A DETAILED STUDY OF THE

SETTLING VELOCITIES OF AN ESTUARY MUD

by

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SUMMARY

Detailed tests on a mud, obtained from Avonmouth in the Severn Estuary, were carried out in bottom withdrawal tubes up to 2.0 metres high to determine the effect of suspended concentration, salinity, and depth of settling on the sedimentation rate.

The settling velocity was found to increase with concentration up to about 14 g/l, when hindered settling begins, and with salinity up to about 30 g/l. Initially the settling velocity reduced with increasing depth, reaching a minimum value at about 1.0 metres, but it increased thereafter up to a depth of about 2.0 metres, when settling velocity became constant.

A review of the basic theory of flocculation is included.

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INTRODUCTION

1. A comprehensive research programme to study the properties and behaviour of muds is in progress at the Hydraulics Research Station, and the first phase, to review the available literature, has already been reported.[1] This report presents the results of detailed tests on the settling velocity of Avonmouth mud, in particular to study the effect of salinity, concentration and depth of settling on the settling velocity. The intention is to repeat several of these tests for muds from various other estuaries, and to compare the results obtained.

2. The settling velocity of cohesionless particles, such as coarse silt, sand and gravel (using the B.S. size classification[2])can be calculated in a low concentration suspension using well defined expressions (e.g. Stokes' Law), from the relative density, size and shape of the particles, since the only forces involved are gravity and the flow resistance of the particle. When the particle concentration is high, and the various particles interact to alter the flow resistance, the fall velocity diverges from the low-concentration value as a function of the volume concentration of the particles in suspension. Several of the formulae describing this divergence are reviewed and compared by Happel and Brenner.[3]

3. The settling of cohesive particles, however, cannot yet be calculated from any theoretically derived expression. Such particles are usually in the fine silt and clay size ranges, where Brownian motion is significant compared with gravitational motion. Table I, for instance, compares the mean displacement per second of particles of various sizes in water, due to Brownian motion, and settling under gravity. For the finest particles, the Brownian motion would be sufficiently strong to maintain the particles in suspension for a very long time but another mechanism 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, thus forming aggregates of particles, or flocs. These flocs can be large enough to overcome Brownian motion, and to settle out. The basic unit of settling of cohesive particles is therefore a floc, the size and formation of which 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, and the electro-chemical nature of the suspending medium: the frequency of collision due to turbulence, Brownian motion, etc. depends on the volume concentration of the particles 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.

REVIEW OF THEORY OF FLOCCULATION

As previously stated, flocculation depends on two separate processes - collision and cohesion. Particles collide due to Brownian motion, turbulence, velocity gradients, and differential settling, and under certain conditions adhere to each other, being held by the cohesive forces. Both of these processes have been reported extensively by Krone,[4] Einstein and Krone,[5,6] and Partheniades,[7,8] and reviewed in the previously mentioned Literature Review,[1] but are repeated here for convenience.

Collision

5. The probability of collision of a single particle due to Brownian motion is calculated from the expression, derived by Smoluchowski and summarised by Leivich[9], as

$$I = \frac{4\ k\ T\ n}{3\ \mu} \qquad \text{..........I}$$

where I is the number of collisions per unit time
k Boltzmann's constant
T absolute temperature
n the number of particles per unit volume
μ is the dynamic viscosity

For suspensions in estuaries the direct effect of temperature in this equation is not very great, since temperature varies only over a range of about 20° C in most cases, or a change of about 7 per cent in absolute value. However, the associated effect of temperature on viscosity plays a greater part, since dynamic viscosity is almost halved as the temperature increases from 4°C to 24°C. However the most important parameter in the equation in estuarial problems is the number of particles per unit volume, which, for a given particle density, is directly related to the concentration by weight of the material in suspension. This is because concentrations can vary from about 10 mg/l to about 10 g/l, at least a 1000-fold range.

6. For collision due to internal shearing of the fluid, the expression is[9]

$$J = (4/3)\ nR^3\ \frac{du}{dz} \qquad \text{..........II}$$

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
$\frac{du}{dz}$ is the local velocity gradient.

The product nR^3 is a measure of the volume occupied by the particles in suspension, and one might expect that for a given concentration by weight it would be constant, giving constant J. However, 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.

7. 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. However Krone(4) reported that Muller had investigated this, and found that there were two limiting particle sizes: the minimum radii of the particles were respectively

$$r \geqslant \left(\frac{40\ k\ T}{\pi\ g\ \rho}\right)^{1/4} \quad \text{for settling particles} \quad ....\text{III}$$

$$\text{and } r \geqslant \left(\frac{1.2\ kT}{\pi\ g\ \rho}\right)^{1/4} \quad \text{for caught particles,} \quad ....\text{IV}$$

where ρ is the density of the particle or floc. The corresponding sizes for primary particles of a typical clay would be 5.0 and 2.1 microns respectively. For clay flocs, the sizes vary greatly according to the amount of flocculation present, since the density varies so much.

Cohesion

8. The cohesive forces exerted between two clay particles depend both on the mineralogy of the clay, and on the electro-chemical nature of the suspending medium. 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. These forces are discussed in detail by Lambe.[10] As far as the engineer is concerned, the attractive forces are due to the interaction of the electrical fields formed by dipoles in the individual molecules. These forces, commonly known as van der Waal's forces, vary inversely with the seventh power of distance between particles.

9. The surface of clay particles made up of the common clay minerals is usually negatively charged. In a clay suspension, where the total electrical charge of the system must be neutral, the charge on each clay particle is neutralized by ions from the suspending medium, which swarm around the clay particle. Because these ions are subject to thermal vibration, and also to attraction by other ions and clay particles, they do not reach the surface of the particles, but are positioned in equilibrium between the various forces, forming a cloud of 'exchangeable ions'. 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.

10. The resultant force can be either attractive or repulsive, depending on the relative magnitude of the constituent forces. In suspensions with a low ion concentration, the ion cloud is large, and the repulsive forces keep the particles too far apart for the van der Waal's attractive forces to have effect. As the ion concentration or ion valency is increased, the ion cloud is reduced in size, and eventually the repulsive forces are small enough for the particles to come close together, and for the attractive forces to prevail: the particles then join together to form flocs. With a negatively charged clay mineral, such as montmorillonite or illite, the addition of common salt, sodium chloride, causes flocculation to occur, the monovalent sodium cations forming the ion cloud around the clay particles. Sea water has an even stronger flocculating effect, since it usually contains several salts of higher valency metals.

11. From the preceeding paragraphs, it may seem that flocs may grow indefinitely in size. However, the floc size is limited by the fluid shear the particle bonds can withstand. As flocculation proceeds the flocs get larger until the fluid shear exerted on them by the settling velocity equals the interparticle bond strength. The flocs will then have reached a terminal size and settling velocity.

SCOPE OF TESTS

12. The general method of grading sediments is by size. In the case of channel bed sediments of a cohesionless nature, this is useful in determining the channel roughness and the initial rate of sediment movement. However, in the case of suspended sediments it is invariably the settling velocity of the particles which is required. For a non-flocculating suspension of small, near spherical particles, the settling velocity can be directly related to the particle size by Stokes' law, since the particle density is known. Stokes law applies to particles having a Reynolds number (wd/ν) less than 0.1 : for quartz spheres this would correspond to particles smaller than about 50 microns at normal temperatures. The expression for settling velocity is

$$w = \frac{2g}{9\nu}(\rho_s - \rho_1)\, r^2$$

where
- w is the settling velocity
- ρ_s is the sediment specific gravity
- ρ_1 is the liquid specific gravity
- r is the particle radius
- ν is the kinematic viscosity.

However, in flocculating suspensions, both the size and specific gravity of the flocs change as flocculation occurs: in order to obtain the settling velocity it is therefore necessary to tabulate both the floc size and specific gravity under a wide range of conditions. Moreover, as the standard methods of grading such fine sediments are based on settling velocity tests, it is impossible to obtain a true floc size, without very complicated methods of measuring the floc density while it is in suspension. One way of obtaining a size is to convert the settling velocities into equivalent quartz sphere diameters, or Stokes diameters. However, this can cause a complete misconception of the physical size of flocs. For instance, a floc having a settling velocity of 1 mm/s, giving a Stokes diameter of about 0.04 mm, could have a physical size of 1 mm or more. For these reasons therefore, it would seem to be more practical to grade flocculating sediements in suspension by their settling velocity, and in this report no attempt has been made to convert settling velocities to diameters, Stokes or otherwise, except where the material was deliberately de-flocculated by means of various additives.

13. As previously mentioned, the rate of collison of particles depends strongly on concentration, and thus a series of tests was carried out, at various fixed salinities, to determine the effect of concentration on the settling velocity of the material. The concentration was varied from 0.25 to 32.0 g/l.

14. The salinity of the suspension alters the cohesive forces between particles, by depressing the ion clouds as explained previously, and thus an increasing salinity increases the probability of a collison resulting in a floc being formed, rather than the particles bouncing off each other. A series of tests to determine the effect of salinity on the settling velocity was therefore carried out at various fixed concentrations. The salinity was varied from 2.0 to 48.0 grams of Sodium Chloride per litre.

15. Where differential settling occurs the frequency of collision is higher, and, where this happens, increases with the depth of settling. However, at a certain depth the rate of growth of the particles, due to flocculation, must equal the rate of break-up of the particles due to the increased fluid shear. A series of tests were therefore carried out, at various concentrations and salinities, to determine

the effect of depth on settling velocity, and to determine the depth at which the settling velocity attained a constant value. Preliminary tests were carried out in a settling tube 9 metres high, but the main series were in tubes 0.5, 1.0, 1.5 and 2 metres high.

DETAILS OF MUD TESTED

16. The supply of mud was obtained, with the cooperation of the Port of Bristol Authority, from the entrance to the Royal Edward Docks at Avonmouth. The mud was dredged by the P.B.A. suction dredger S.D. Severn at high tide (H.W. level 10.8m or 35.5 ft above Port datum), and the samples taken from the overspill. The salinity in the entrance at that time was 18 g/l, and the concentration of the mud supply was 170 g/l.

