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Hydraulics Research
Wallingford

THE HYDRAULIC ENGINEERING
CHARACTERISTICS OF ESTUARINE MUDS

A working manual and literature review

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ABSTRACT

The feasibility of many engineering works, both new developments and maintenance programmes, within a coastal or estuarine environment may significantly depend in economic and ecological terms on the ability to predict the movement of fine cohesive sediments. The behaviour of such sediments, or muds as they are commonly called, ^{is} ~~are~~ controlled by a complex array of physical and chemical factors, which are only partly understood, and by the hydrodynamics of the flow. Prediction of mud behaviour is therefore very difficult from its physical and chemical properties alone. Accordingly, the engineering approach usually adopted has been to determine in the laboratory for a given flow condition the behaviour of a sample of mud taken from the field.

Within mud there is a large proportion of particles which are very small such that the effect of the surface physico-chemical forces becomes as important as the effect of gravity forces. Flocs will form as a result of collisions and cohesion of individual particles. The maximum floc size is governed by the particle size, concentration, mineralogy, ^{pH} ~~ph~~ and ionic strength of mud, chemical composition of the fluid, and hydrodynamic parameters such as velocity and turbulence structure, internal shear and bed shear stress.

Mud may be considered to exist in four states, namely, a mobile suspended sediment, a near bed stationary suspension of high concentration, a partially consolidated bed and a settled bed. Flocs may settle towards the bed and become part of the bed or may be re-suspended from the partially consolidated bed and the settled bed. The processes of deposition, consolidation and erosion may be identified in terms of floc behaviour. Up to now, the majority of work has considered these processes in isolation although there is an increasing awareness that it is necessary to more closely simulate the cyclic elements of estuarine conditions.

An engineering guide is presented which gives practical advice on the approaches to be taken in predicting the behaviour of mud. It is recognised, however, that the emphasis must still be placed on empirical relationships.

A state-of-the-art review of the available data on the engineering properties and behaviour of estuarine muds is presented. Work has been collated under the topics of deposition, consolidation and erosion. Both laboratory and field based research are described and comparisons are drawn between the data from different sources.

In the concluding remarks, some important areas of mud behaviour in need of further research are identified.

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1 INTRODUCTION

The ability to predict the movement of cohesive sediment within coastal, estuarine or inland waters has a significant economical and ecological importance in the development of new engineering works and the maintenance of existing installations. The future viability of a proposed new port, for example, could largely depend on the cost of routine dredging necessary to sustain its accessibility to shipping. Many other schemes, such as the reclamation of intertidal flats, or the construction of flood protection structures or the laying of outfalls, also require a sound engineering appraisal of the likely changes in the patterns of sediment movement which will result after the scheme is built. Furthermore, the capability to predict the movement of cohesive sediment is crucial in the understanding of the distribution of certain pollutants, in particular heavy metals which are adsorbed on to clay and silt particles.

The processes of deposition, consolidation and erosion of cohesive sediment are controlled by a complex array of physical and chemical factors which are only partly understood. Any attempt to predict the movement of cohesive sediment must first investigate the nature of the hydrodynamics of the water and then relate the movement of water to the movement of cohesive sediment. As yet, it is not possible to predict the behaviour of a cohesive sediment from its physical and chemical properties alone and the principal thrust of research has been to determine in the laboratory, for a given set of flow conditions, the behaviour of a sample of the cohesive sediment taken from the field. Solutions in this instance, are therefore, based on empirical data and have limited value to other sites.

The complexity of cohesive sediment may be demonstrated by reference to a characterisation of cohesive sediment presented by Hayter and Mehta (1982) and reproduced in Table 1. The number of parameters which need to be determined to completely describe a cohesive sediment is quite considerable. Hence it is easier to understand why studies of cohesive sediment have been empirical and site specific rather than of a more fundamental nature.

Even the laboratory studies to date, however, have had the drawback of considering only one process in isolation, e.g. deposition or erosion, and even then usually at a constant rate of flow. In natural conditions the processes are often strongly cyclic with the deposition, partial consolidation and re-erosion of cohesive sediment occurring repeatedly with the tides. Laboratory simulation of the tidal

cycle in relation to the physical processes of cohesive sediment has only recently been commenced.

