{-1}$).

(iv) the Humber mud only reached 45% of its former suspended solids concentration level after re-erosion, whereas the kaolinite reached 74% of its former level.

Future work

These three preliminary experiments, highlight the need to investigate certain events that take place during the deposition process.

In all of these experiments the suspended solids concentration remains relatively constant until the shear stress is reduced to a particular level at which the suspended sediment begins to settle out. One obvious question that arises from this is: is there a unique critical stress for deposition to occur or is it concentration dependent?

A test should be carried out on mud suspensions of different initial suspended solids concentration, subjecting them at first to a high shear in the carousel, then gradually reducing it until deposition occurs. The rate of deposition should also be monitored to examine the effect of varying velocity below the critical value.

Figures

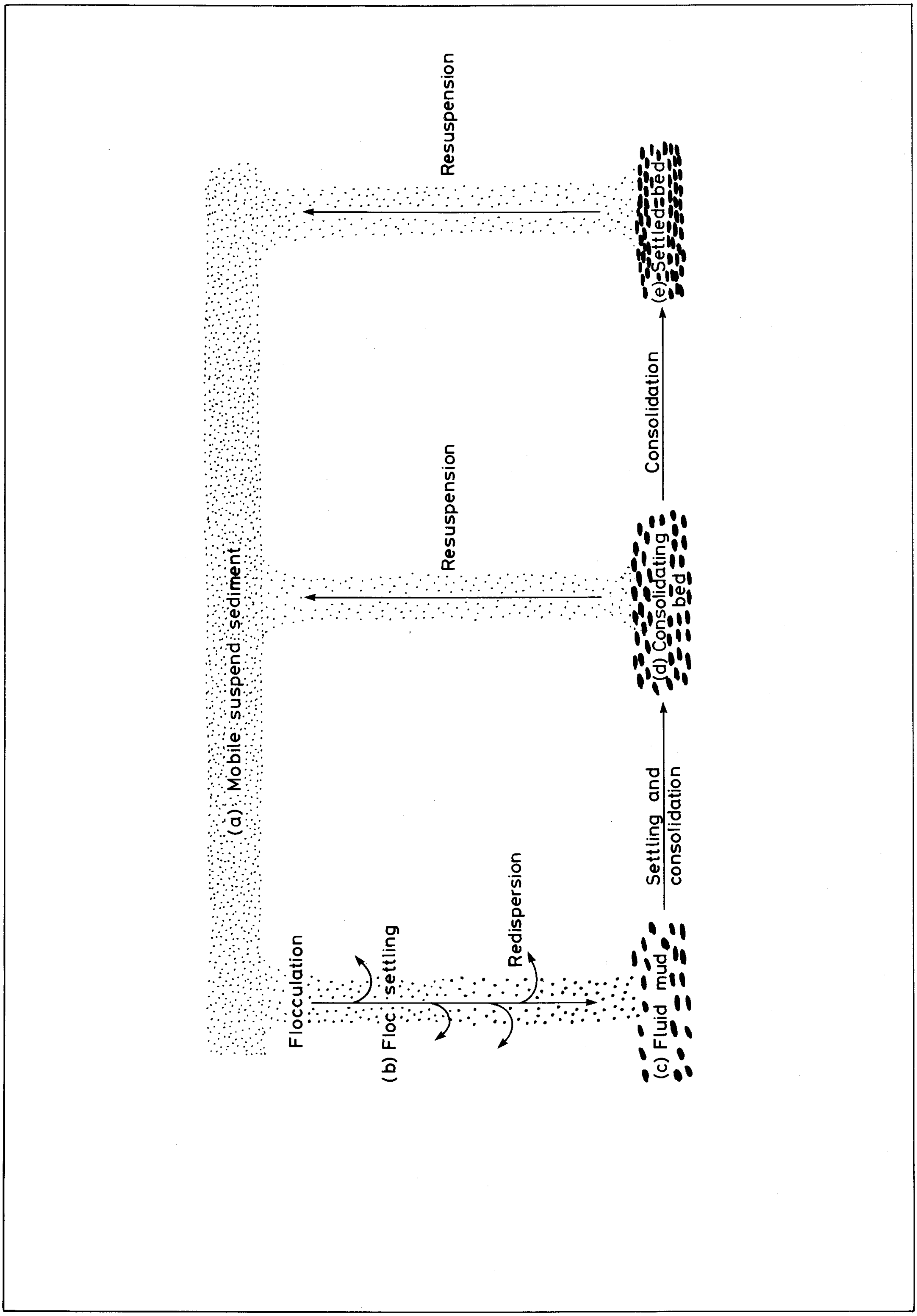


Fig 1 States of sediment

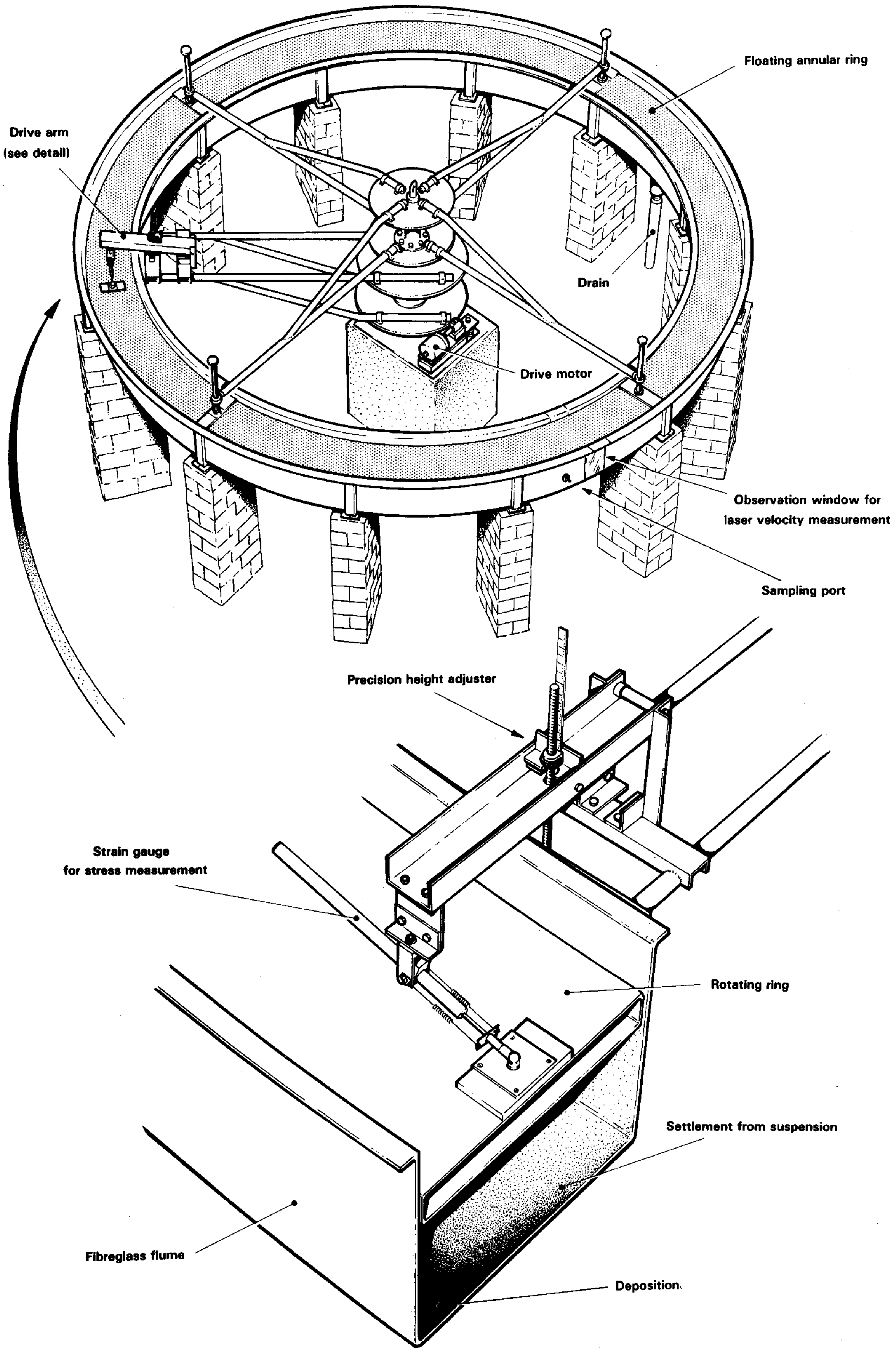


Fig 2 The Carousel

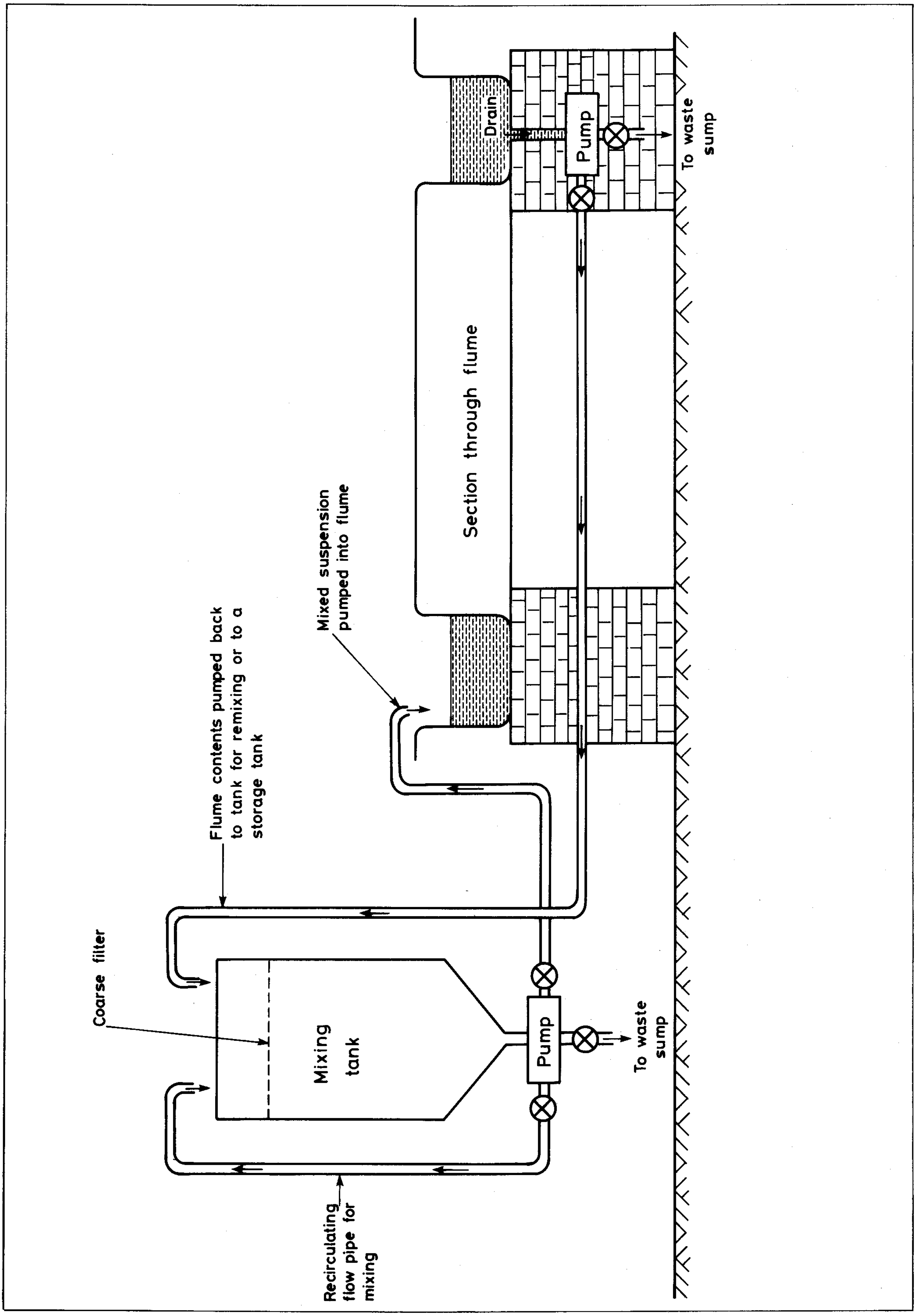


Fig 3 Filling and emptying system

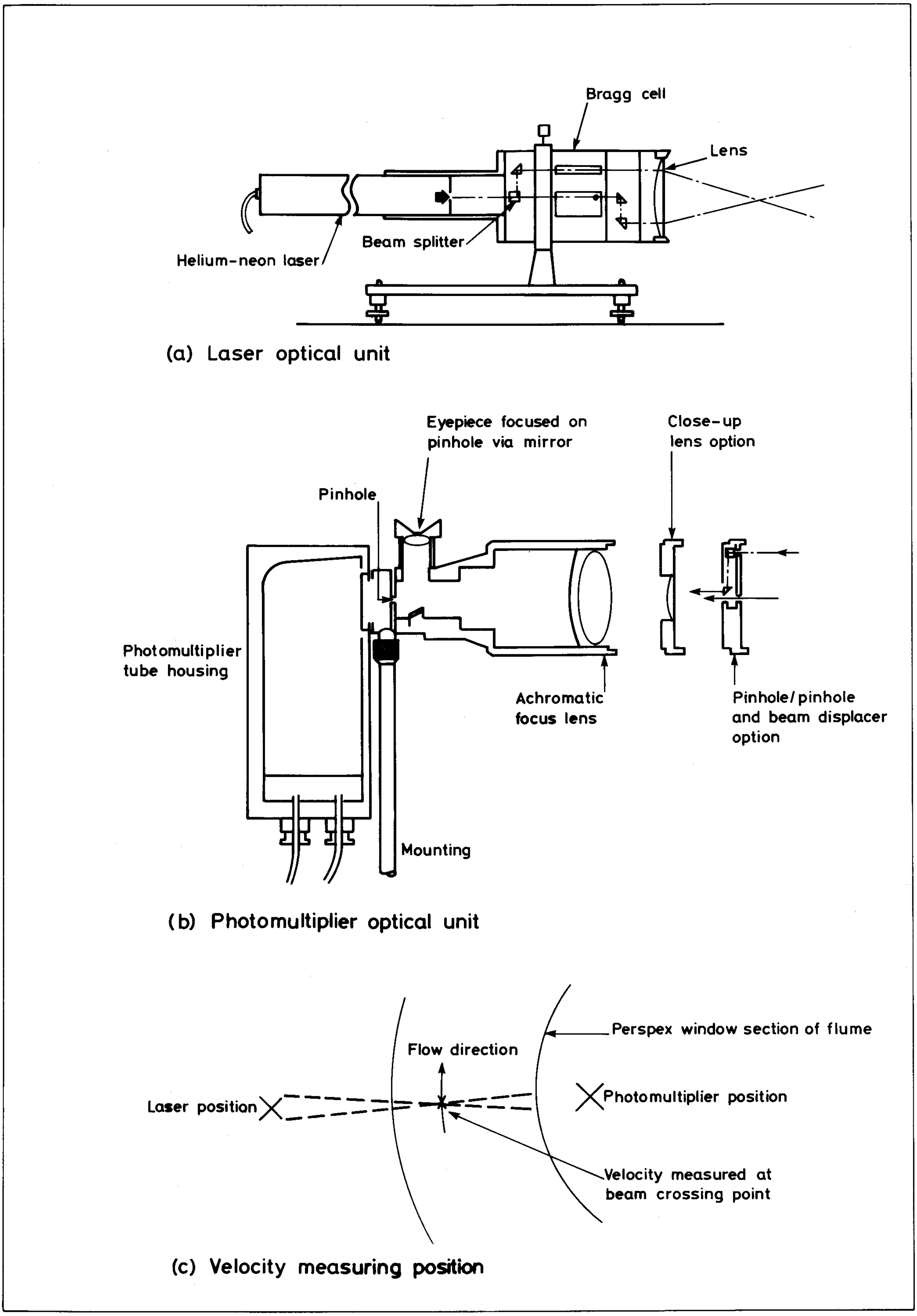


Fig 4 The laser velocity meter

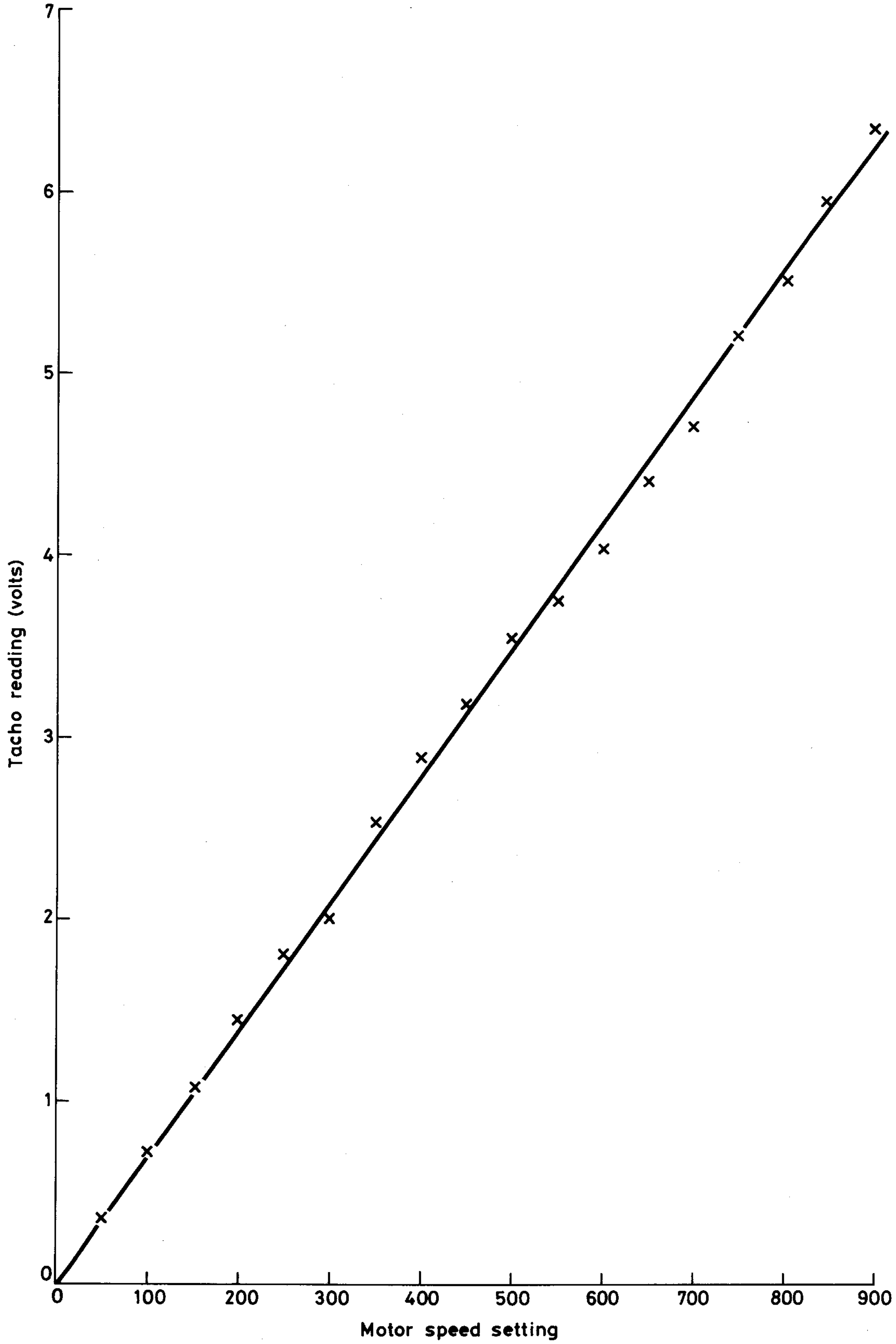