In the tests the fraction of the mud which passed through a 75 micron B.S. sieve was used, which generally accounted for 95-100 per cent of the total weight of the sample. The size grading of this sub-sieve size fraction was obtained by de-flocculating a small sample of it, and subjecting it to both sedimentation tube and centrifugal settling tests. Because the material was de-flocculated, and the density of the primary particles known, the settling velocity grading could be converted into a size grading. The settling velocity grading by the two methods is shown in Fig. 1 and the equivalent size grading in Fig. 2.

17. A mineralogical analysis of the supply of mud was not carried out, but the results of an analysis by the U.K.A.E.A. laboratory at Harwell of samples obtained at the same location by the U.K.A.E.A. laboratory at Wantage were kindly made available. The clay minerals kaolinite, illite, montmorillonite and chlorite were present, the percentages of basal areas on the X-ray diffraction charts being as in table II.

These percentages are proportional to the quantities of the various minerals present. There is no reason to suppose that the particular mud supply used in this study would differ significantly from the samples obtained by the Wantage laboratory.

The approximate cation exchange capacity was calculated from the percentage of each clay mineral present, and the mean of the published exchange capacities of each mineral: the value obtained was 34 milli-equivalents (meq)/100g. However, the cation exchange capacity was also measured experimentally on the size fraction less than 75 microns, and the value obtained was 17 meq/100g, or half the calculated value. The cation exchange capacity of materials depends to a large extent on the size of the particles, generally increasing as the size reduces, and the published values for the pure clay minerals vary widely, by up to a factor of five in some cases. Bearing these in mind, and recognising that the X-ray diffraction method of mineralogical analysis gives only an estimate of the proportions of the clay minerals present, the difference between the measured and calculated values is not unreasonably large.

DESCRIPTION OF APPARATUS AND PROCEDURE

18. The standard method of determining the settling velocity of the material in suspension was by bottom withdrawal sedimentation tube, using the standard method, with slight modifications to speed up the analysis of the results. A tube length of 2.0 metres was adopted for most of the tests, and a drawing of the tube is shown in Fig. 3. The material to be tested is first measured out to give the correct concentration by weight in the sedimentation tube, and then thoroughly dispersed in distilled water. Immediately prior to the test, enough common salt solution is added to give the desired salinity, and the resultant suspension topped up with distilled water to give the

correct volume for the tube. It is then poured into the tube, thoroughly shaken, and allowed to settle. Samples are withdrawn at the bottom of the tube at various time intervals, and the weight of sediment measured after drying. From the weights, times, and sample volume, the settling velocity distribution can be calculated by graphical methods. The settling velocities were adjusted to a standard temperature of 20°C by correcting for the changes in water viscosity with temperature. The actual temperatures varied from this value by about ± 2°C.

19. For determining the grading of the very fine portions of the basic mud in its de-flocculated state, a centrifugal sedimentation method was used. The apparatus consists basically of a disc-like cylinder, diameter 100 mm (4 in), height 6.4 mm ($\frac{1}{4}$ in), rotating at up to 8,000 rpm. The effect of the rotation is to increase the 'gravity' settling forces on the particles. By introducing the particles at the centre of the disc, and withdrawing samples at given radii at various time intervals, the settling velocity can be calculated directly, and the size grading calculated from the Stokes law.

Salinity and concentration tests

20. To determine the effect of concentration and salinity on the settling velocity, tests were carried out in the 2.0 metre high settling tube at salinities of 2.0, 8.0, 16.0, 32.0 and 48.0 g/l (1 g/l ≃ 1 ppt) for each of the following suspended sediment concentrations by weight:- 0.25, 1.0, 4.0, 16.0, 32.0 g/l. For each test a settling velocity grading curve was obtained by analysis, and from these curves the median settling velocity, and the upper and lower deviations were measured. The upper deviation is defined as the ratio of the 84% to the 50% (median) settling velocity, and the lower as the ratio of the 50% to the 16% settling velocity. These deviations thus give a measure of the width of the grading curve.

Depth of settling tests

21. Some preliminary tests were carried out in the 9 metres high settling column, although the main series of tests were carried out in tubes 0.5, 1.0, 1.5 and 2.0 metres long. The 9 metre column, 92 mm diameter, was provided with sampling ports at intervals of 1.525 metres up the tube as shown in Fig. 4, the highest one being at 0.4 metres from the top. By sampling the suspension at these positions at frequent time intervals, to determine the concentration profile in the settling tube, the mean settling velocity at any elevation can be calculated by a method due to McLaughlin [12], from the equation

$$\bar{w}_D c_D = -\frac{\partial}{\partial t}\int_0^D c \, dz$$

where c is the suspended concentration at elevation z

D is the depth being considered

$\bar{w}_D$ is the mean settling velocity at depth D

c_D is the suspended concentration at depth D

t is time.

The main series of tests in the 0.5 to 2.0 metres long settling tubes was carried out by the bottom withdrawal method. Concentrations of 0.25, 1.0 and 4.0 g/l, with salinities of 2.0, 8.0 and 32.0 g/l were tested.

RESULTS AND DISCUSSION

22. The complete results of the tests carried out to determine the effects of concentration and salinity are given in Table III. This gives the salinity and concentration for each test, and the values obtained for the median settling velocity, upper deviation, and lower

deviation. To achieve the best consistency in the interpretation of the results, they were plotted on a suspended concentration - salinity graph, and lines of equal settling velocity drawn. The contoured diagram obtained by this method, Fig. 5, gives a good impression of the interaction of the effects of salinity and concentration. Within certain limits, increasing either salinity or concentration or both increases the settling velocity. There is an absolute maximum value of settling velocity which can be obtained, in this case about 0.9 mm/s at about 40 g/l salinity and 5 g/l concentration. The much greater settling velocities obtained when flocculation occurs can be seen by comparing Fig. 5 with the de-flocculated state in Fig. 1.

23. The effects of either suspended concentration or salinity can also be examined independently, by marking off the intersections of lines of constant salinity or concentration respectively with the settling velocity contours. The settling velocity can then be plotted against suspended concentration for various salinities, as shown in Fig. 6, or against salinity for various concentrations as shown in Fig. 7.

Effect of concentration

24. For cohesionless particles, the effect of increasing concentration by weight is to reduce the settling velocity by increasing the volume concentration of the suspension. This continues as the settling develops more and more into hindered or blanket settling, when the particles settle en bloc, forming a clear interface with the overlying water. For cohesive particles, the effect of concentration is rather more complicated. As the concentration is increased, the increased frequency of inter-particle collision causes greater flocculation, resulting in large flocs of low density. Individually these flocs can have a greater or lesser settling velocity depending on the relative changes in density and size, but usually a higher settling velocity results. However the increase in volume concentration of the suspension when flocculation occurs tends to lessen this increase, until eventually the stage is reached when the effect of high volumetric concentrations outweighs the effect of flocculation, and the

settling velocity is reduced. For cohesive particles this stage usually corresponds to the onset of hindered or blanket settling which was confirmed by visual observation in some of the tests. The settling process then becomes rather like a bed consolidation process, with water moving through the pores between the particles, in contrast to the normal settling process of particles moving through the water.

25. The effect of the suspended concentration on the median settling velocity is shown in Fig. 6 and typical settling velocity grading curves for a constant salinity and various concentrations are plotted in Fig. 8. Fig. 6 shows all the features discussed above, with the settling velocity gradually increasing with concentration up to a peak value, and then decreasing again. For relatively low concentrations of about 4 g/l and below, and salinities of below about 16 g/l, the settling velocity increases relatively evenly with concentration, the slope on the log-log plot being about 0.4. At higher salinities the maximum slope is greater, approaching 0.9 at 48 g/l but varies more with concentration.

26. The onset of hindered settling occurs at varying concentrations according to the salinity, the values tending to reduce as the salinity increases. At 2 g/l salinity hindered settling begins at a concentration of about 20 g/l, whereas at 48 g/l salinity it begins at about 4 g/l. On the diagram showing settling velocity contours, Fig. 5, the onset of hindered settling shows up as a type of curved 'ridge', and it can be seen that at very high salinities hindered settling does not occur at concentrations below 4 g/l. As hindered settling is primarily a function of the volumetric concentration of the suspension, the variation of its onset with the salinity of the test is not surprising. The volumetric concentration depends both on the weight concentration and the amount of flocculation, so that the same volumetric concentration can probably be achieved with high weight concentrations and little flocculation (low salinities) or lower concentrations and greater flocculation (high salinities).

27. It is interesting to compare these results with those obtained by authors with muds from different sources, and using different methods

Krone has studied San Francisco Bay mud [4], and Migniot a large number of mainly French muds.[13] The former, measuring the settling velocity by timing visible flocs between two marks on the side of the settling container, found that the resulting settling velocity increased with the 4/3 power of concentration. The tests were at concentrations below 1.0 g/l and salinities up to 24 g/l, and a line showing Krone's results for the maximum settling velocity obtained at each concentration is also plotted in Fig. 6. Later in his report he also stated that hindered settling occurred at concentrations above 10 g/l, based on visual observation in a separate series of tests.

Migniot, in an article dealing comprehensively with results of tests of many different muds, stated that the settling velocity generally increased linearly with concentration, and reached a peak value at a concentration between 10 and 20 g/l. Migniot's analysis was carried out with results from settling velocity tests using the pipette sampling technique.

The difference between these three sets of results, is due to different techniques of analysis, and to the differences in the muds tested. Avonmouth mud seems to be quite different, with its high illite content, from those tested by Krone or Migniot. A few tests were carried out at a constant salinity of 8 g/l for Thames mud, which has a high Montmorillonite content. These results are also plotted in Fig. 6, and show general agreement with Migniot's work, with settling velocity increasing almost linearly with concentration.