Estuarine cohesive sediment, commonly called mud, is composed primarily of silt and clay. For example, the size distributions of five muds investigated at Hydraulics Research are given in Figure 1. The mineralogy and cation exchange capacity of three of the muds are presented in Table 2. Mud contains a large proportion of very small particles which have a large specific area such that the effect of the surface physico-chemical forces becomes as important as the effect of gravity forces. Some of these individual particles are less than 1 micron in diameter and may be kept in suspension by Brownian motion alone. Flocculation of particles will take place when the net physico-chemical interparticle forces become attractive.

The size and settling velocity of the flocs may be much larger than that of the individual particles and rapid deposition may occur as a result of flocculation. The importance of flocculation may be demonstrated by considering the data given by Migniot (1968) which is shown in Figure 2. The flocculation factor, F , is the ratio of the settling velocity of flocculated sediment to that of the chemically dispersed sediment. This factor is seen to vary with mean particle diameter from a figure in the order of 10^4 for particles with a diameter of 0.1 micron to unity for particles with a diameter of about 60 microns. This implies that the cohesive behaviour of sediment ceases for particles with a mean diameter greater than 60 microns.

The maximum floc size is governed by the particle size, concentration, mineralogy, pH and ionic strength of the mud, by the chemical composition of the pore water and suspending water, and by the hydrodynamic parameters of the water such as the velocity and turbulence structure, internal shear and bed shear stress. The settling unit is therefore the floc rather than discrete particle grains as in non-cohesive sediment. This dependence therefore inhibits the development of a set of universal equations.

Cohesive sediment can be considered to exist in four states. These four states are illustrated in Figure 3 and may be described as a mobile suspended sediment, a near bed stationary suspension of high concentration with a small cohesion which is sometimes referred to as fluid mud, a partially consolidated bed, and a settled bed.

The three processes of cohesive sediment of primary interest to the engineer are deposition or settling, consolidation and erosion or resuspension. Deposition involves the settling through the water column and on to the bed of flocculated sediment. Consolidation of a deposit is the gradual expulsion of interstitial water by the self weight of the sediment accompanied by an increase in both the density of the bed and its strength with time. Erosion is the removal of sediment from the surface of the bed due to the stress of the moving water above the bed.

2 ENGINEERING GUIDE

2.1 Introduction

This section summarises in an engineering form the main processes of cohesive sediment behaviour, namely, deposition, consolidation and erosion. The data presented are intended to show the practising engineer which parameters are important in each of the processes and to enable broad estimates of the rates of deposition, consolidation and erosion to be made based on a limited knowledge of the field conditions.

The behaviour of cohesive sediment does vary considerably in quantitative terms from one source to another. Therefore, it is crucial that the engineer appreciates that estimates based on the data presented herewith may well be in error by half an order of magnitude.

For most serious engineering problems involving cohesive sediment it would be essential to undertake a detailed study. This would involve some of the following techniques : field measurements, laboratory testing of sediment, numerical modelling of hydrodynamics and sediment transport and physical modelling of hydrodynamics.

2.2 Deposition

2.2.1 Settling velocities

The basic parameter used in determining rates of deposition in either still or flowing water is the settling velocity of the flocculated sediment. This is usually represented by the median settling velocity W_{50} . Half the sediment by weight settles at a greater velocity than W_{50} . The data collated during the literature survey on settling velocities are summarised below. This is followed by a procedure for determining or estimating the settling velocities of flocs for a specific location.

Knowledge

- Measurement of the settling velocity of flocculated sediment must be done in the field as removal of a sample to the laboratory changes the floc structure. The data shown in Figure 4 implies that laboratory measurements could be an order of magnitude lower than those measured in the field.
- Settling velocity of cohesive sediment is very dependent on the suspended sediment concentration. Settling velocities increase with higher suspended concentrations, see Figure 4.
- Salinity may have a secondary but inconsistent effect on the settling velocity of cohesive sediment. This is illustrated by the Thames field data in Figure 5.
- Variation in settling velocities is considerable for sediment from different locations. The data in Figure 6 are from eight estuaries and show an order of magnitude difference for the extreme ranges.
- Individual flocs of a suspension have settling velocities which differ considerably. The general equation for Thames data is given in Figure 7.
- Hindered settling of flocs in high concentration suspensions results in a reduction of the settling velocity. This is shown for the Severn Estuary in Figure 8.