Fig 5 Motor speed control calibration

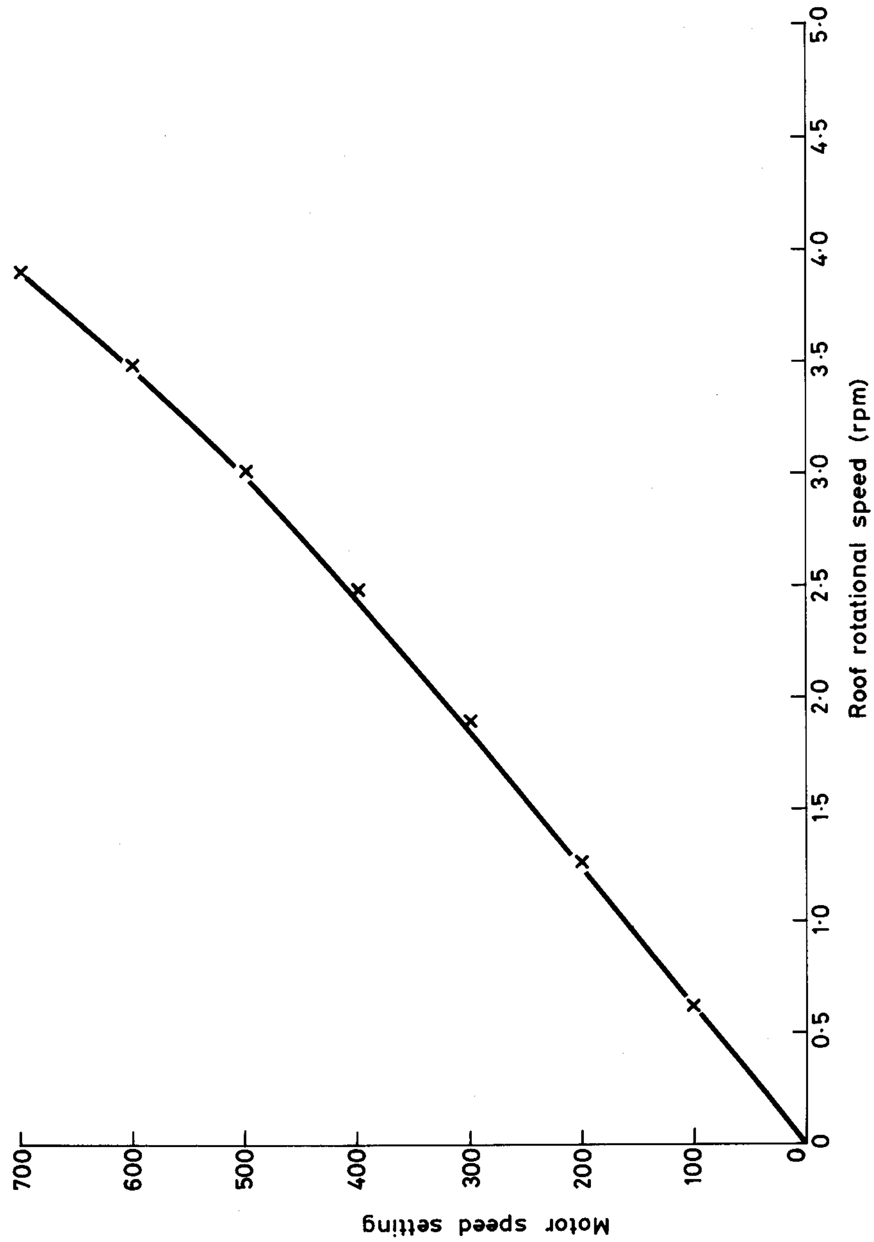


Fig 6 Roof speed calibration

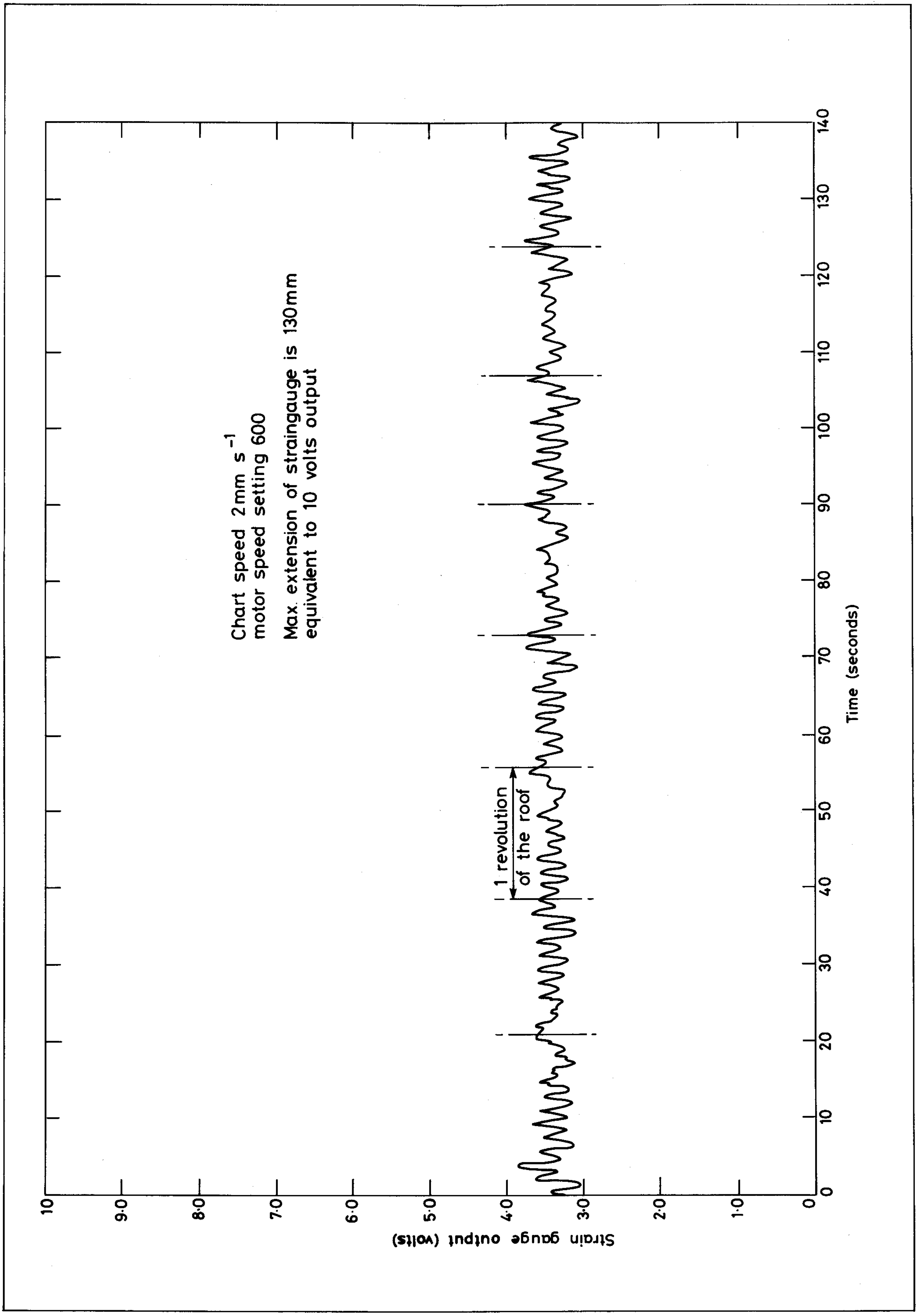


Fig 7 Short term stability of roof rotation

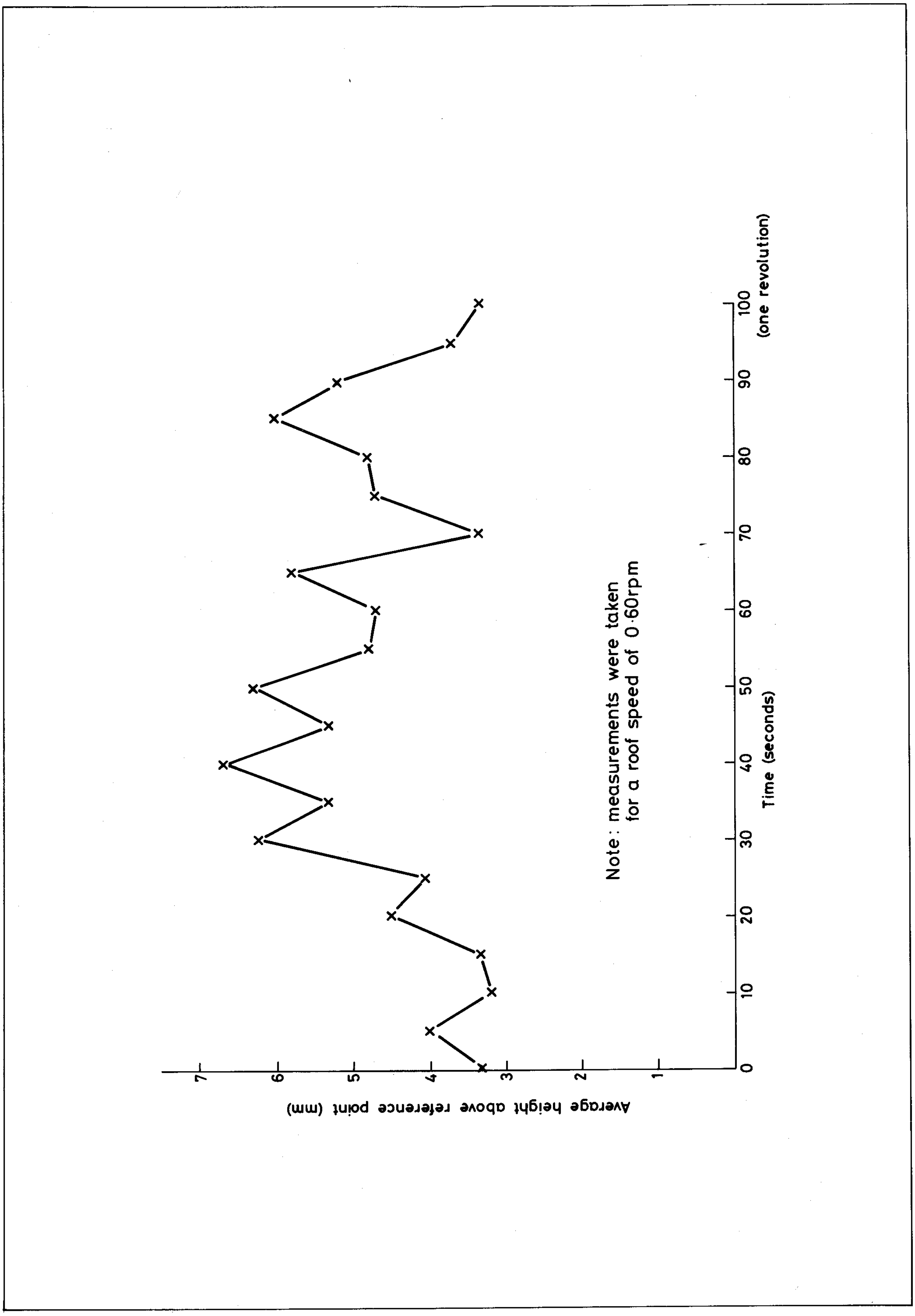


Fig 8 Variation in roof height during rotation

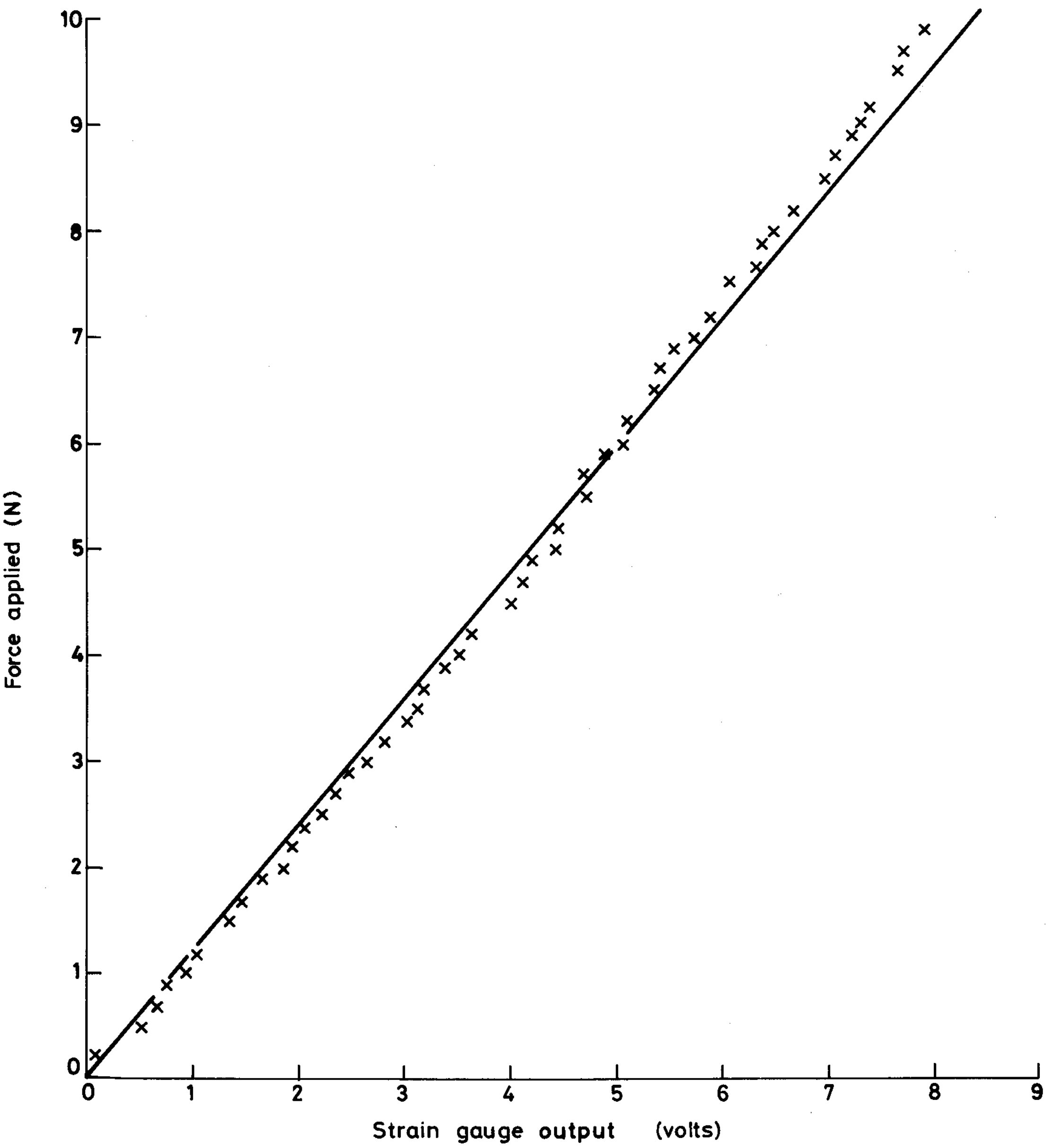


Fig 9 Calibration of strain gauge

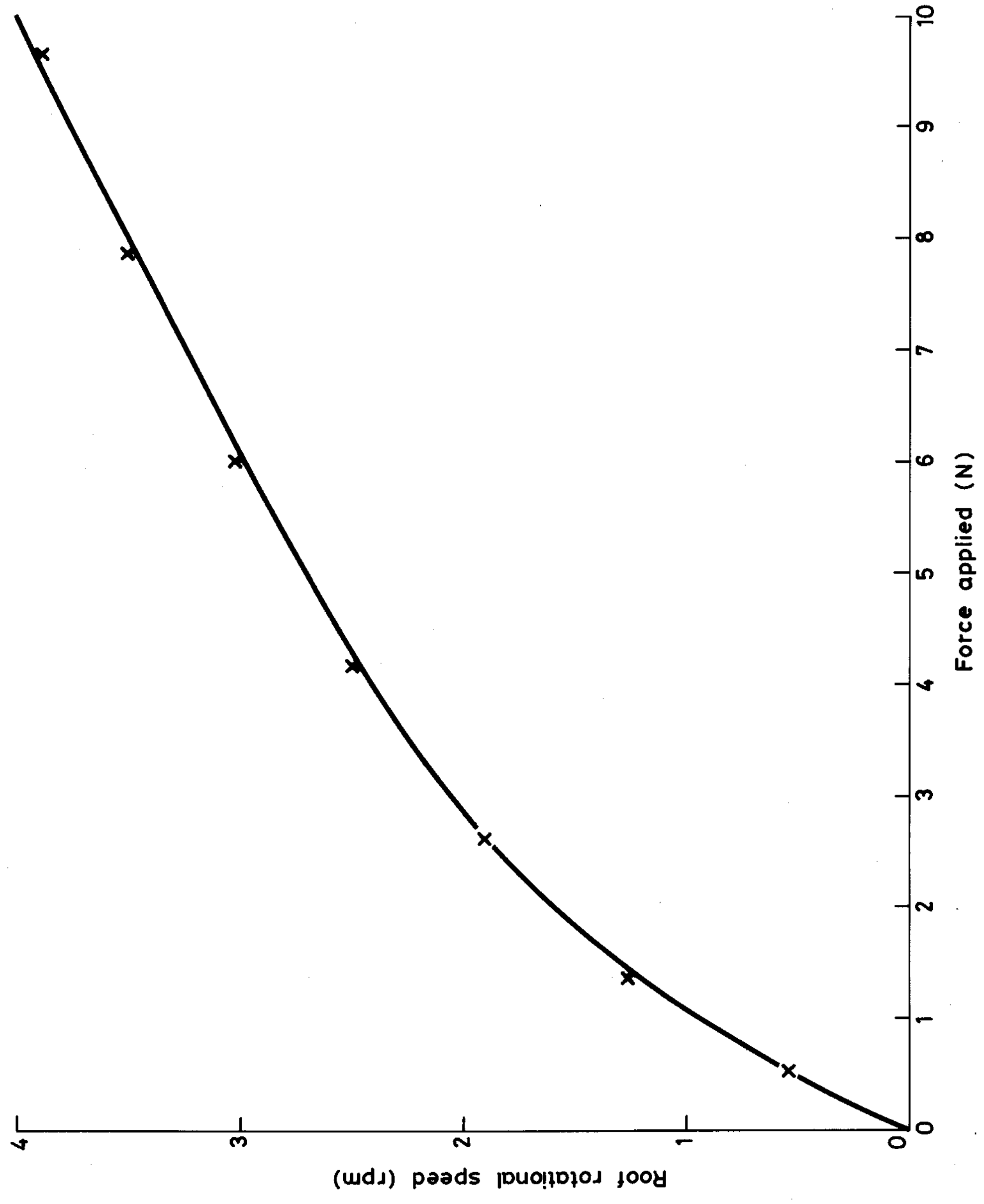


Fig 10 Energy input calibration