Effect of salinity

28. For cohesionless particles, the only effect of salinity is to increase the specific gravity of the suspension, and thereby slightly reduce the settling velocity. For cohesive particles however there is a much greater effect, as increasing salinity increases flocculation; a greater proportion of collisions result in the formation of flocs when the repulsive forces are reduced by increasing salinity. As stated previously increased flocculation usually results in greater

settling velocities.

29. The effect of salinity on the measured settling velocities is shown by Fig. 7, and typical settling velocity grading curves at a constant concentration, varying salinities, are shown in Fig. 9.

Fig. 7 shows that at salinities below about 30 g/l the effect of increased flocculation far outweighs the effect of increased specific gravity of the suspension, and the settling velocity increases fairly rapidly with salinity. At suspended concentrations of about 4 g/l and below, this rate of increase is relatively constant, the slope on the log-log plot being about 0.6. However, at higher concentrations the slope falls off rapidly, being only about 0.1 at a concentration of 32 g/l, indicating that salinity has very little effect on settling when the concentration is well into the hindered settling zone.

30. For each of the suspended concentrations the settling velocity reaches a peak value at concentrations in the region of 30 g/l, and then reduces again. This appears to indicate hindered settling at high salinities, but is in fact some other type of retarded settling. Returning to the contoured settling velocity diagram, Fig. 5, it can be seen that these peak settling velocities at salinities near 30 g/l give rise to another 'ridge', quite distinct from the hindered settling ridge, and they must therefore be different processes. The true cause of the fall in settling velocities after the peak is not known, but it may be that the effect of salinity on flocculation is completed by about 30-40 g/l, and the flocs either behave essentially as cohesionless particles, or there is even some de-flocculation at very high salinities. Further increases in salinity therefore reduce the settling velocity by increasing the specific gravity of the suspension, and by de-flocculation. This explanation is borne out to some extent by the fact that, until hindered settling occurs the peak settling velocity occurs at progressively greater salinites as the suspended concentration is increased, varying from about 28 g/l at 0.25 g/l concentration, to about 43 g/l at 4 g/l concentration. This suggests that there is a critical salt/mud relationship to achieve maximum flocculation, though it is evidently not a direct ratio by

weight. If the retarded settling ridge on Fig. 5 is approximated by a straight line, the ratio for maximum flocculation appears to be

$$\frac{\text{salinity}}{(\text{concentration})^{1/6}} \simeq 35 \ (g/l)^{5/6}$$

although the exact significance of this is not apparent. However, as the settling velocity does not begin to reduce appreciably until the salinity is greater than that normally occurring in most estuaries, the matter is perhaps somewhat academic.

31. Again, it is interesting to compare these results with those obtained by Krone and Migniot. The highest concentration and salinity tested by Krone were 1.0 g/l and 23 g/l respectively. Below these limiting values he found that settling velocity was independent of salinity above 5 g/l for 0.12 g/l concentration and up to 20 g/l for 1.0 g/l concentration. By plotting the salinity against concentration for complete flocculation for Krone's tests, the critical salt/mud relationship for San Francisco Bay mud appears to be

$$\frac{\text{salinity}}{(\text{concentration})^{2/3}} = 20 \ (g/l)^{1/3}$$

i.e. much closer to a direct linear relationship.

Migniot found that the settling velocity was constant at salinities above 3 g/l for low concentrations, and 10 g/l for high concentrations. He also found that the settling velocity was reduced at salinities greater than about 30 g/l. Again, the differences between the three sets of results must be due partly to differences in technique, but mainly to the differences in the muds tested.

Effect of depth of settling

32. Very little work has been reported in the literature on the effect of depth of settling on the settling process of relatively low concentrations. The exceptions are work by McLaughlin [12], and by the Water Pollution Research Laboratory.[14] McLaughlin, using the method referred to in para. 21, found that the settling velocity of clay in a

0.9 metre settling depth was twice as great as in a 0.4 metre depth. The Water Pollution Research Laboratory, studying mud from the estuary of the River Mersey, did not specifically determine settling velocity, only measuring the cumulative percentage settled as a function of time of settling. However, from their results in tubes 12.2, 2.75 and 1.22 metres high (40, 9 and 4 ft respectively), which show that the times required to obtain equal percentages settled in the 12.2 and 1.22 metre tubes were in the ratio of only two to one, it is possible to deduce that the settling velocity was about five times greater in the longest tube than in the shortest. In view of these last results, it was decided to carry out the first tests in a tube 9 metres (30 ft) high, which, as well as being about the highest possible indoors, represents a typical average depth of water in docks, harbours and estuaries. Results from these tests were conclusive in only one respect however. Any variation in the settling velocity was present only in the top 1.9 m of the depth. It was decided therefore to switch the main effort to sedimentation tubes up to 2 metres high, and thus release the 9 metre tube for other tests. The results obtained from the main tests are given in Table IV, and are plotted in Fig. 10 as settling velocity versus depth of settling for the various concentrations and salinities tested. Typical settling velocity grading curves for a fixed concentration and salinity are shown in Fig. 11. Some rather unexpected results appear from these tests. It was anticipated that the results would show the settling velocity gradually increasing with depth, as flocculation due to differential settling occurred, until a terminal value was reached, at which the fluid shear on the floc, by reason of its settling velocity, equalled the bonding strength of the particles forming the flocs. The results obtained, are however, quite different. In most of the tests the settling velocity was actually reduced as the depth of settling increased from 0.5 to 1.0 metres, by as much as a factor of five in the extreme case. As the depth increases from 1.0 to 1.5 metres, the settling velocity then rises, and becomes larger in value than at 0.5 metres. For the highest concentrations tested, the settling velocity begins to fall off again beyond a depth of 1.5 metres, but for the other concentrations there is no definite trend, some having a maximum velocity at about 1.5 metres, and others still rising at 2.0 metres. The overall conclusions are that, for Avonmouth mud at least, settling tests in the standard length, 1 metre, bottom withdrawal tube give results unrepresentative of normal depths of settling, and that, for concentrations below 4 g/l, the settling velocity reaches its terminal value somewhere between 1.5 and 2.0 metres.

33. The reason for the existence of a minimum settling velocity at about 1.0 metres is not known, but a possible explanation could be the following. Because of the extremely small size of the primary particles of the mud, the suspension will be stable until some flocculation occurs. At the beginning of each settling test, there is therefore an interval, during which flocculation due to Brownian collision occurs, before settling begins. The resulting flocs are made up of a small number of particles, and therefore have a relatively high density, and settle relatively rapidly through the water, gathering up other flocs as they settle. Because of the time available, and height involved, the flocs settling in the 0.5 metre tube do not increase appreciably from their initial size as a result of the Brownian flocculation. In the 1.0 metre tube however, the extra depth of settling means that, as the flocs settle this distance, and gather up other flocs in the process, they become very large and loose, having a relatively low density. This low density implies a high volume concentration in the suspension, which, as explained previously, retards the settling process, and causes considerable counter-flow of the water, which could be observed in the 1.0 metre tube during the tests. As further depth of settling is made available in the 1.5 and 2.0 metre settling tubes, the flocs increase in size, and reduce in density, until they become so large and loose that the fluid shear exerted by virtue of the settling velocity is greater than the weaker cohesive bonds, and they break up to form stronger, higher density flocs with an increased settling velocity. Eventually a stage is reached at which the fluid shear is equal to the strongest cohesive bonds, and an equilibrium settling velocity is maintained. Unfortunately, this explanation has been impossible to verify, as the

basic measurement required would be the density of the flocs actually in suspension which, as far as is known, has never been achieved. Attempts were made to deduce this from the density of the deposited bed, but the results proved inconclusive, and the explanation therefore remains hypothetical.

General results

34. A study of the typical settling velocity grading curves in Figs. 8, 9 and 11, shows that an increase in the value of the median settling velocity is generally accompanied by a reduction in the width of the grading curve. This can be seen also from the values of the upper and lower deviations in Tables III and IV. Increasing flocculation tends to combine most of the particles into flocs of relatively uniform size, density, and thus settling velocity. This is probably a phenomenon of settling in sedimentation tubes where the flocs are each subjected to the same flocculation rates. In an estuary, where the rates of flocculation differ widely as a result of the different degrees of turbulence, increasing flocculation would not necessarily result in a reduction of the width of the settling velocity grading curve of a sample.[15]

FUTURE STUDIES

35. Based on the framework of these detailed tests on the settling velocities of Avonmouth mud, similar but less extensive tests should be carried out on muds from other rivers and estuaries, both in the United Kingdom and overseas. An overall picture of the similarities and differences in the settling processes of various types of mud can then be formed.

These tests have all been carried out at the ambient temperature in the laboratory, which was $20^{\circ}C \pm 2^{\circ}C$. Using apparatus to provide water at a given temperature, tests should be carried out to determine the effects of temperature on settling velocities. Theoretically one would expect increasing temperature to increase the settling velocity, by both increasing flocculation (equation I) and reducing the suspension viscosity.

CONCLUSIONS

Detailed studies of the settling velocities of Avonmouth mud have given the following results.

1. The median settling velocity increases with concentration up to a value - between 4 and 20 g/l, depending on the salinity - at which hindered settling begins, and reduces thereafter.

2. The median settling velocity increases with salinity (except during hindered settling) up to a value - between 28 and 43 g/l depending on the concentration - where some form of retarded settling occurs, and decreases thereafter.

3. For a fixed depth of settling, there is an absolute maximum value of settling velocity, which is attained at a fixed salinity and concentration. The salinity and concentration required are however greater than normally found in estuaries.

4. The effect of depth of settling is fairly complex, the settling velocity reducing to a minimum at a depth of 1.0 metres, and then increasing with depth to reach its terminal value at something less than 2.0 metres.