Procedure

- measure settling velocity in the field for a range of suspended sediment concentrations to determine W_{50} against concentration and w_n/W_{50} ratio against concentration.

or

- if estuary is on Figure 6 use regression line to find W_{50} against concentration.

or

- use equation $W_{50} = 1.0 C^{1.0}$ (W_{50} in mm/s, C in g/l) for C in the range 0.05 to 2.0g/l.
- for an estimate of w_n/W_{50} use Figure 7.

2.2.2 Rate of deposition in still water

Knowledge

The rate of deposition of cohesive sediment onto the bed is given by

$$\frac{dm}{dt} = -C \cdot W_{50}$$

where C is the concentration of suspended sediment near the bed and W_{50} is the median settling velocity corresponding to the near bed concentration.

The average rate of deposition over a period of time can only be calculated if the depth of the water and the depth variation of initial concentration of suspended sediment are known or assumed. For the purpose of providing some data a simple series of calculations were made for water depths of 5m and 20m. It was assumed that the initial surface concentration of suspended sediment was one half of the depth mean concentration and that the near bed concentration was initially twice the depth mean concentration. The median settling velocity, W_{50} , was given by $W_{50} = 1.0 C^{1.0}$ (mm/s and g/l).

Procedure

- instantaneous rate of deposition can be calculated easily for the particular variation of W_{50} with C and the near bed concentration of suspended sediment.

or

- instantaneous rate of deposition from Figure 9 for low values of suspended sediment concentrations and from Figure 10 for high concentrations if W_{50} against C is unknown.
- average rate of deposition over a time period can be calculated using a time step model with the depth of water, initial concentration of suspended sediment variation with depth and W_{50} or W_n against C as the governing parameters.

or

- average rate of deposition from Figures 11 and 12 if initial suspended sediment concentration profile and W_{50} against C are unknown.

2.2.3 Rate of deposition in flowing water

Laboratory tests in straight and circular flumes have shown that deposition in flowing water is controlled by the shear stress exerted by the moving water on the bed of the flume.

Knowledge

- for a given flowing suspension there exists a bed shear stress below which all the sediment will eventually deposit. The magnitude of this critical bed shear stress, τ_{cd} , is about 0.06 N/m^2 .
- for a given flowing suspension there exists a high bed shear stress, τ_m , above which none of the sediment will deposit.
- the amount of sediment which deposits when the bed shear stress is reduced from τ_m to a shear stress higher than τ_{cd} is a proportion of the initial total amount of sediment and is independent of concentration.
- the rate of deposition for a bed shear stress τ_b , where $0 < \tau_b < \tau_{cd}$ may be estimated by

$$\frac{dm}{dt} = -p C W_{50}$$

the probability p takes the value between 0 and 1, given by

$$p = (1 - \tau_b / \tau_{cd})$$

Procedure

- instantaneous rate of deposition by calculation knowing W_{50} against C and assuming τ_{cd} .

or

- instantaneous rate of deposition from Figure 13 if w_{50} against C is unknown.
- average rate of deposition during the time period at slack water when $\tau_b < \tau_{cd}$, see Figure 14, may be calculated by a time step approach if the depth, suspended sediment concentration profile with depth and W_{50} against C are known and τ_{cd} is assumed.

or

- average rate of deposition during the time when $\tau_b < \tau_{cd}$ may be found from Figures 15 and 16 if W_{50}

against C is unknown. This assumes that the near bed concentration of suspended sediment is always twice the mean.

2.3 Consolidation

2.3.1 Bed formation depth

The growth of a loose bed from a suspension of cohesive sediment is depicted diagrammatically in Figure 17. From an initial homogenous suspension the suspension/water interface falls at a near constant rate until it meets the rising suspension/bed interface. At this point the bed is at its formation depth from which time the newly formed water/bed interface slowly reduces.

Knowledge

- the formation mean density as measured in tests in settling columns is largely independent of both suspended solids concentration (Fig 18) and salinity (Fig 19) and may be approximated to 75g/l.