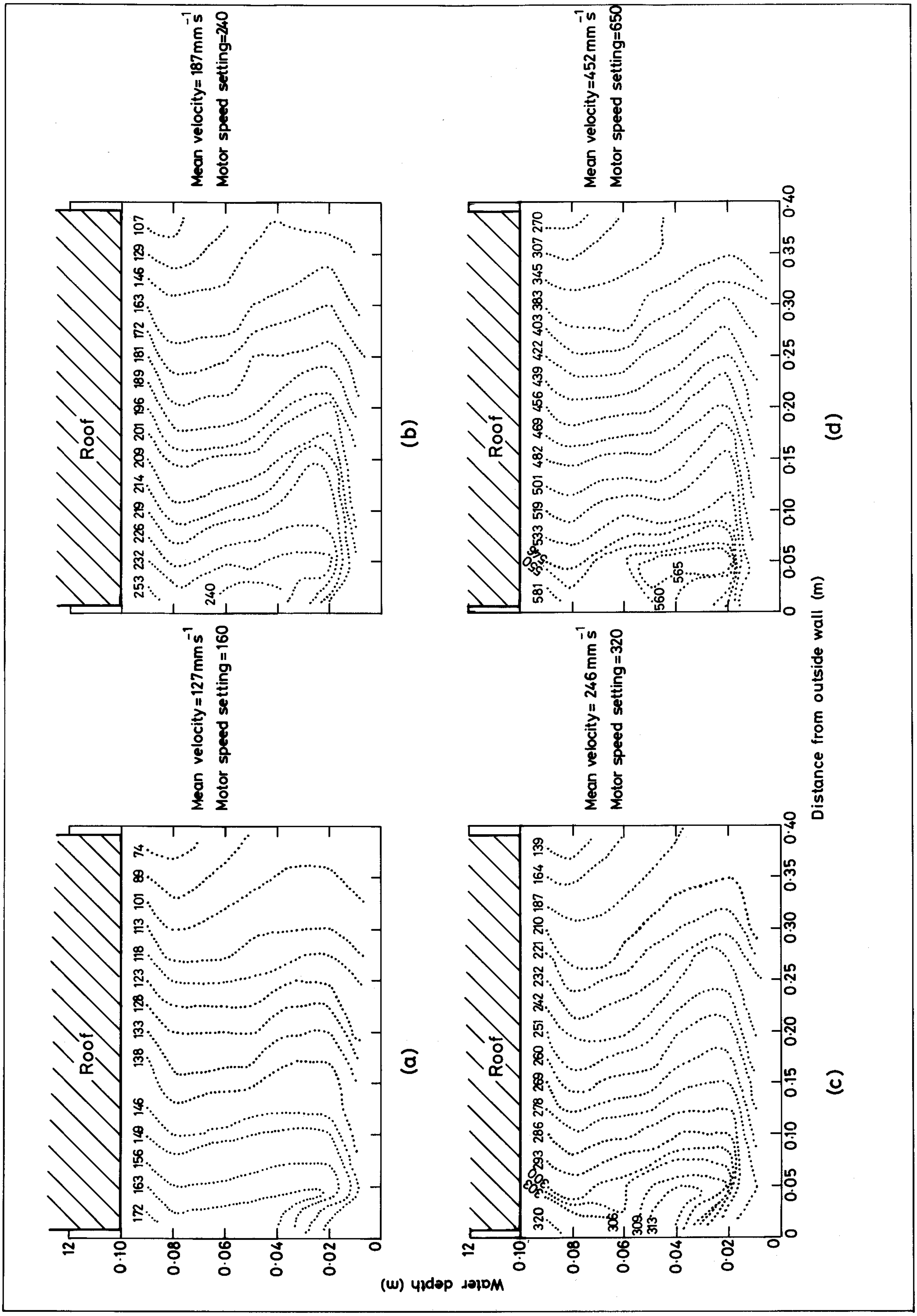


Fig 11 Cross - sectional velocity contours

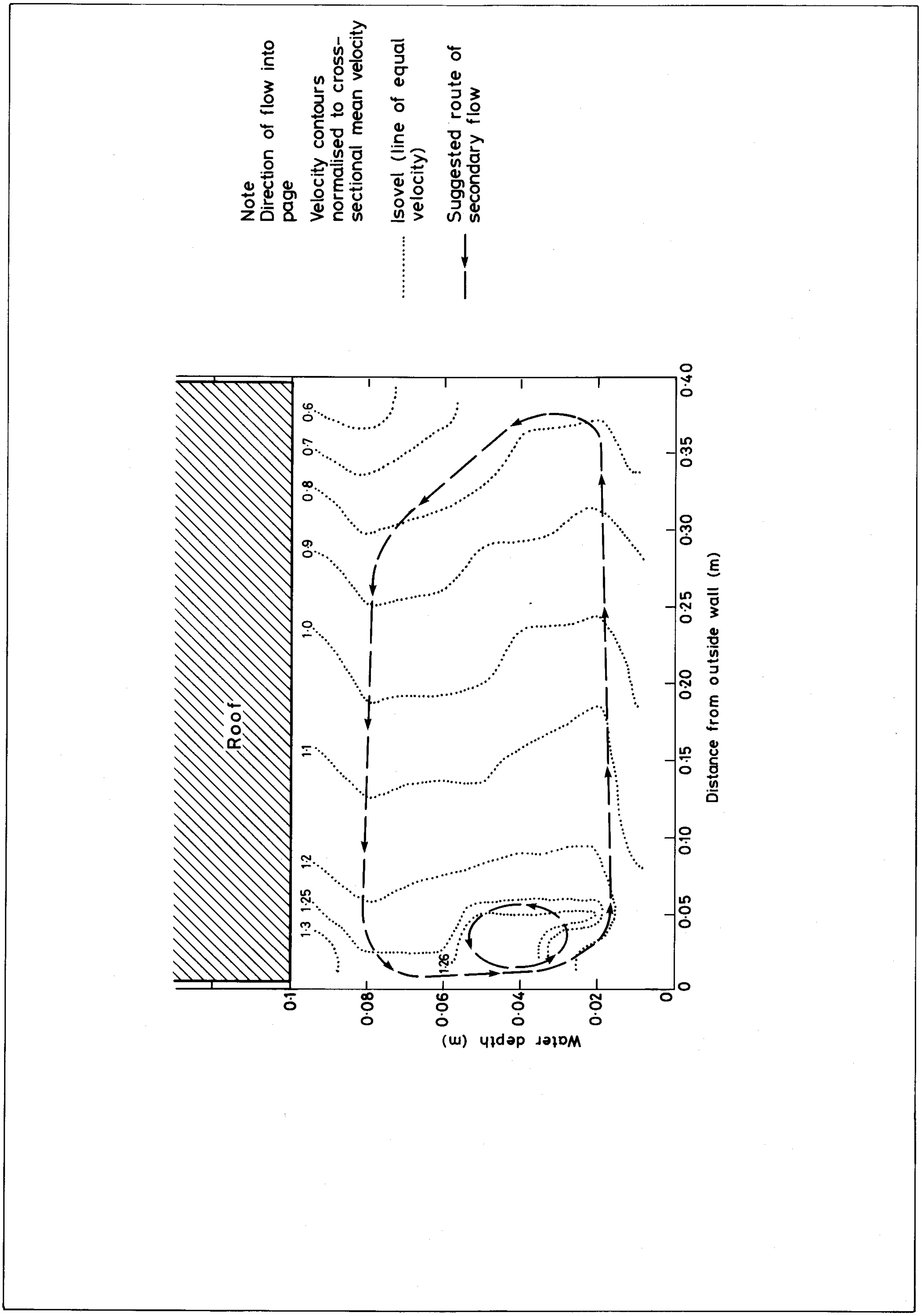


Fig 12   Generalised velocity contours

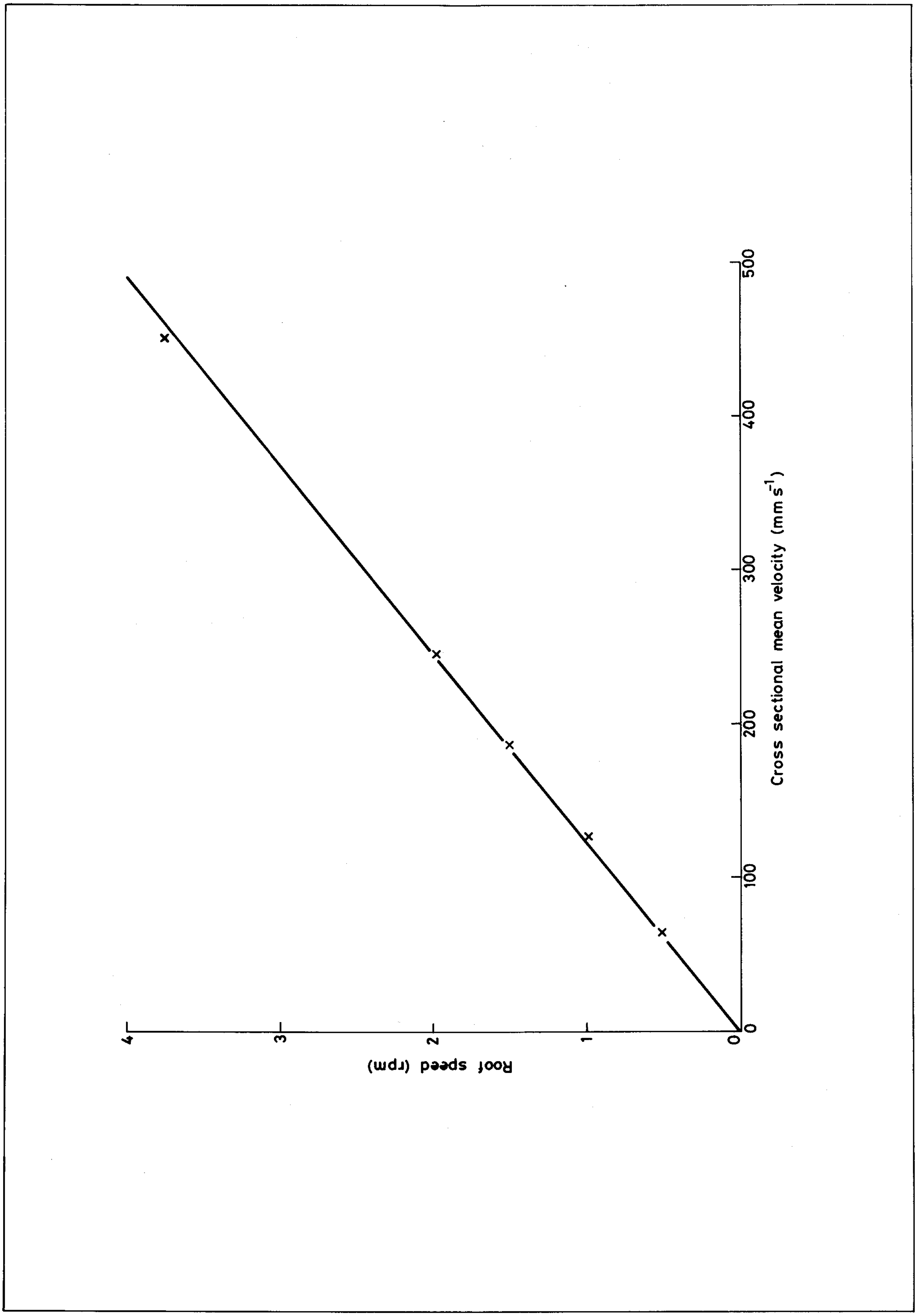


Fig 13 Roof speed versus cross sectional mean velocity

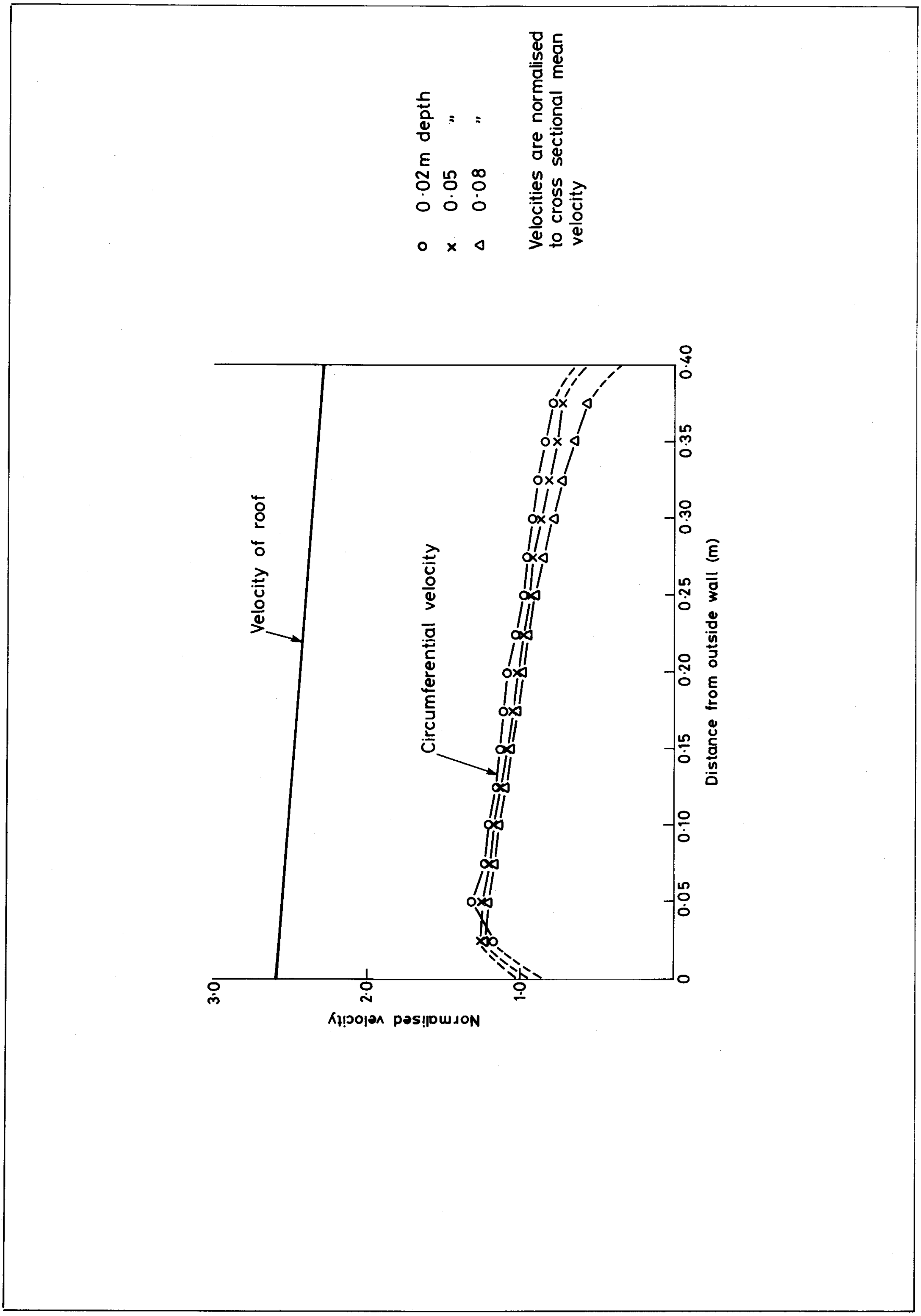


Fig 14   Velocity variation across the width

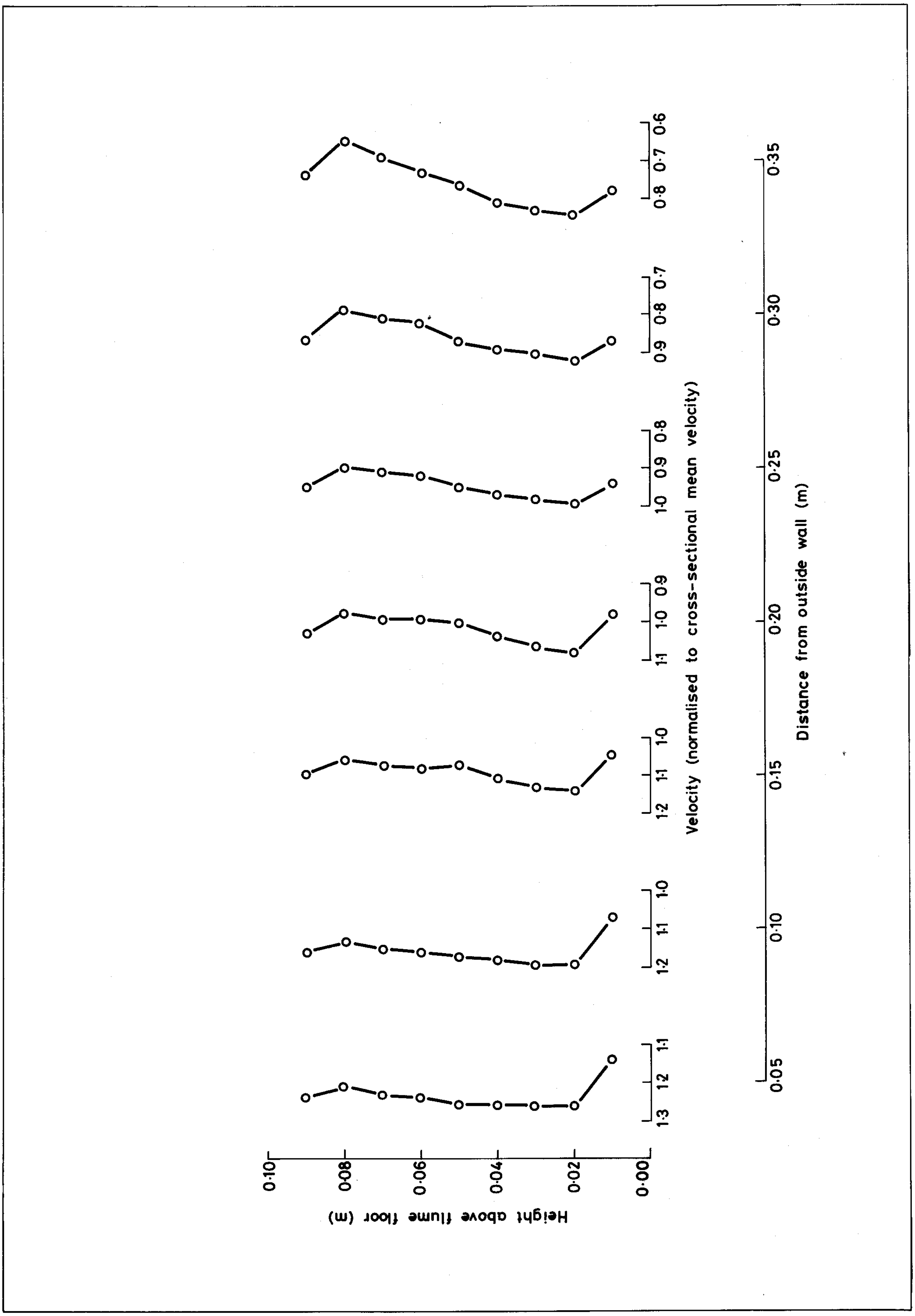


Fig 15 Velocity variation through the depth