5. Similar tests on muds of widely different types are necessary to gain a complete picture of the dependence of settling velocity on concentration, salinity, and depth of settling.

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NOTATION

c	- suspended concentration by weight
D	- depth of settling
g	- acceleration due to gravity
H	- particular elevation in settling column
I	- frequency of collisions due to Brownian motion
J	- frequency of collisions due to internal shearing
k	- Boltzmann's constant
n	- number of flocs or particles per unit volume
R	- effective floc or particle radius
r	- floc or particle radius
T	- absolute temperature
du/dz	- local velocity gradient
w	- settling velocity
$\bar{w}$	- mean settling velocity
w_{50}	- median settling velocity
w_{16}, w_{84}	- settling velocity at 16% and 84% undersize levels respectively
z	- general elevation in settling column
ν	- kinematic viscosity
μ	- dynamic viscosity
ρ	- density of particle or floc
ρ_s	- specific gravity of suspended sediment
ρ_l	- specific gravity of suspending liquid

TABLES

TABLE I

COMPARISON OF BROWNIAN AND GRAVITATIONAL DISPLACEMENTS FOR PARTICLES SUSPENDED IN WATER

Particle Diameter: microns	Displacement per second: microns	
	Brownian Motion	Gravitational Motion
0.1	2.36	0.005
0.25	1.49	0.0346
0.5	1.05	0.138
1.0	0.745	0.554
2.5	0.471	3.46
5.0	0.334	13.8
10.0	0.236	55.4

Water temperature 21°C

Particle specific gravity 2.0

After Happel and Brenner (3)

TABLE II

MINERALOGICAL ANALYSIS OF MUD TESTED

Clay mineral	Basal area %
Kaolinite	20
Illite	52
Montmorillonite	15
Chlorite	12

TABLE III

RESULTS OF CONCENTRATION AND SALINITY TESTS

2 metre settling tube

Test Number	Concentration g/l	Salinity g/l	Median Settling Velocity w_{50} mm/s	Upper deviation w_{84}/w_{50}	Lower deviation w_{50}/w_{16}
Aa	0.26	2.12	0.048	15.8	160*
Ac	0.25	8.16	0.094	10.6	9.8
Ad	0.22	17.5	0.17	6.1	21
Ae	0.23	36.8	0.155	6.4	23.8
Ag	0.25	51.6	0.085	4.6	-*
Ca	0.94	2.12	0.071	7.6	760*
Cc	0.86	8.64	0.155	5.2	29.0
Cd	0.92	17.2	0.29	2.5	9.6
Ce	0.93	34.9	0.49	2.8	8.6
Cg	0.91	46.4	0.097	3.5	5.1
Ea	3.66	2.24	0.14	5.9	39
Ec	3.60	8.34	0.54	2.4	19.3
Ed	3.86	16.8	0.49	1.7	10.6
Ee	4.05	32.68	0.73	1.9	3.5
Eg	3.93	51.1	0.57	1.4	2.6
Eg(R)	3.75	46.8	0.90	1.7	1.8
Ga	15.40	2.45	0.37	2.1	16.8
Gc(R)	15.38	7.61	1.2	1.6	1.7
Gd	16.97	17.6	0.54	2.7	1.8
Ge	16.18	34.8	0.70	1.8	1.8
Gg	15.95	47.2	0.41	1.3	1.4
Ha	31.4	3.73	0.33	1.9	3.8
Hc	30.9	8.69	0.36	2.3	1.3
Hd	32.2	18.67	0.27	1.6	1.3
He	33.7	35.58	0.41	3.3	1.5
Hg	32.5	50.4	0.41	2.6	1.4

*w_{16} very small, and inaccurately determined

TABLE IV

RESULTS OF DEPTH OF SETTLING TESTS

Test Number	Concentration g/l	Salinity g/l	Median Settling Velocity w_{50} mm/s	Upper deviation w_{84}/w_{50}	Lower deviation w_{50}/w_{16}
		0.5 metre settling tube			
Aa	0.212	2.20	0.0125	29.2	20.5*
Ac	0.278	7.96	0.001	164	- *
Ae	0.262	30.85	0.021	12.4	35.0*
Ca	1.030	2.88	0.0001*	4200*	
Cc	1.240	8.48	0.024	9.2	
Ce	0.940	32.20	0.115	3.4	3.7
Ea	4.00	2.50	0.129	2.9	12.9
Ec	3.92	8.14	0.152	2.6	2.5
Ee	4.20	30.51	1.08	1.4	2.9
		1.0 metre settling tube			
Aa	0.226	2.20	0.0064	29.4	25.2*
Ac	0.222	8.22	0.0095	23.2	23.7*
Ae	0.264	32.28	0.015	11.2	
Ca	0.955	2.05	0.0074	37.3	- *
Cc	0.960	8.83	0.027	12.0	28.9
Ce	0.926	31.36	0.058	2.7	6.3
Ea	3.86	2.00	0.041	9.3	22.8
Ec	4.30	8.30	0.10	3.8	56.1
Ee	4.30	32.05	0.19	2.0	2.0
		1.5 metre settling tube			
Aa	0.222	2.71	0.065	17.2	- *
Ac	0.235	9.32	0.0078	55.1	
Ae	0.248	35.8	0.085	12.9	
Ca	0.880	2.56	0.027	15.2	- *
Cc	0.945	9.09	0.225	2.1	66.2
Ce	0.965	33.4	0.44	1.5	10.8
Ea	3.78	2.44	0.4	3.0	19.1
Ec	3.74	9.32	0.98	1.7	4.3
Ee	3.98	33.2	1.15	1.4	1.7
		2.0 metre settling tube (Results extracted from table III)			
Aa	0.260	2.12	0.048	15.8	160 *
Ac	0.250	8.16	0.094	10.6	9.8
Ae	0.227	36.8	0.155	6.4	23.8
Ca	0.940	2.12	0.076	7.6	760 *
Cc	0.860	8.64	0.145	5.2	29.0
Ce	0.932	34.9	0.460	2.8	8.6
Ea	3.66	2.24	0.140	5.9	39
Ec	3.60	8.34	0.54	2.4	19.3
Ee	4.05	32.68	0.73	1.9	3.5