Procedure

- conduct a laboratory settling column test and measure the depth of the bed formed.

or

- for a given average rate of deposition and time period the bed formation depth can be estimated by assuming a mean density of 75g/l. This is done in Figure 20.

2.3.2 Mean density variation with time

Self weight consolidation of loose beds with the accompanying large strains is difficult to model mathematically without the laboratory determination of certain relationships. Therefore, it is necessary to rely on the data from the laboratory work already conducted or to initiate laboratory tests using a sample of the cohesive sediment from the study area.

Procedure

- conduct a laboratory settling column test and measure height of bed and time.

or

- determine from the data in Figure 21 an estimate for the mean density of a bed with time.

2.3.3 Density variations with depth

Knowledge

Theoretical approaches to determining the variation of density through a bed are limited and emphasis has to be placed on laboratory results.

Procedure

- conduct a laboratory settling column test and measure in-situ density throughout the depth.

or

- the density at a certain depth within a bed may be estimated from the laboratory data presented in Figure 22.

2.4 Erosion

2.4.1 Threshold of erosion

Knowledge

- a consolidating bed of cohesive sediment has an increasing density with depth (see Fig 22).
- laboratory studies have shown that the resistance of a bed of cohesive sediment to erosion is a function of the density of the exposed surface.
- the flowing water exerts a shear stress, τ_b , on the bed and the erosion resistance may be represented by the shear stress, τ_{cr} , which is just insufficient to cause erosion (see Fig 23).

Procedure

- conduct laboratory tests in an erosion flume and settling column using samples of cohesive sediment from the study area to determine surface τ_{cr} , density against depth, and τ_{cr} against density.

or

- assume a density profile for the bed and use the relationship shown in Figure 24 to find τ_{cr} against density.

or

- use the threshold values of τ_{cr} given in Table 3.

2.4.2 Rate of erosion

Knowledge

- when the bed shear stress, τ_b , exceeds the critical shear stress, τ_{cr} , the rate of erosion is a function of the difference, $\tau_b - \tau_{cr}$, termed the excess shear stress.
- variation in experimental data is considerable both for a particular cohesive sediment and between different cohesive sediments.

Procedure

- instantaneous rate of erosion, ϵ , as a function of excess shear stress $\tau_b - \tau_{cr}$ may be determined by laboratory testing a sample of cohesive sediment in a mud flume.

or

- instantaneous rate of erosion, ϵ , may be estimated from the data in Figure 25 as $\epsilon = 2(\tau_b - \tau_{cr})$.
- average rate of erosion for the period during the tidal cycle when $\tau_b > \tau_{cr}$ may be calculated by a time step model provided that the relationships of density against depth, critical shear stress against density and rate of erosion against excess shear stress are known.

or

- average rate of erosion and depth of erosion for the period during the tidal cycle when $\tau_b > \tau_{cr}$ may be estimated from Figures 27 and 28 for the assumed relationships of density against depth and critical shear stress against density given in Figure 26, and $\epsilon = 2(\tau_b - \tau_{cr})$.

2.5 Conversions between bulk soil parameters

In addition to the dry density of a consolidated bed, the degree of consolidation may also be expressed in terms of the bulk density, the moisture content, the water voids ratio, or the voids ratio. The definitions of the various parameters are as follows:

$$\text{Dry density} = \frac{\text{Mass of dry mud}}{\text{Volume of wet mud}}$$

$$\text{Bulk density} = \frac{\text{Mass of wet mud}}{\text{Volume of wet mud}}$$

$$\text{Moisture content} = \frac{\text{Mass of water in mud}}{\text{Mass of dry mud}}$$

$$\text{Water voids ratio} = \frac{\text{Volume of water in mud}}{\text{Volume of wet mud}}$$

$$\text{Void ratio} = \frac{\text{Volume of voids}}{\text{Volume of soil}}$$

Figure 29 shows the relationship between the first four of these parameters for a mud having a specific gravity of 2.65.

2.6 Calculation of field bed shear stress

Knowledge

The rate of deposition of cohesive sediment from a suspension and the rate of erosion of material from a cohesive bed are controlled by the bed shear stress, τ_b . There are three ways in which the bed shear stress may be calculated : by direct field measurement, by estimation of the bed roughness and use of approximate formulae, and by hydrodynamic computer modelling (which again requires a knowledge of the bed roughness). The procedure will be given for the first two of these methods.