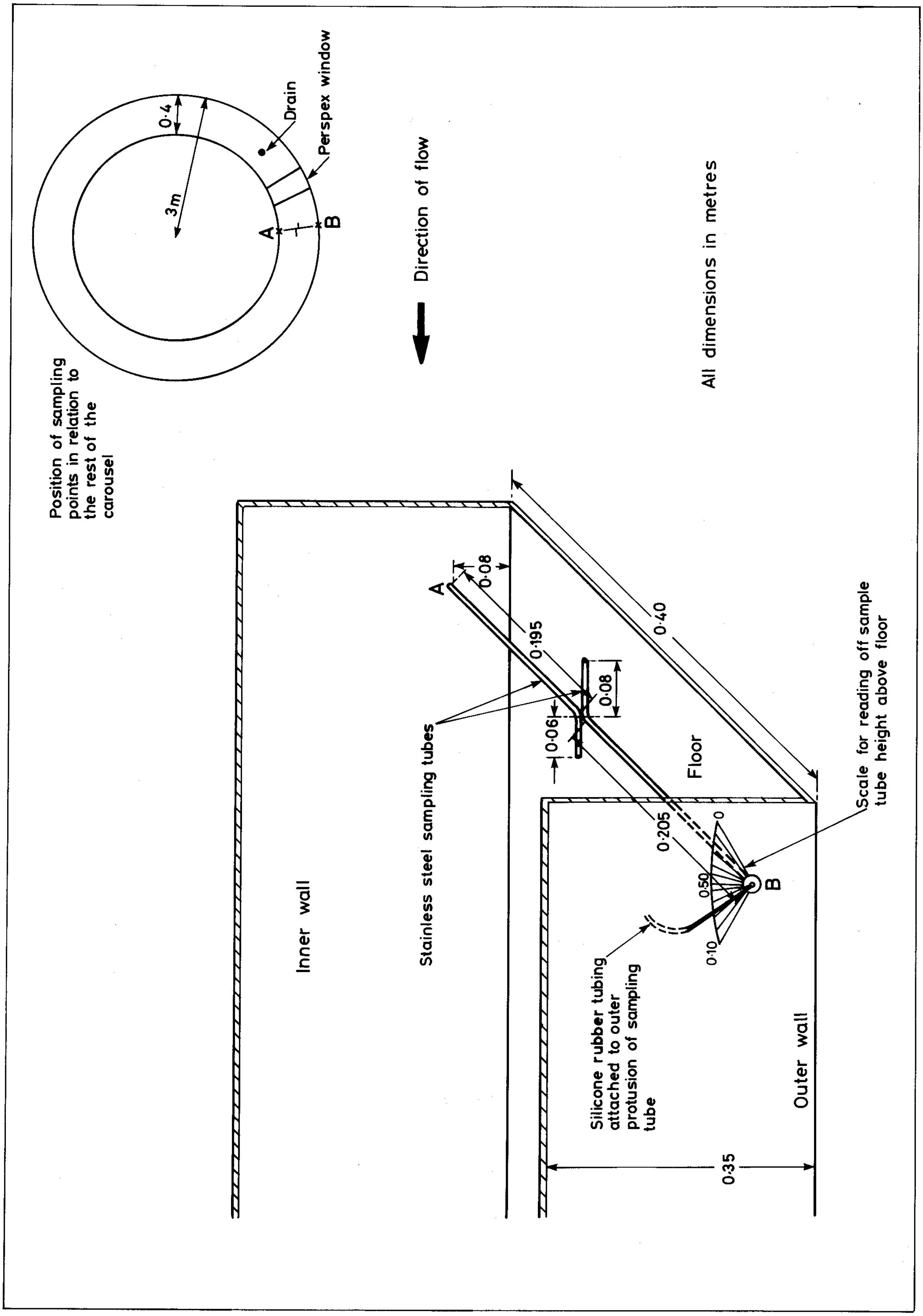


Fig 16 Suspended solids sampling system

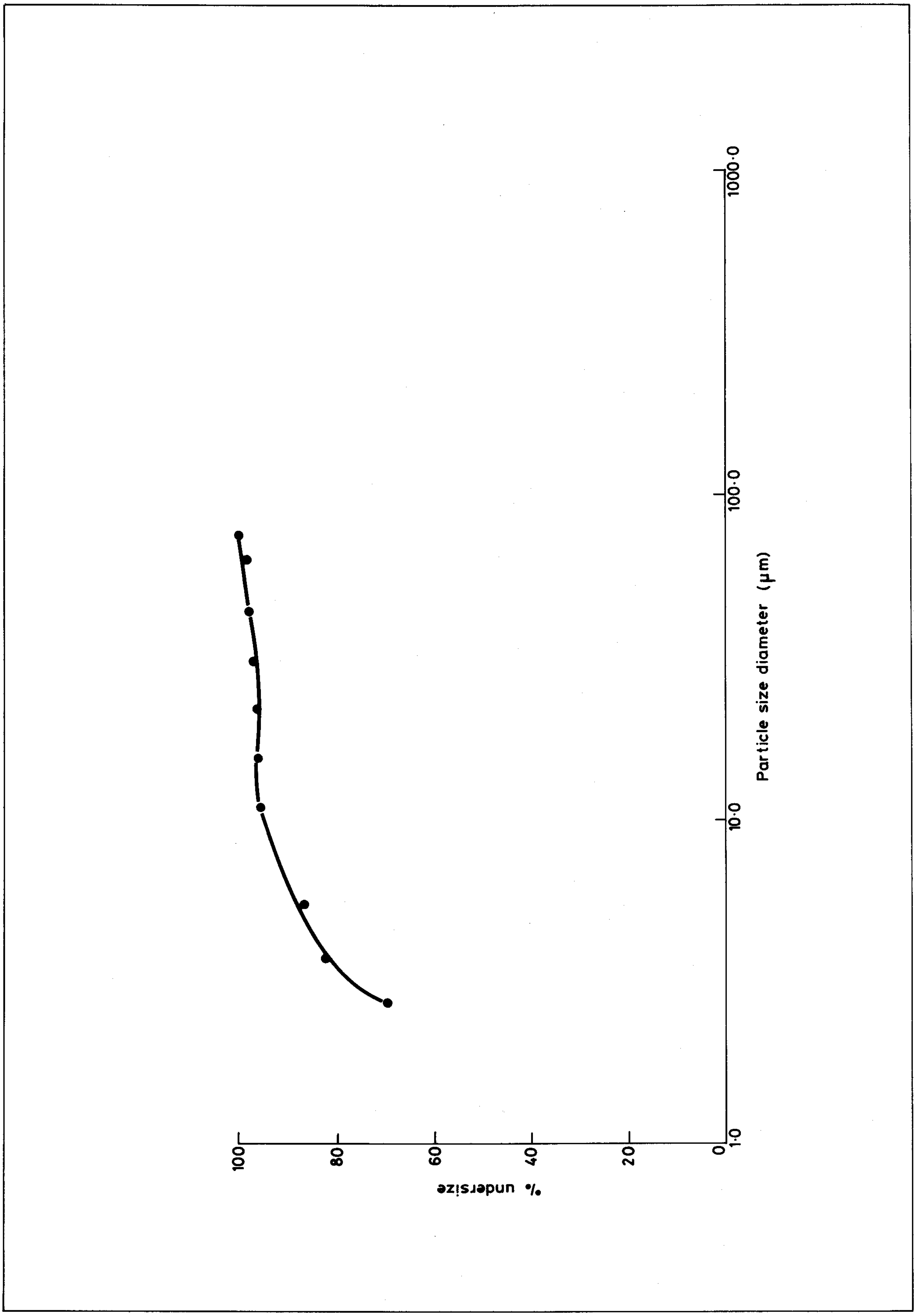


Fig 17 Particle size analysis : kaolinite

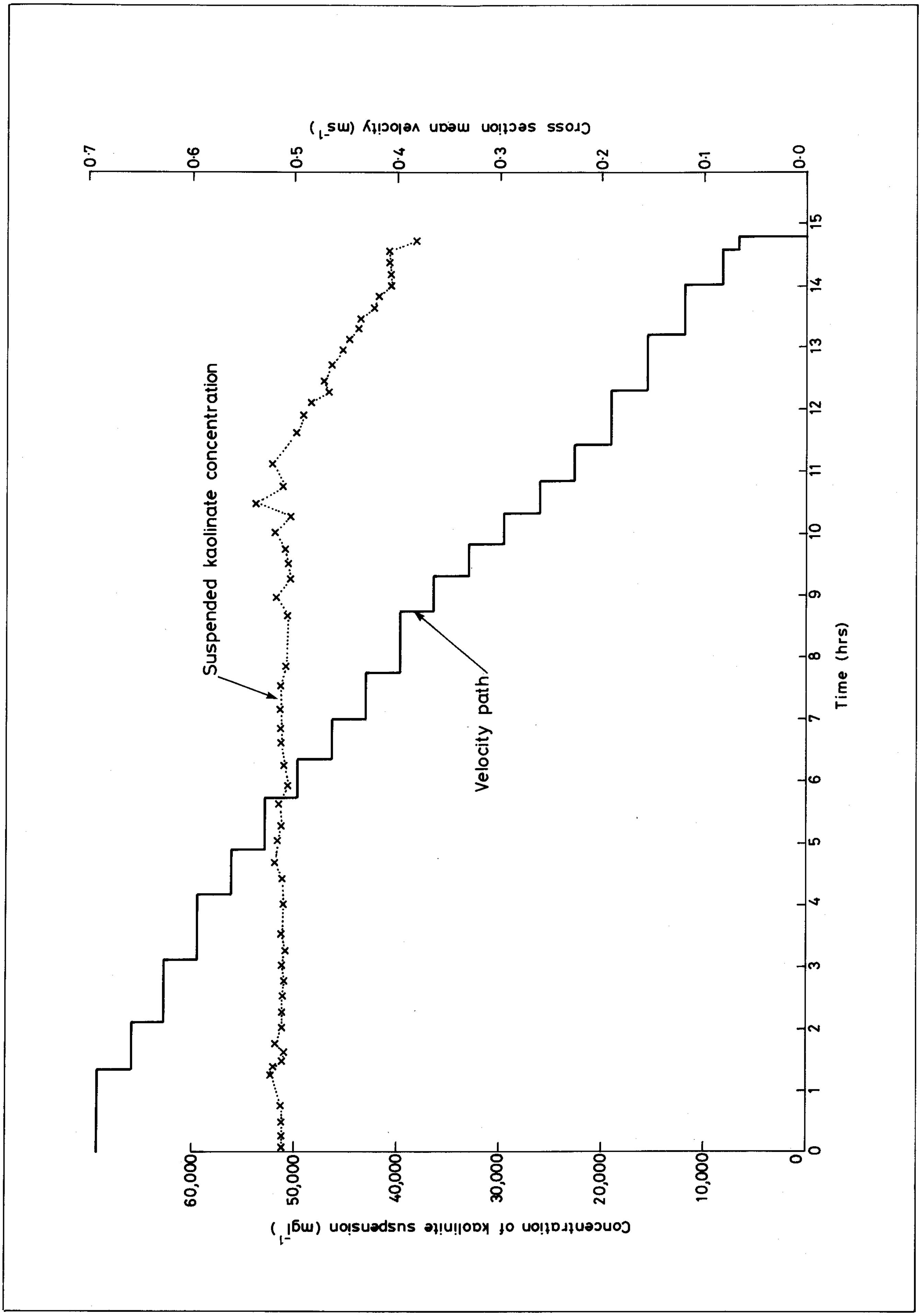


Fig 18 Concentration versus time : kaolinte test

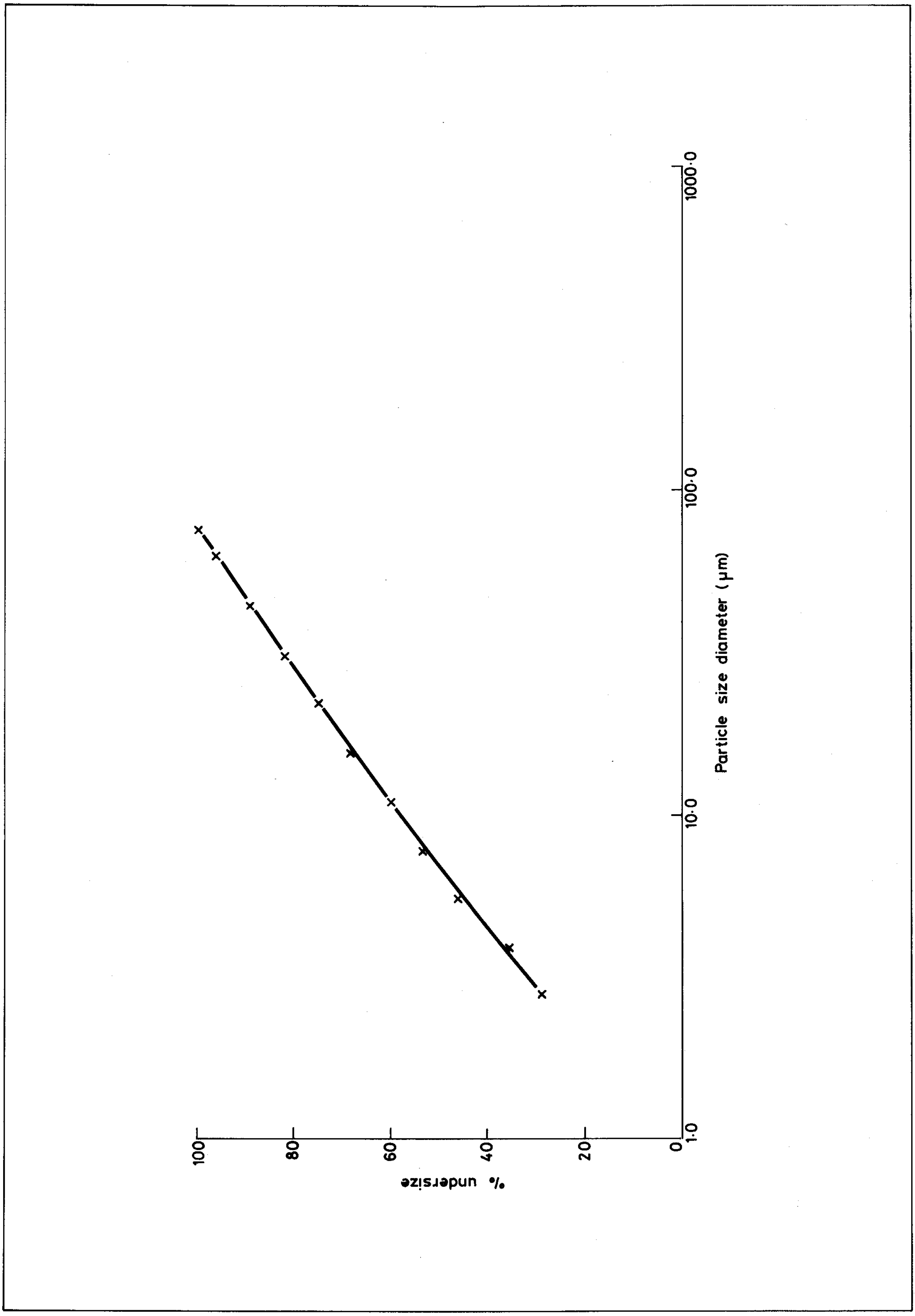


Fig 19 Particle size analysis : Humber mud

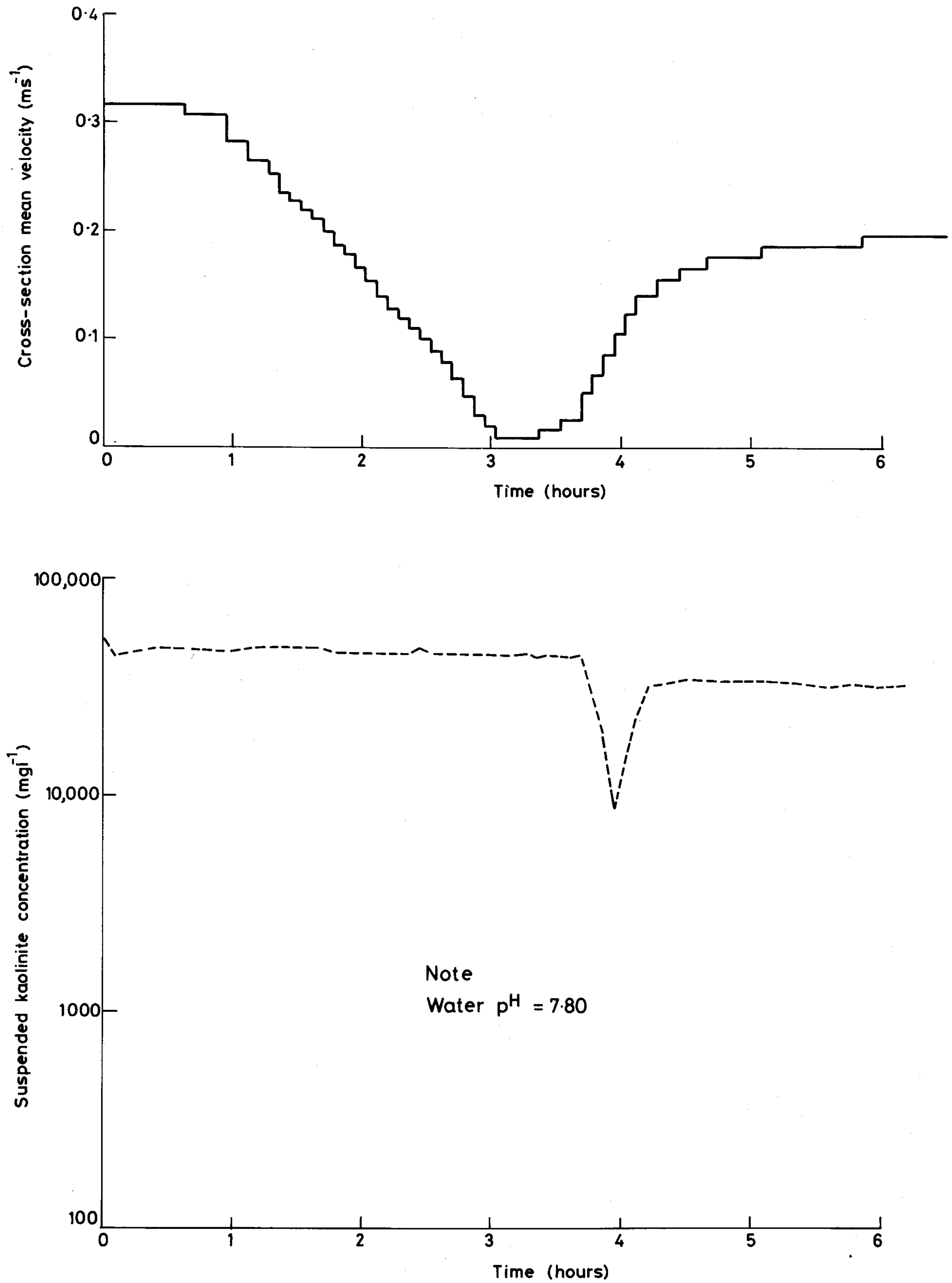


Fig 20 Simulated tide tests : kaolinite