*Settling velocity too low to be accurately determined

FIGURES

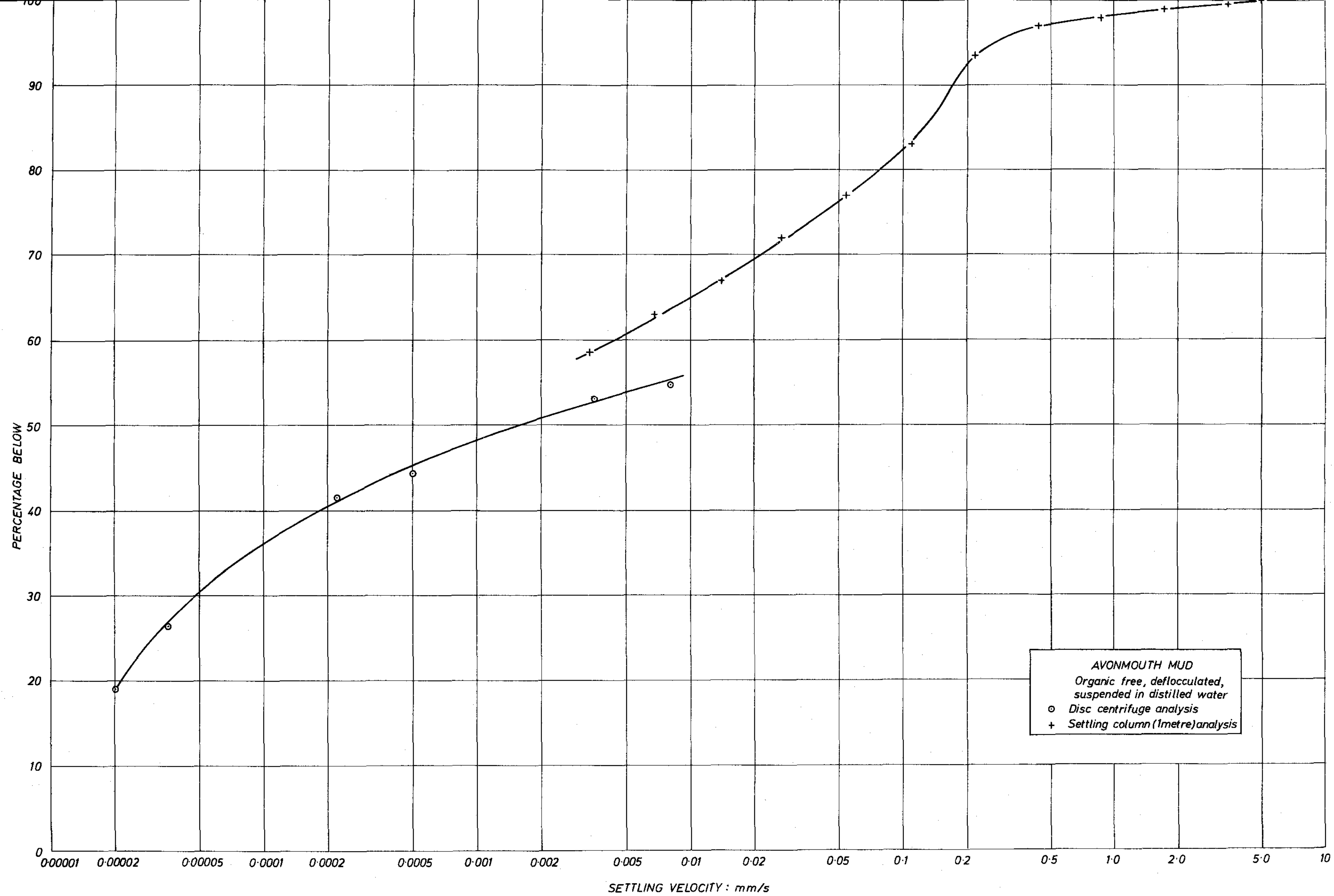
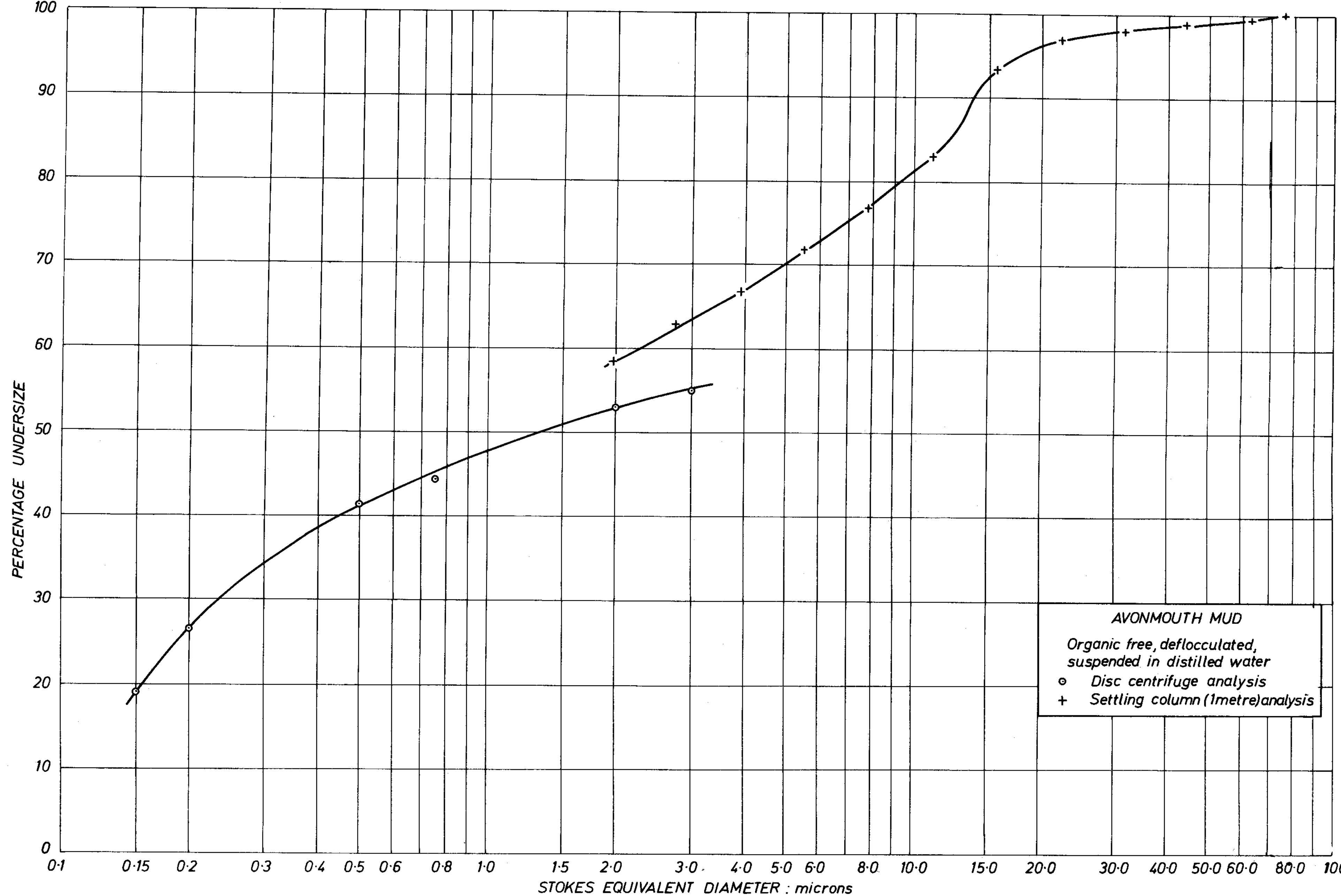


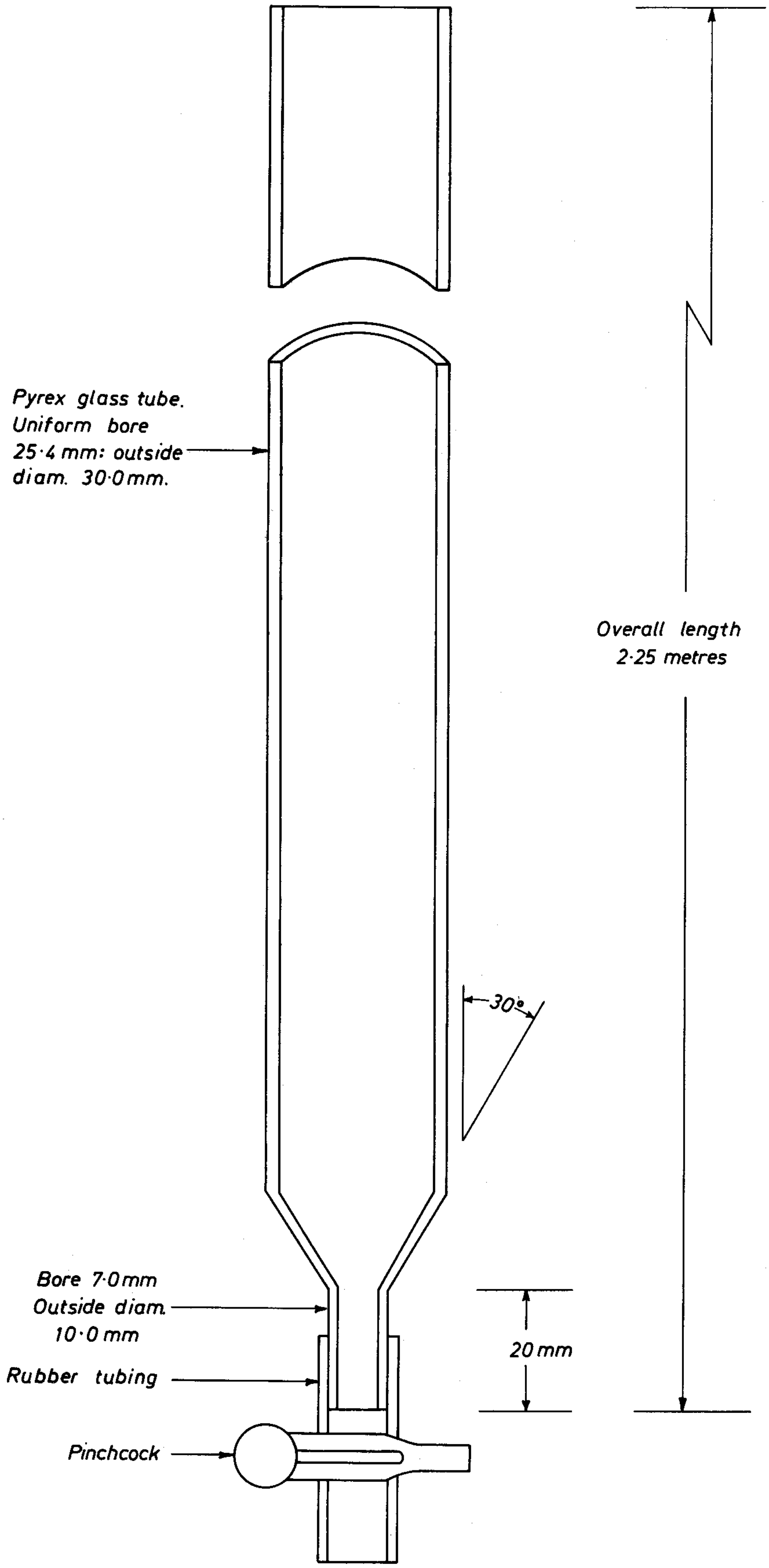
FIG 1

SETTLING VELOCITY OF DEFLOCCULATED MUD BY DISC CENTRIFUGE AND SETTLING TESTS



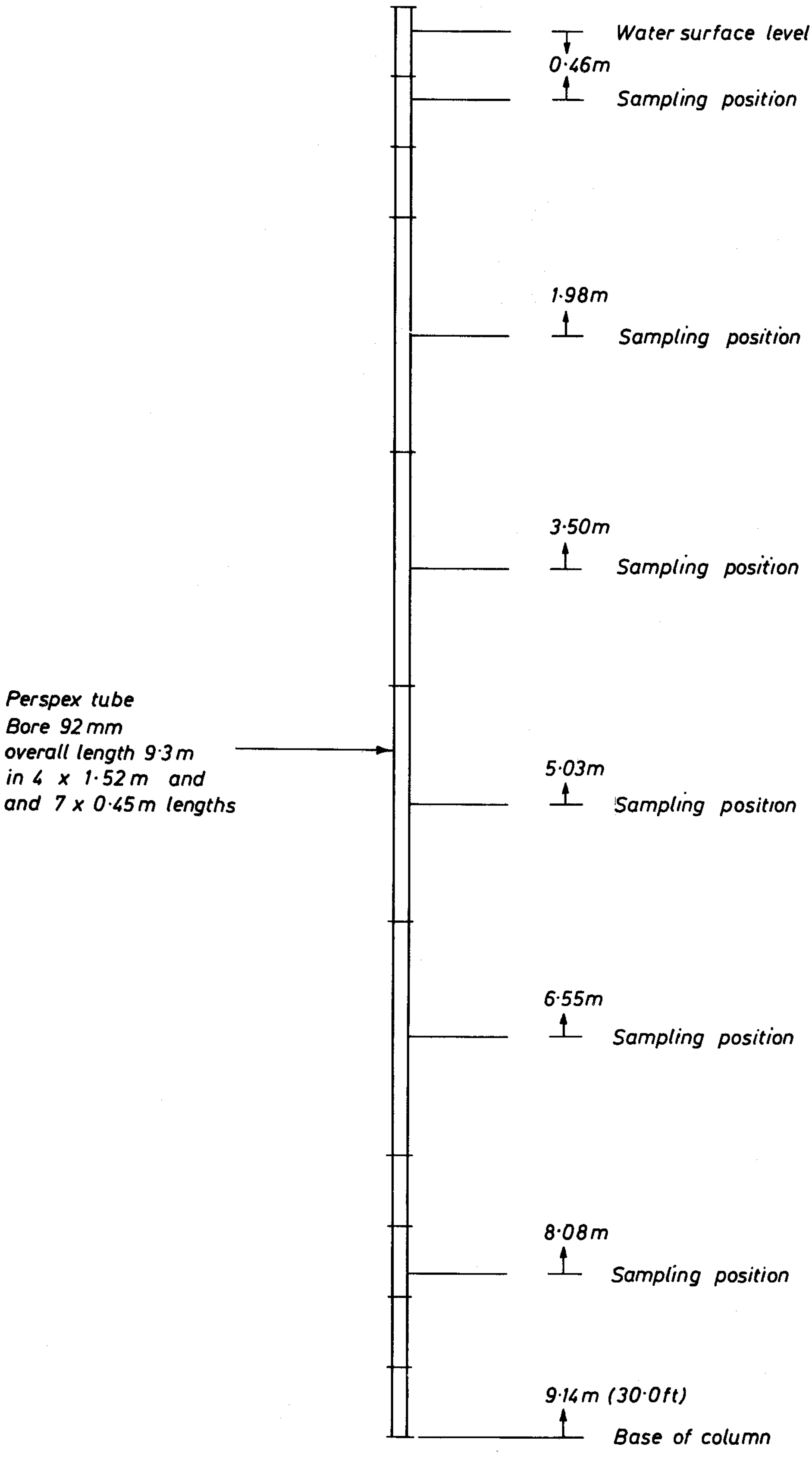
EQUIVALENT STOKES DIAMETER OF DEFLOCCULATED MUD