Procedure

- measure the current velocity in the field at a number of points in a vertical line (typically about five) near to the bed i.e., 1m and below, throughout a tidal cycle. A plot of velocity against the logarithm of height above bed for a particular instant in time should give a near straight line. The value of the shear velocity U_* is given by the reciprocal of 5.75 times the gradient of the slope. The bed shear stress is related to the shear velocity by

$$\tau_b = \rho U_*^2$$

where ρ is the density of the water at the approximate temperature and salinity.

or

- use the relationship between shear velocity and mean water velocity $\bar{U}$ given by

$$U_* = \bar{U} \cdot n \sqrt{g/h}^{1/6} \quad (\text{m-s units})$$

where n is the Manning bed roughness coefficient (typically in the range 0.018 - 0.025)

g is the acceleration of gravity

h is the depth of flow.

The bed shear stress can be calculated using

$$\tau_b = \rho u_*^2$$

where ρ is the density of the water at the appropriate temperature and salinity.

3 DEPOSITION

3.1 Introduction

As previously stated the settling unit differs in cohesive sediment from that in non-cohesive sediment. Individual particles flocculate and form flocs which can have a settling velocity large enough to settle out of the suspension. This section considers the processes of flocculation and quiescent settling, field measurements of settling velocities and settling from flowing water.

3.2 Flocculation

Flocculation of sediment particles is a well known phenomenon and is the consequence of particles sticking together as they are brought into contact with each other. Collision and cohesion are therefore the essential processes of flocculation and these factors are virtually independent of one another and are well described by Krone (1962) and Partheniades (1962).

Cohesion is understood to be determined by the attractive surface forces of clay particles. These forces are strong at short distances, but fall inversely with the seventh power of distance for spheres and inversely with the square or cube of the distance for parallel plates. Particles will cohere if these short range forces dominate the repulsive forces generated by the clouds of cations around the particles. The strength of the repulsive forces depends on the charge on the mineral surface, which is determined by the mineral composition, and by the amount and types of cations present in the suspending fluid.

Collisions of particles are the result of one of three mechanisms, namely, Brownian motion of the suspended particles, internal shear of the water, and differential settling velocities of the particles or flocs.

Brownian motion is caused by the thermal agitation of the suspending medium and results in erratic movement of small suspended particles. The frequency of

collision on a single particle, I , was described by Fuchs (1964), as

$$I = 4 k T n / (3 \mu) \quad (1)$$

where k is Boltzman's constant, T is absolute temperature, n is the number of particles per cubic centimetre and μ is the viscosity of the water.

Collisions of particles may occur due to internal shearing, or local velocity gradients in the fluid. The first treatment of flocculation in a uniform shear field was that of Smoluchowski (1917) who derived an expression for the frequency of collisions between spherical particles moving along straight parallel streamlines:

$$J = 4 n R^3 / (3 G) \quad (2)$$

where R is the collision radius (sum of radii of particles which collide) and G is the local velocity gradient.

Differential settling velocities of particles will also give rise to interparticle collision. The collisions on a settling particle per second, H , is

$$H = \pi E R^2 V n \quad (3)$$

where E is the capture coefficient and V is the relative velocity between particles.

All three of these mechanisms operate in an estuary although Krone (1972) concluded that the formation of large aggregates is predominantly due to internal shearing.

Nevertheless, the size of flocs formed by collisions from any of the three mechanisms is limited by the maximum rate of internal shear that the flocs can withstand. It is evident, therefore, that internal shearing can both promote the growth of flocs and limit their size. Hence, suspended flocs should attain a maximum size given constant conditions of internal shear. Krone (1963) derived an expression which related the maximum size of floc and shear in a laminar flow field

$$R = \frac{\tau_{\max} \cdot \Delta R}{du/dz} \quad (4)$$

where ΔR is the surface roughness of the floc and $\tau_{\max}$ is the maximum shear strength of the floc. This radius is the limiting value for two equal sized flocs to collide and adhere to each other although flocs of this size will still gather smaller ones. The order

of aggregation of a floc was shown by Krone (1963) to influence its shear strength as measured by both capillary and rotating cylinder viscometers.