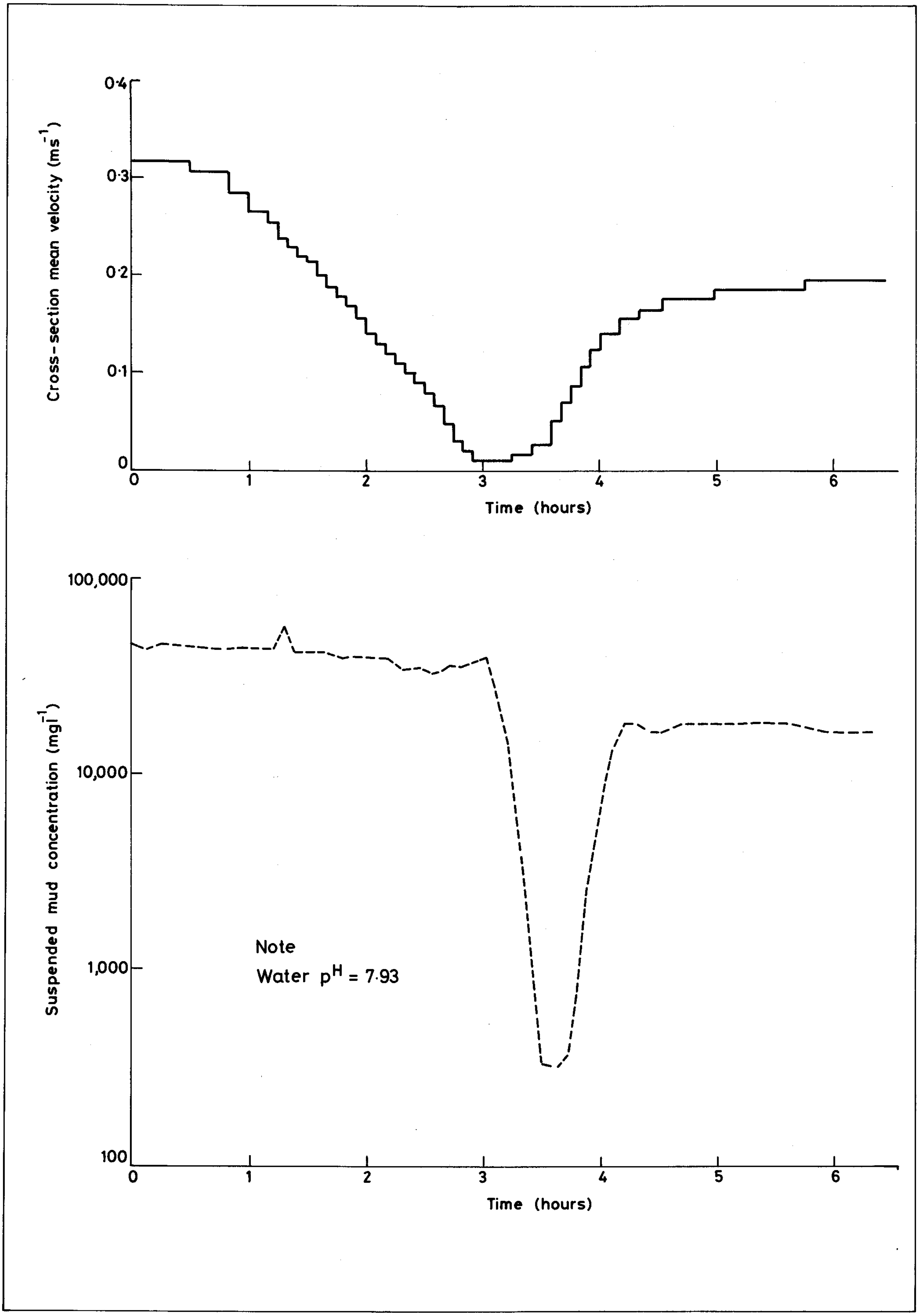


Fig 21 Simulated tide test : Humber mud

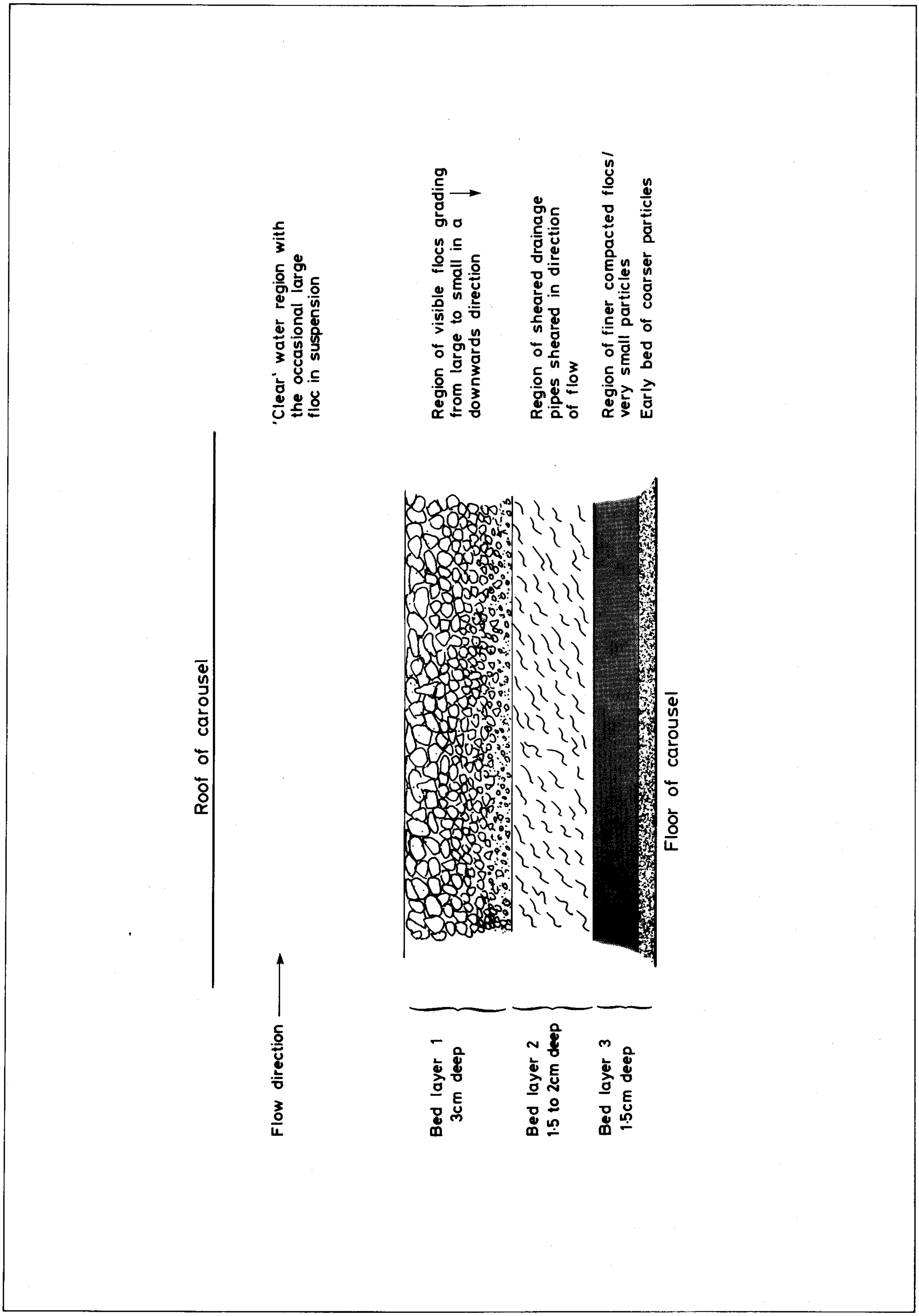


Fig 22 Mud layers observed in the carousel

Plates

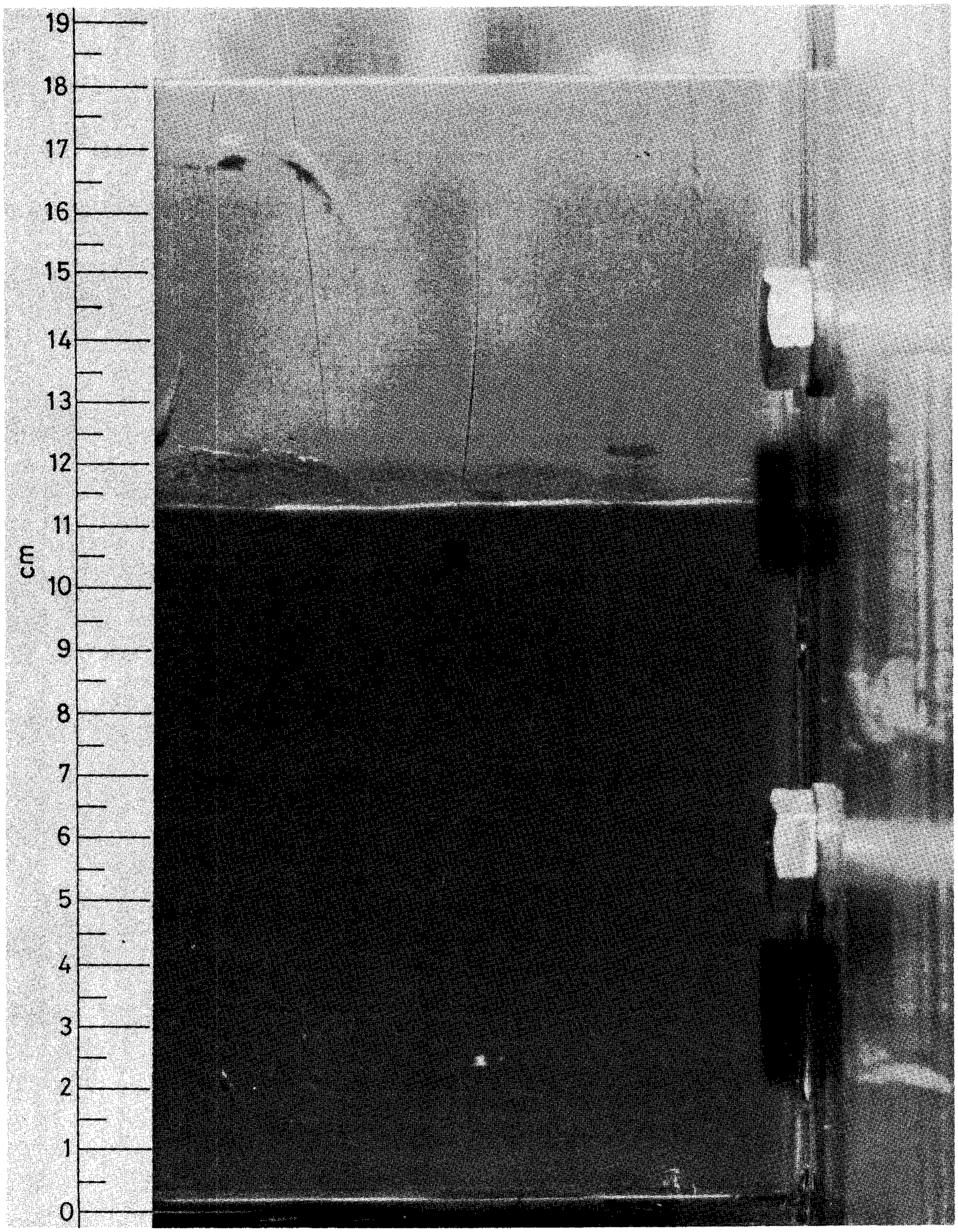
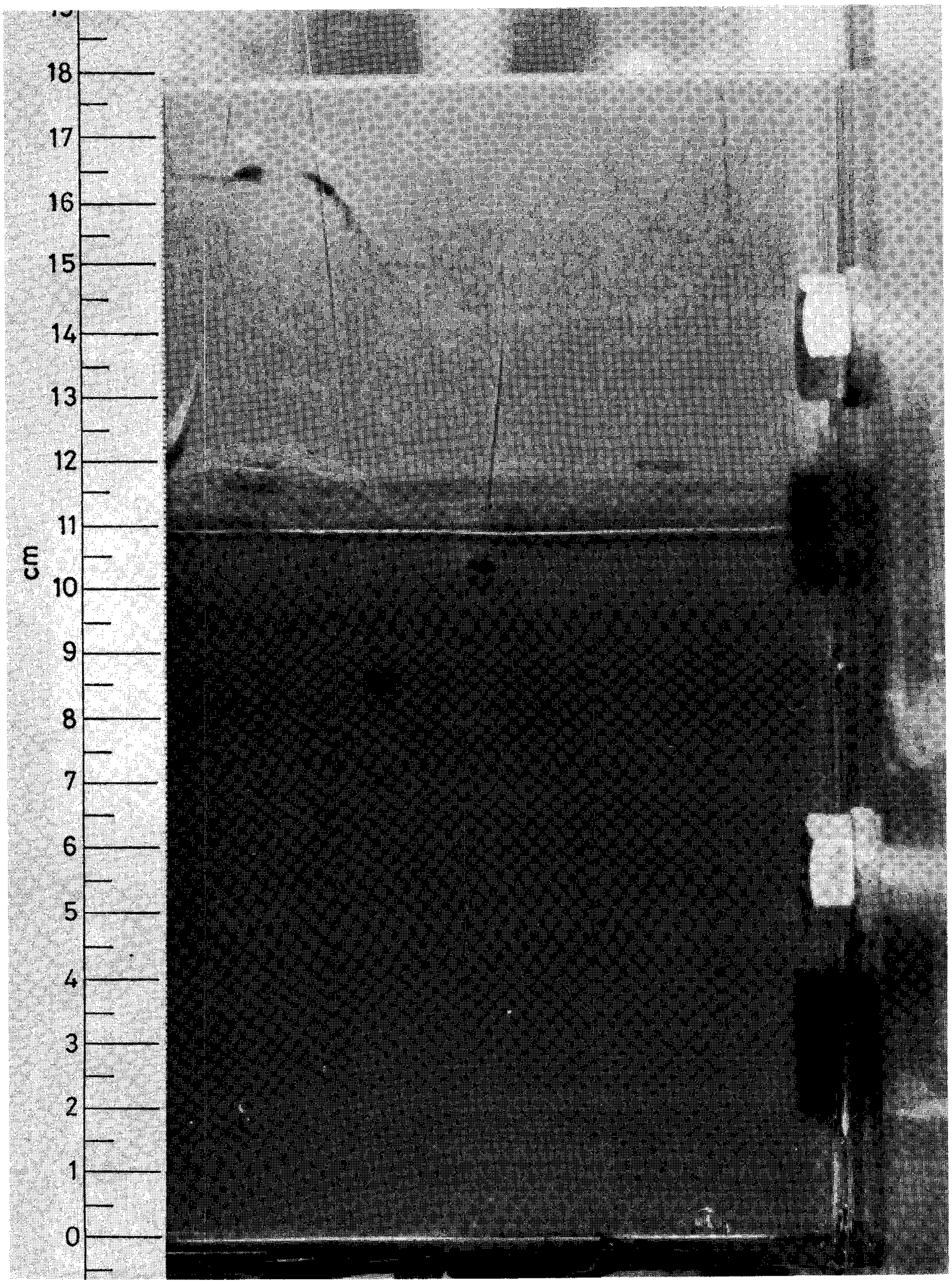


PLATE 1



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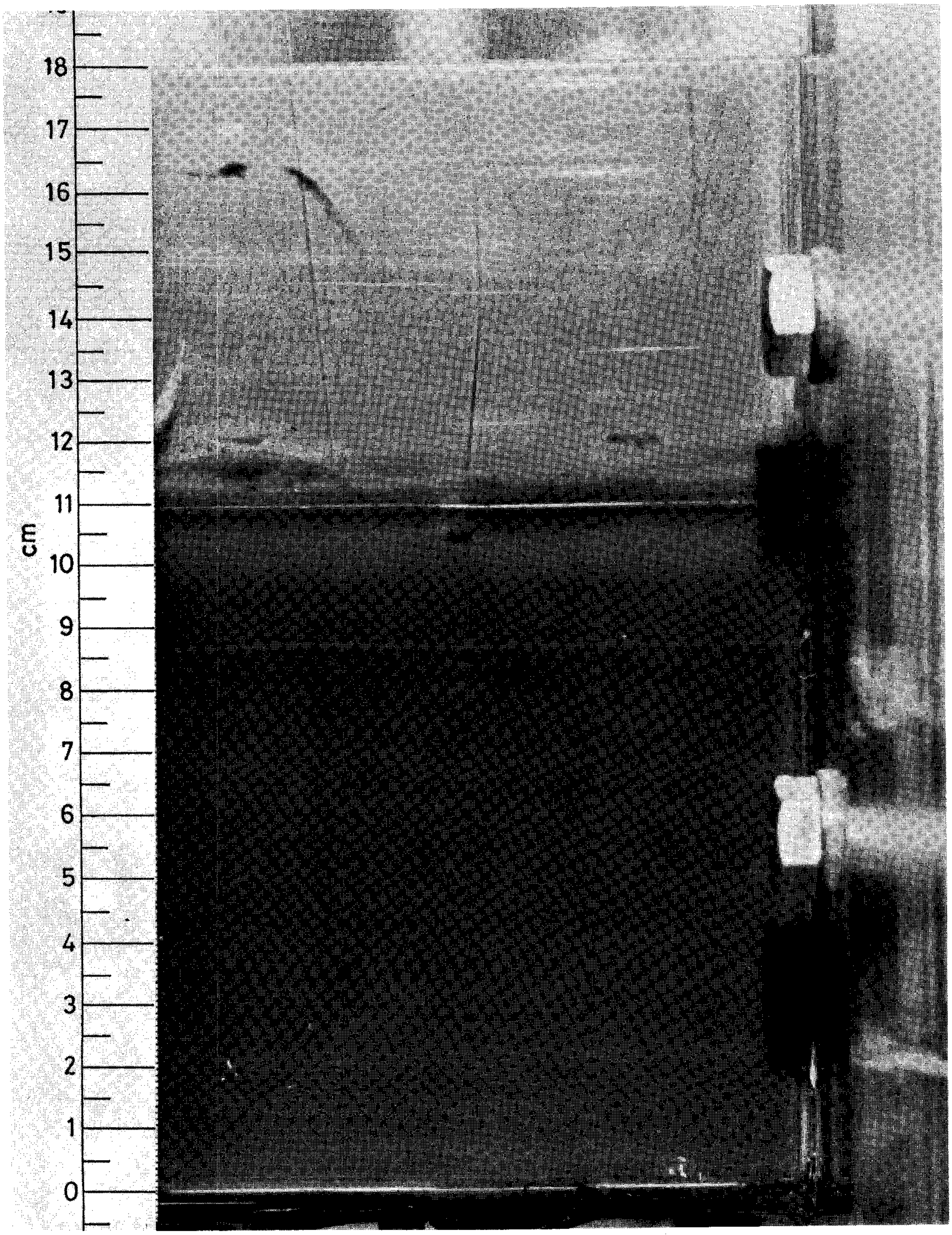

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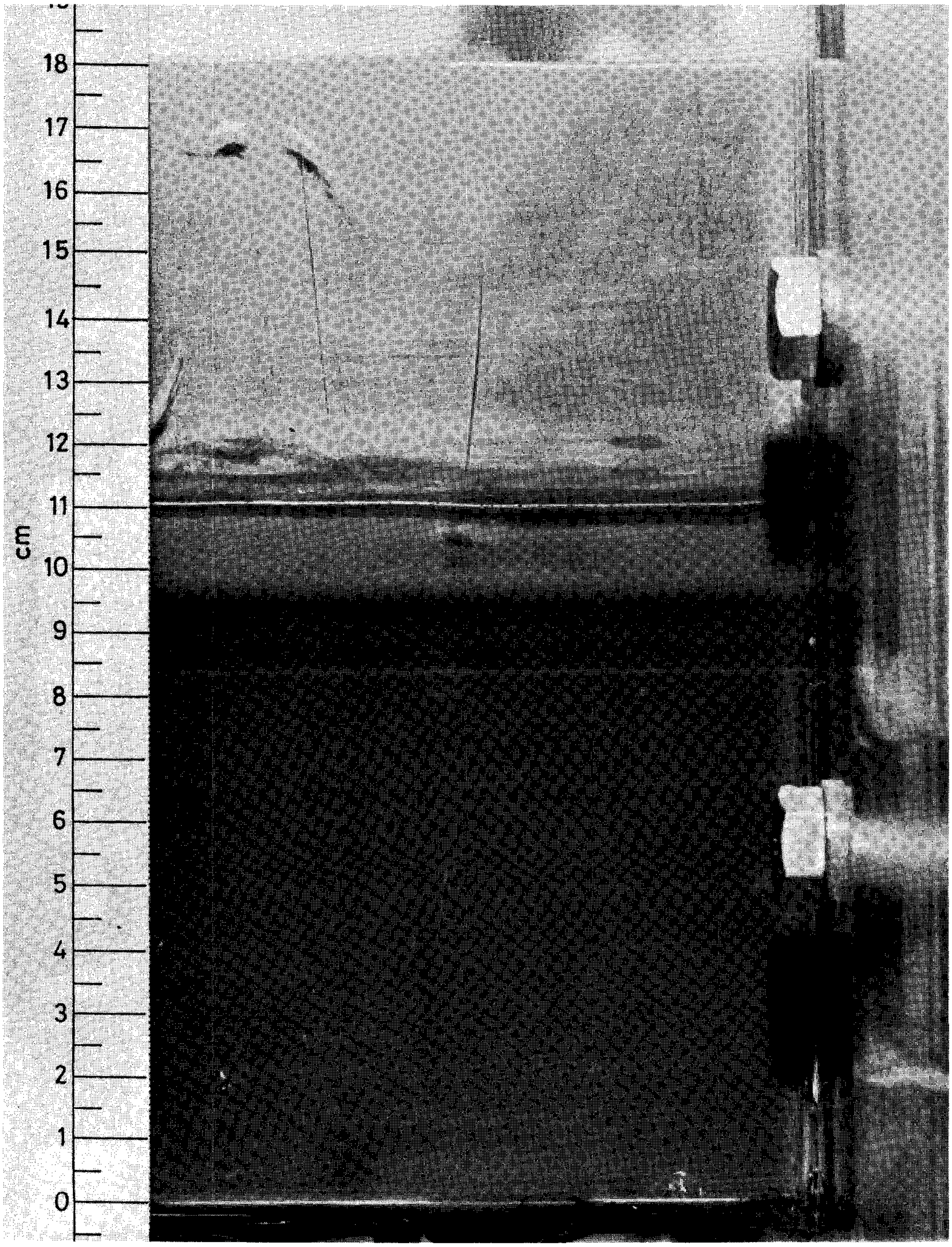