FIG 2



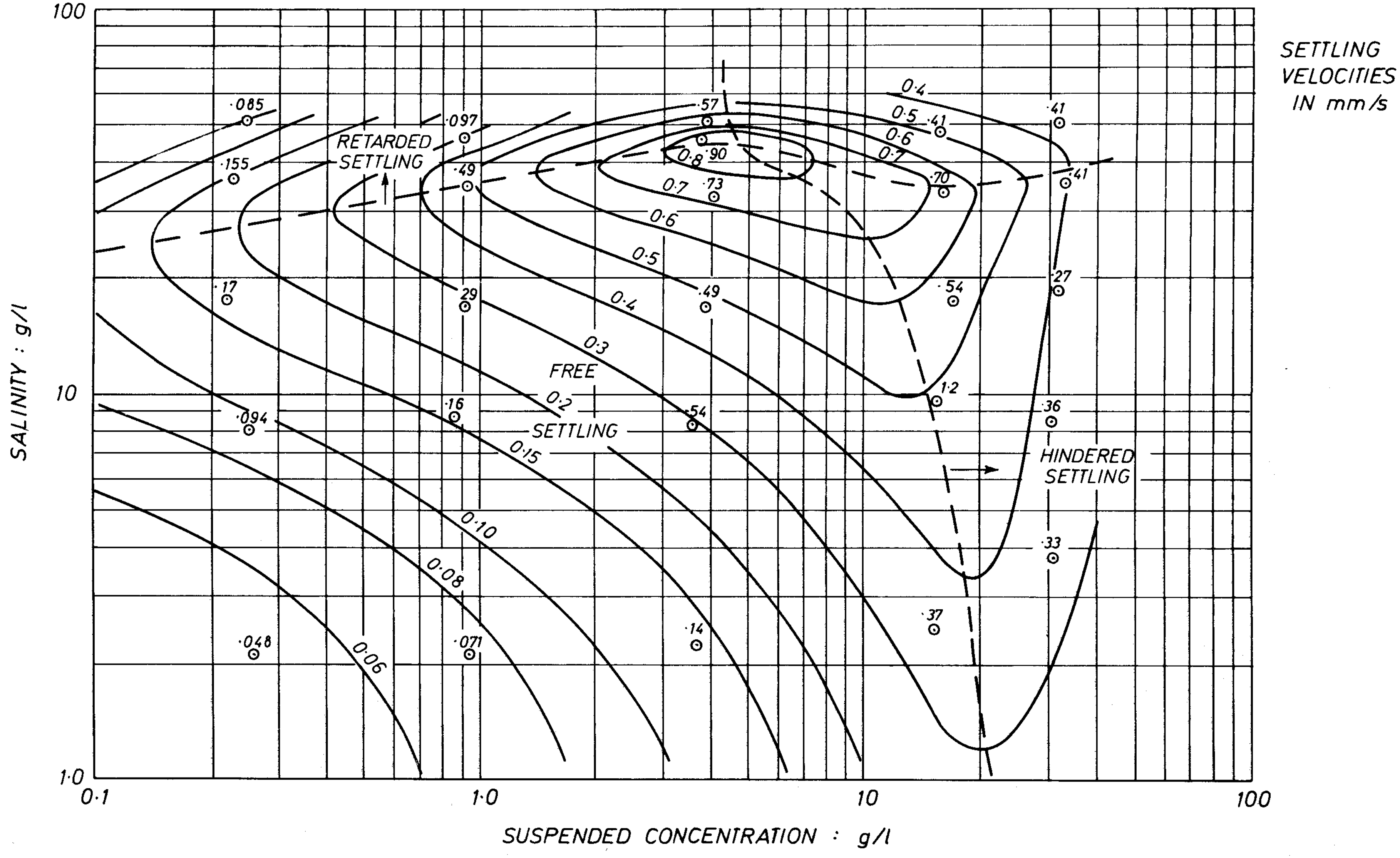
2 METRE BOTTOM WITHDRAWAL SETTLING TUBE

FIG 3



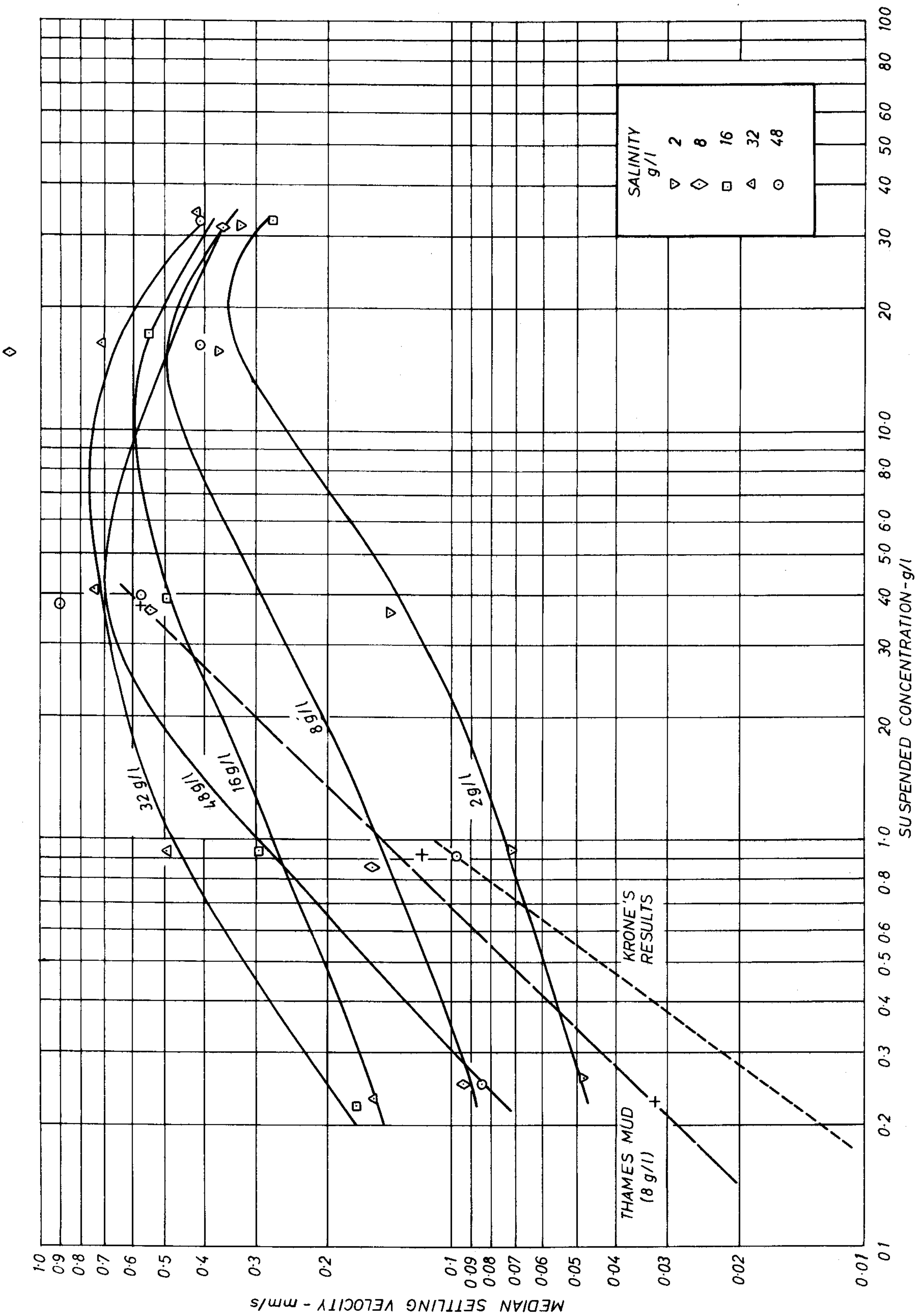
9 METRE SETTLING COLUMN

FIG 4