More recently however, experimental and theoretical studies by Van de Ven and Mason (1977) have highlighted a fundamental weakness of the Smoluchowski theory. The presence of a particle in fact causes streamlines to deviate from straight lines and approaching particles must follow curvilinear paths rather than rectilinear as assumed by Smoluchowski. Van de Ven and Mason used a rigorous hydrodynamic analysis and found that for smooth, spherical particles in simple shear the collision efficiency was much less than unity.

An important consequence of the modernised theory, especially from a practical point of view, is the fact that the collision efficiency depends quite strongly on the particle size, whereas simple theory predicts no size dependence. Thus, as aggregates grow larger, the collision efficiency should decrease quite markedly. Gregory (1981) concluded that this may partly explain the common observations that, for a given shear rate, flocs tend to grow only to a certain limiting size, although this effect is usually explained in terms of floc break-up.

Migniot (1968) discussed flocculation and stated that within certain limits a suspension of cohesive sediment in water will flocculate more quickly with smaller elementary particles, higher concentration and greater content of flocculant salts in the water. Flocculation will considerably reduce the range of mean sinking rates from between 10^{-5} mm/sec and 10^{-1} mm/sec for elementary particles to between 1.5×10^{-1} mm/s and 6×10^{-1} mm/s for flocs, a reduction in ratios of 1 in 10000 to 1 in 4.

Peijiu (1982) analysed the primary factors affecting the flocculation of cohesive sediment and derived formulae based on dynamic equilibrium for the limiting settling velocity and equivalent floc diameter. From a consideration of the relationship between the flocculation and rheological properties of a slurry a formula for the Bingham yield stress was derived and shown to be consistent with experimental data.

3.3 Quiescent Settling

Studies of the settling behaviour of suspended mud have been conducted both in the laboratory with suspensions which had predetermined levels of concentration and salinity and in the field where undisturbed samples were obtained and immediately tested. Of the former category, early work was

carried out by the DSIR (1938), which was followed by work of McLaughlin (1959), Krone (1962) Peirce and Williams (1966) and Migniot (1968). However, it was Owen (1970 and 1972) who made the first detailed study of settling velocities of a mud. Kranck (1980) investigated the significance of flocculation, and the factors which effect flocculation, in relation to settling velocities of fine-grained sediment. More recently Leussen (1986) reported on tests carried out in a large settling column. Field studies of naturally flocculated suspended mud by Owen (1971) showed settling velocities up to ten times greater than normal methods of sampling. Other field studies have been reported by Krone (1972), Burt and Stevenson (1983), Stevenson and Burt (1985) and Puls and Kuehl (1986).

3.3.1 Laboratory

The effect of four factors on the settling velocity of mud have been studied in the laboratory experiments listed above. These were, the initial concentration of the suspended mud, the salinity of the suspending water, the depth of the settling tube and the temperature of the suspension. The DSIR Water Pollution Research Station (1938) measured the times required for equal percentage deposition in 40 ft and 4 ft settling tubes of River Mersey mud and found they were in the ratio of two to one compared to the height ratio of ten to one. Subsequent tests were made with the addition of sewage which had the effect of increasing the flocculation and hence mean settling velocities for the 4 ft column but not in the 40 ft tube. This indicated that the flocs had reached a terminal size governed by fluid shear after settling less than 40 ft.

McLaughlin (1959) performed experiments in a 95.2 mm internal diameter glass settling tube 1.2 m long in which samples were withdrawn at depths of 298, 496 and 1,113 mm. The initial concentration was 655 ppm and the settling velocity at 900 mm was found to be twice that at 600 mm.

For free settling at concentrations up to a maximum of 1000 ppm Krone (1962) found that the settling velocity is proportional to the concentration to the $4/3$ power which Krone explained by considering the probability of floc collision. Krone conducted tests to study the influence of salinity and concentration on the settling velocity and found that it was independent of salinities above 5 g/l for a concentration of 0.12 g/l and up to 20 g/l for 1.0 g/l concentration.