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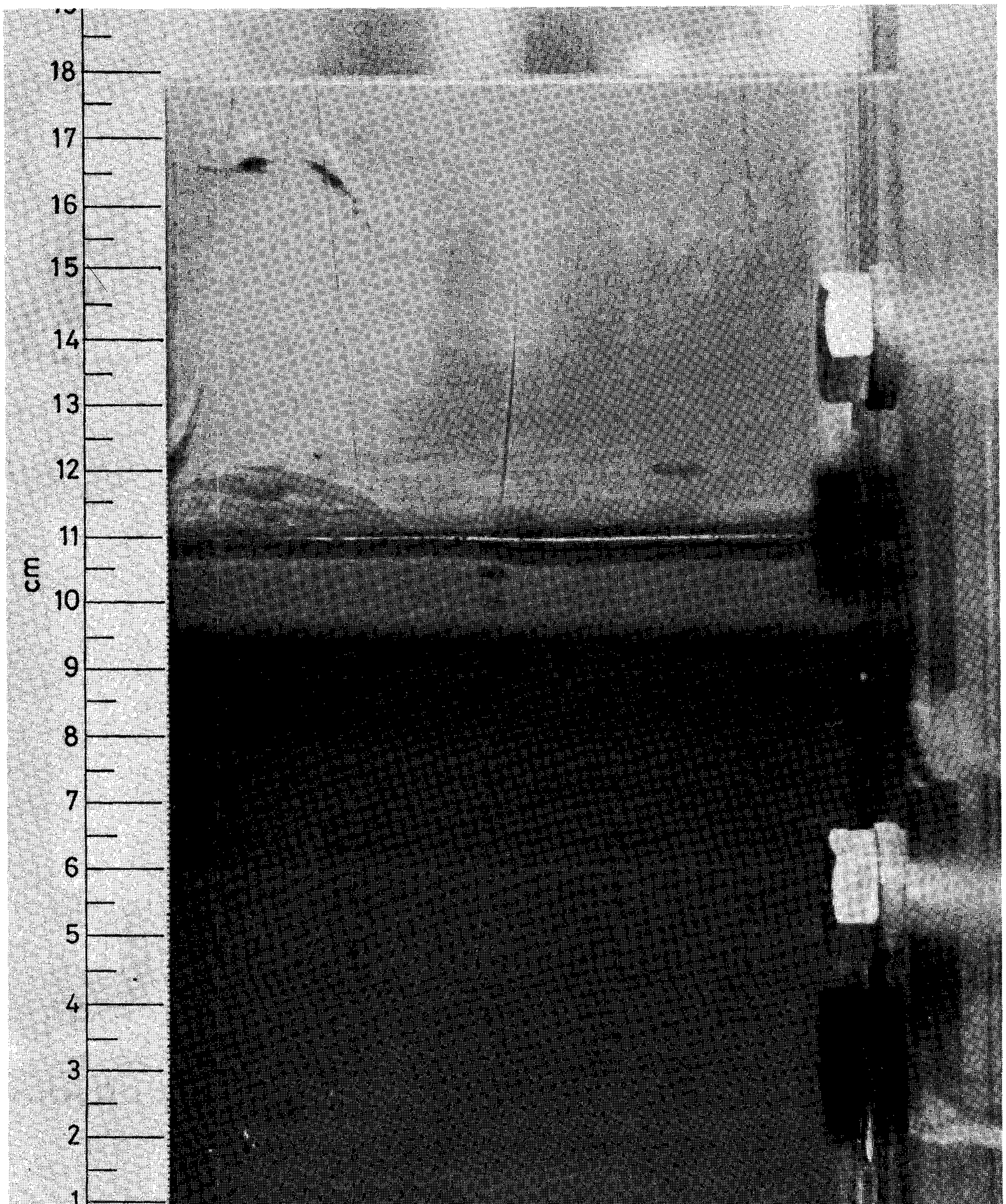

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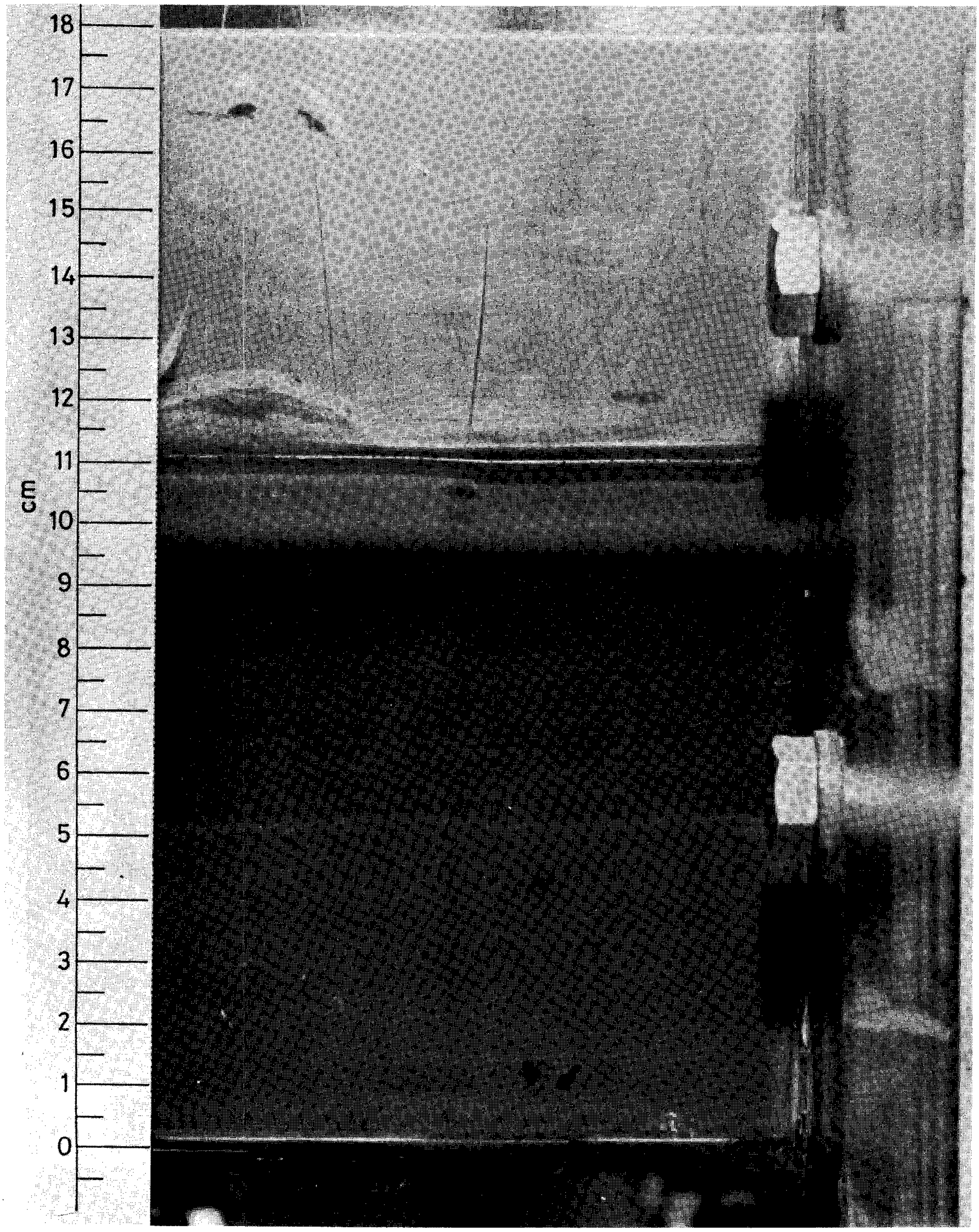

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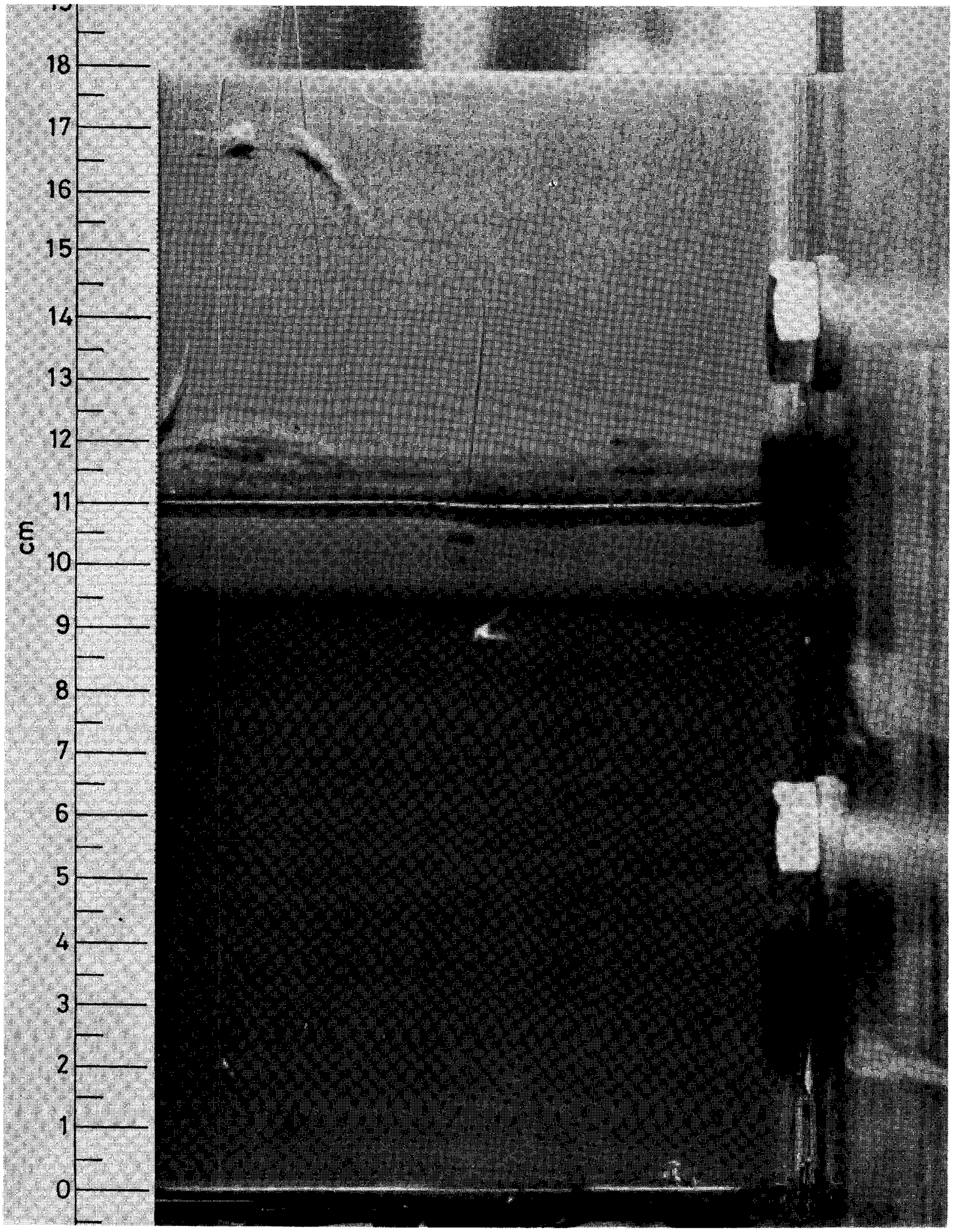

PLATE 7

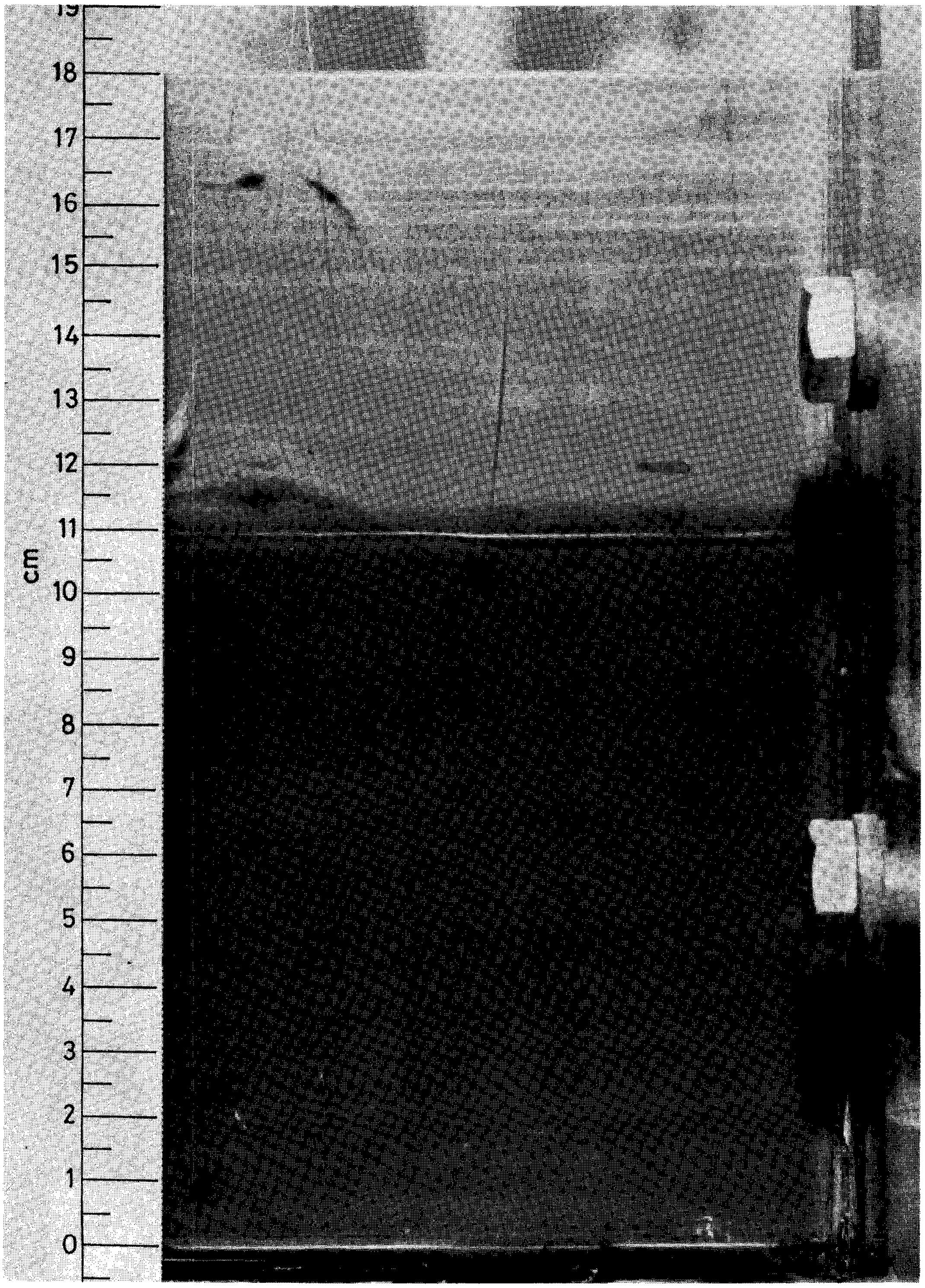

PLATE 8