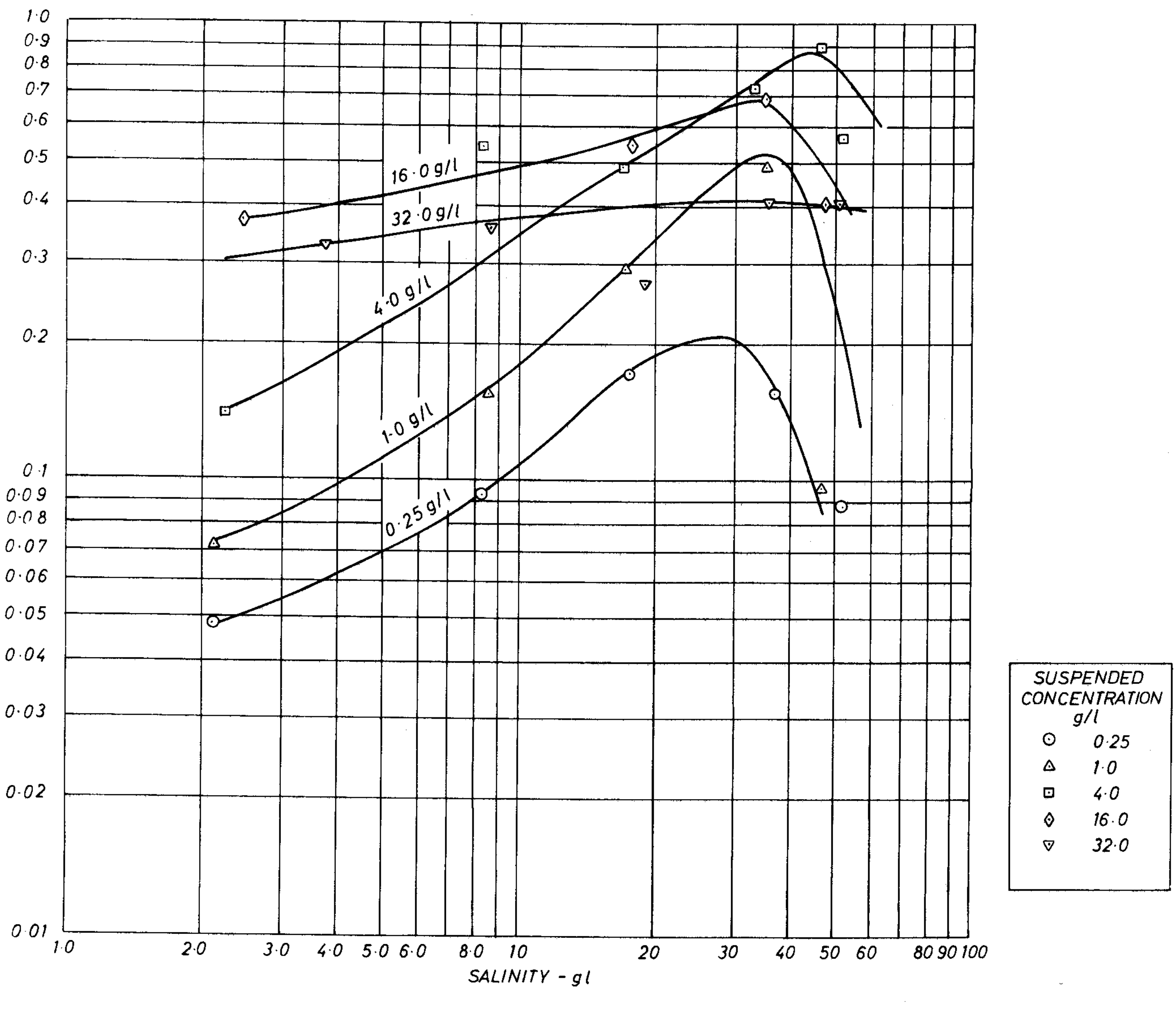
LINES OF EQUAL SETTLING VELOCITY FOR VARYING CONCENTRATION AND SALINITY

FIG 5



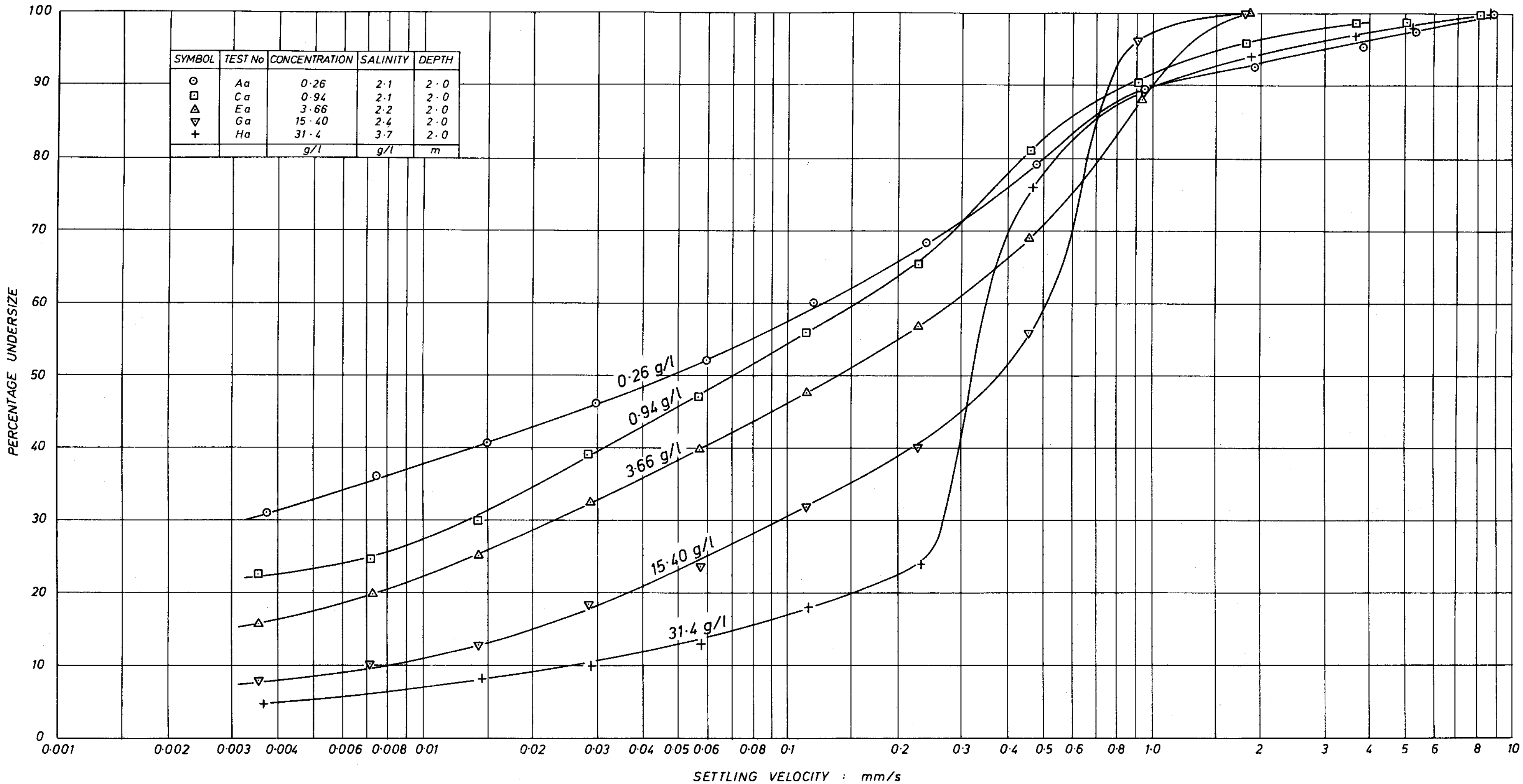
EFFECT OF CONCENTRATION ON SETTLING VELOCITY