Peirce and Williams (1966) investigated the effect of concentration on settling velocity in the range 20000

to 500000 ppm which was well into the hindered settling zone. They compared the results to a modified form of the Richardson-Zaki equation

$$w_c = w_o \left\{ 1 - \frac{c}{p_f(1-\epsilon)} \right\}^{4.65} \quad (5)$$

where w_c is the settling velocity at concentration c
 w_o is the Stokes' settling velocity of a floc
 p_f is the floc density
 ϵ is the floc voids ratio

Peirce and Williams assumed a value of 5 for the index and plotted values of $w_c^{1/5}$ against concentration which gave two straight lines in the concentration ranges 20000 to 200000 and 200000 to 500000.

Migniot (1968) studied the effect of salinity and concentration on the settling velocity of mud and found that for low concentrations the settling velocity was constant at salinities above 3 g/l and for higher concentrations it was constant above salinities of 10 g/l. There was, however, a reduction observed in the settling velocities for salinities greater than 30 g/l.

Owen (1970) performed tests on an estuarine mud to determine the effect of concentration, salinity and depth of settling on the settling velocity. Some preliminary tests were carried out using a 9 m high settling column although the main experiments were conducted in 0.5, 1.0, 1.5 and 2 m high settling columns.

Within certain limits Owen found that increasing either salinity or concentration or both increased the settling velocity. The effect of settling depth was inconclusive in that unrepresentative results were considered to have been obtained for the 1 m high settling column. In a subsequent study, Owen (1972) found that increasing the temperature had little effect on settling velocities after allowing for changes in the viscosity of the suspending fluid. Only a slight tendency towards greater flocculation and higher settling velocities was noted.

Owen observed that hindered settling started at a concentration of around 20 g/l for a low salinity of 1.0 g/l. This term is applied to the phenomena of a reduction in settling velocity at very high concentrations due to settling of flocs being impeded by trapping water as the mass of flocs settles. As the salinity was increased the onset of the hindered settling phase occurred at a lower concentration such that at a salinity of 40 g/l hindered settling

commenced at 5 g/l. Above certain salinities Owen found that a retarded settling phase was encountered in which further increases in salinity reduced the mean settling velocities. The salinity at which retarded settling commenced varied slightly with concentrations from about 15 g/l at low concentrations of 0.1 g/l, to 40 g/l for concentrations of 4 g/l.

Kranck (1980) used a pipette analysis procedure on sodium chloride solutions and measured the concentration of particles in certain size classes using a Coulter counter. For dispersed solutions the size distribution spectra showed that particles only above a certain size were lost and that this controlling size decreased with time. However, for flocculated sediment, particles of all sizes were lost after a short period of time. From the shape of the size distribution spectra, Kranck was able to deduce that the make up of the flocs which deposited was similar to that in the original suspension. The concentration was shown to vary with time in accordance to a power law relationship with an index of $-4/3$.

Some preliminary results on the settling velocity of flocs were given by Leussen (1986). In a large settling column of height 4.0m and diameter 0.3m the concentrations at 11 sampling points were monitored over a period of time as suspensions of flocculated kaolinite were allowed to settle. Tests with initial concentrations of 1000 mg/l and 50 mg/l in both fresh water and salt water at 32 mg/l were conducted. The principal thrust of the work however was to study the effect of turbulence on the settling velocity by inserting an oscillating grid into the column. Although no results of this part of the work were presented, the basis of simulating the turbulent shear stress of a natural estuary by the energy dissipation per unit time and volume in the settling column is questionable. Krone (1986) argued that it is the local velocity gradient that controls floc growth and break up rather than the rate of energy dissipation.

3.3.2 Field

Important field measurements of the settling velocities of natural flocs in the Thames at Woolwich Ferry Terminals (HRS (1969)) were reported by Owen (1971). An instrument was developed to take undisturbed samples of suspended silt in an estuary and to determine the settling velocity of the silt flocs in their natural state. The effect of turbulence on the settling velocity was investigated by carrying out tests at various positions in the estuary during Spring and Neap tides. The results were compared with conventional methods of sampling

and laboratory testing and showed settling velocities up to ten times greater. Also, the settling velocities were found to vary linearly with concentrations during Spring tides and with the square of concentration during Neap tides. Owen at first attributed these differences to the difference in turbulent structures for the two extremes of tidal range but later considered that the results were inconclusive.