FIG 6



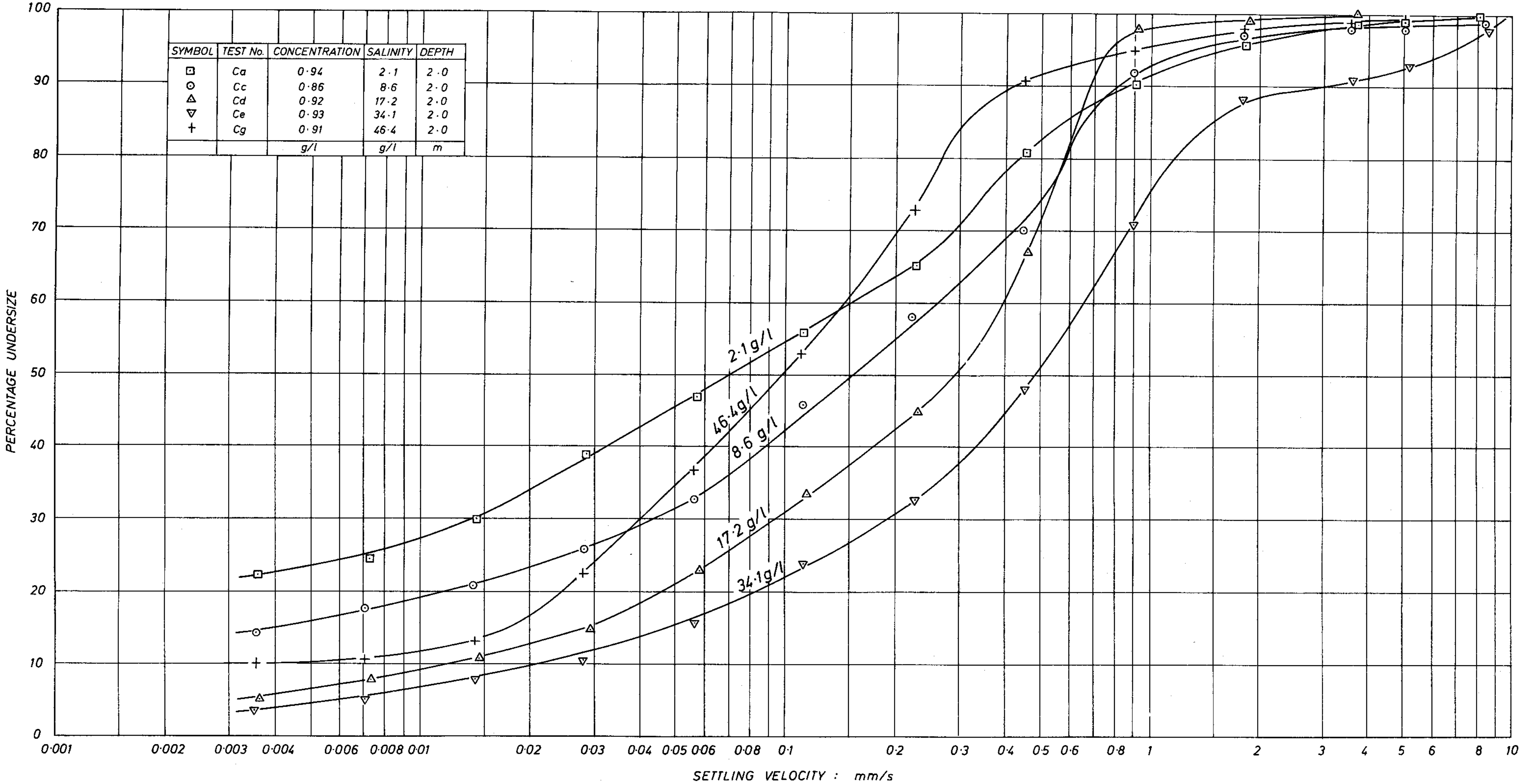
EFFECT OF SALINITY ON SETTLING VELOCITY

FIG 7



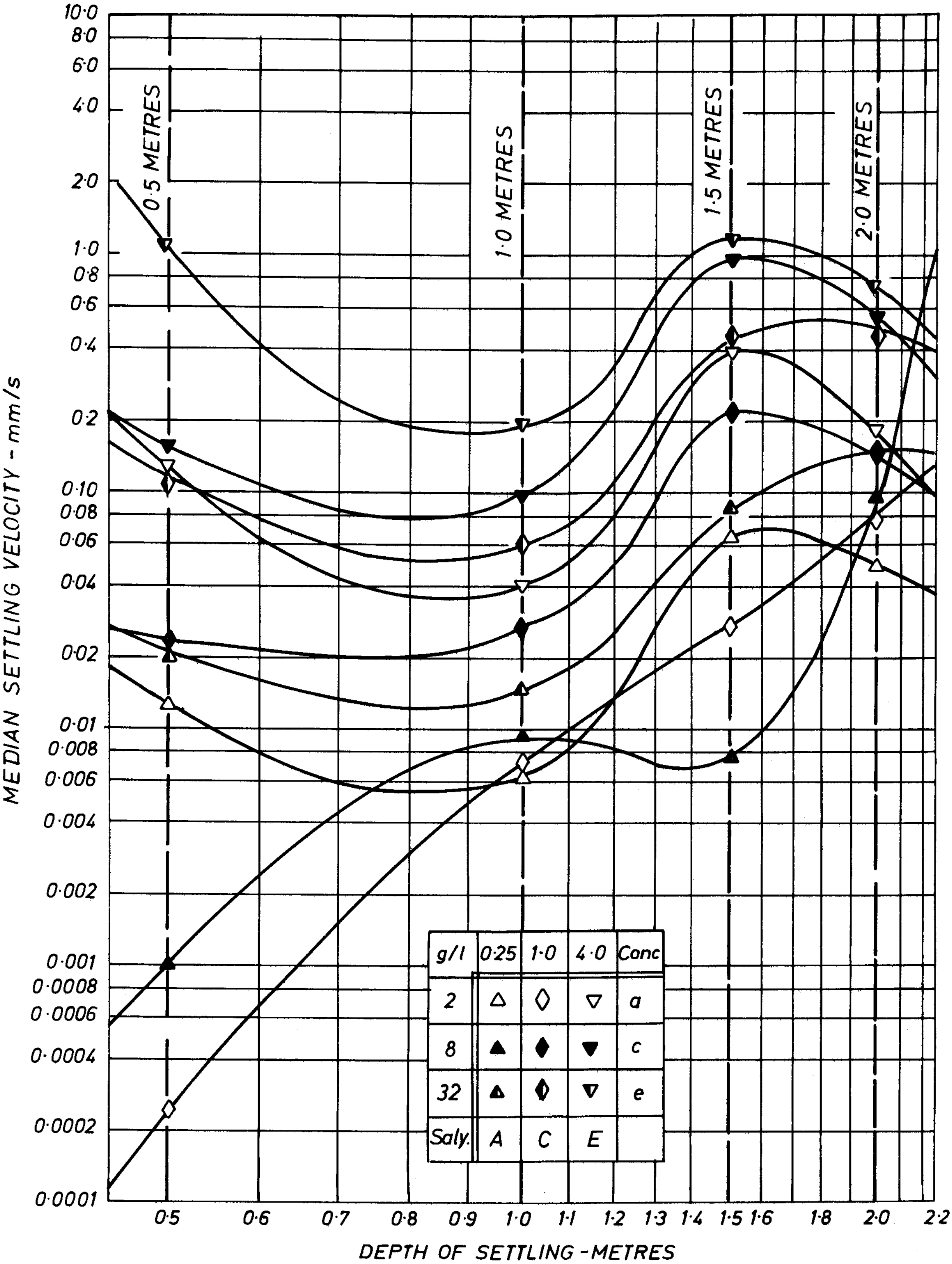
TYPICAL SETTLING VELOCITY GRADING CURVES WITH VARYING CONCENTRATION

FIG 8



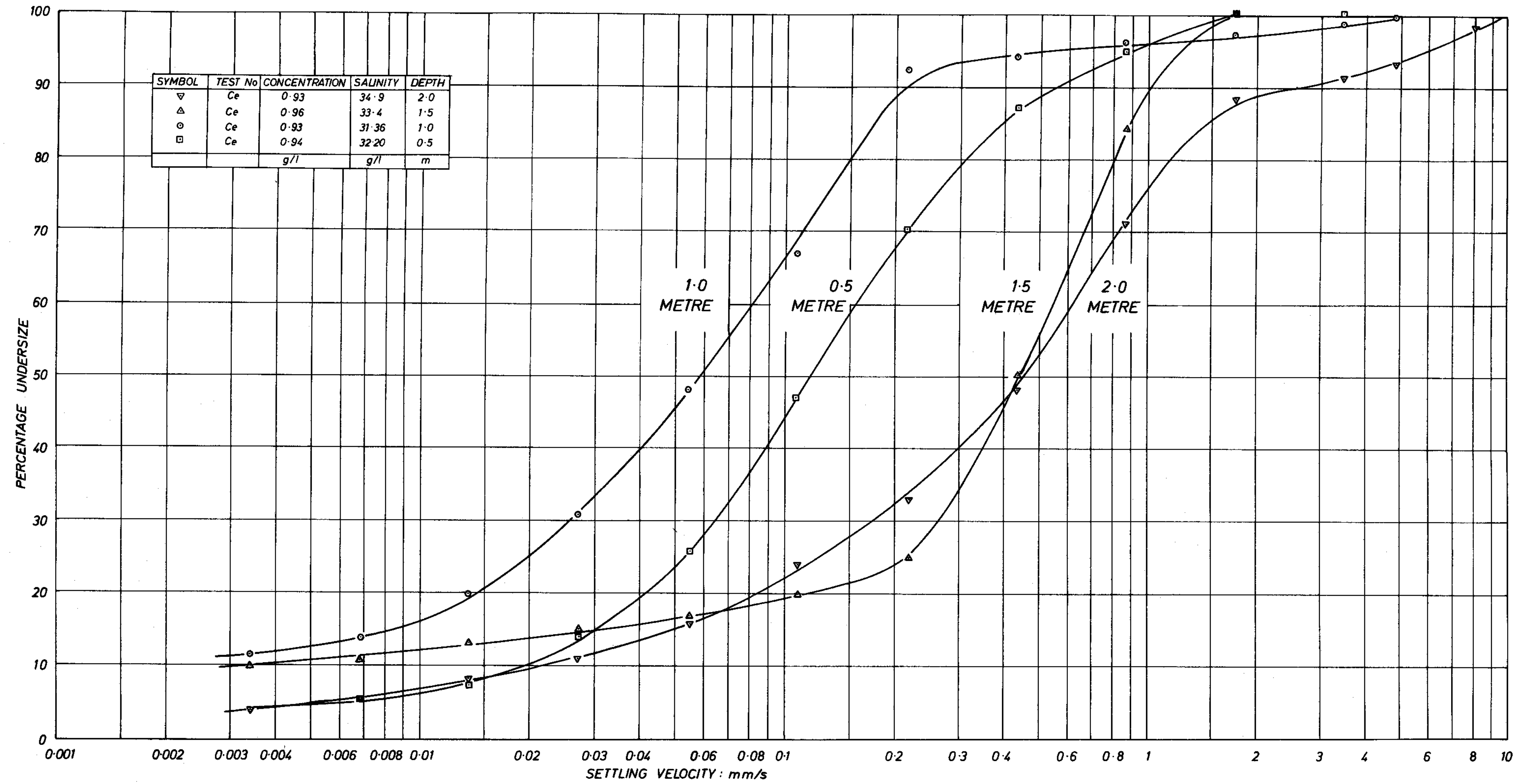
TYPICAL SETTLING VELOCITY GRADING CURVES WITH VARYING SALINITY

FIG 9



EFFECT OF DEPTH OF SETTLING ON SETTLING VELOCITY

FIG 10



TYPICAL SETTLING VELOCITY GRADING CURVES WITH VARYING DEPTH OF SETTLING

FIG 11