A field study by Krone (1972) involved simultaneous measurements of currents, salinities and suspended sediment concentrations at locations around an area of rapid shoaling in an estuary. It was concluded that flocculation processes were an important factor in the estuary as deposition was much faster than could be accounted for by the settling velocities of the individual particles.

Tests using the instrument developed by Owen (1971), known as the Owen tube, were conducted by Burt and Stevenson (1983) and Stevenson and Burt (1985) in the Thames estuary. Rather surprisingly, there was no significant variation in settling velocities with salinity, which varied in the range 1-30 ppt. The principal influence on the settling velocity was the concentration of suspended sediment and this relationship was found to be approximately linear.

Puls and Kuehl (1986) used an Owen tube to measure field settling velocities of flocs in the Elbe estuary, West Germany. The median settling velocity of the mud flocs was found to be proportional to the concentration raised to the power of between 2.5 and 3.0.

Although, the Owen tube was an important development it nevertheless measures the settling velocity of the flocs in the quiescent conditions of the settling column rather than their natural hydrodynamic environment. It has therefore been a common aim of researchers to determine the settling velocity of cohesive sediment in flowing water.

3.4 Settling from flowing water

The deposition of cohesive sediments from flowing water was first studied by Krone (1962) and Partheniades (1962) at the University of California, and by Postma (1962) at Delft Hydraulics Laboratory. Further work was carried out by Partheniades et al. (1966, 1968) at the Massachusetts Institute of Technology, by Kuenen (1965) at the University of Groningen in The Netherlands and later by Mehta and Partheniades (1973) at Florida University. More recently, laboratory experiments have been performed

by Kusuda et al. (1982) at Kyushu University in Japan, and at Hydraulics Research Ltd, where a major mud research facility has been commissioned (Burt and Game (1985)).

The concept of a limiting bed shear stress above which no deposition takes place, was introduced by Krone (1962) following experiments in a 0.91 m wide rectangular flume which had an active deposition length of 27.4 m. The bed was level and flow was returned by two propeller pumps which maintained flow velocities up to 0.30 m/s. Measurements were taken of suspended sediment concentration, flow velocity and time. Tests were conducted with concentrations up to 17,000 ppm of San Francisco Bay mud. Krone derived a general equation which related the suspended sediment concentration to the time from the start of an experiment.

This was given as

$$\log C = \frac{A t_c}{h} \left(\frac{n_p}{n_f} \right) \left[1 - \frac{\tau_b}{\tau_l} \right] \log \left(1 + \frac{t}{t_c} \right) + B \quad (6)$$

where C = concentration

A = constant

t_c = flocculation time

n_p = number of particles per unit volume

n_f = number of flocs per unit volume

h = depth of flow

τ_b = bed shear stress

τ_l = limiting bed shear stress

B = constant

A fraction of the suspended sediment was labelled with a radio-active tracer and Krone concluded that as this deposited faster than the sediment as a whole there must have been some interchange between the suspended and deposited fraction. This has been disputed, however, by Partheniades (1962) and Mehta (1973) who considered that the minimum velocity necessary to prevent deposition was considerably smaller than that necessary for erosion.

Although Partheniades (1962) mainly studied the rate of erosion he also carried out some tests on deposition. The tests were performed in a steel flume 18.3 m long, 0.30 m wide and 0.38 m deep with an initial concentration of 11,500ppm. Starting with a relatively high velocity he observed the change in concentration as the velocity was reduced by a small amount. An apparent equilibrium was attained and this procedure was repeated until a velocity was reached at which all the clay was deposited. The bed shear stress at this limiting velocity was observed to be

about 0.06 N/m^2 which corresponded well with Krone's work.

The first tests in an annular flume were reported by Postma (1962) in a study of the erosion and deposition of mud from Demerara. Four paddles were used to maintain the circular flow of water in the tank which had an inner diameter of 0.44 m, an outer diameter of 0.74 m and a height of 0.33 m. For initial concentrations of 11000 and 26000 ppm it was found that at velocities over 0.10 - 0.15 m/s no deposition took place. Postma also concluded that the velocity required to prevent sedimentation was considerably smaller than the critical velocity at which erosion starts.

Kuenen (1965) used two circular flumes with rotating paddles to investigate turbidity currents and clay suspension. Most of the work concentrated on very high concentrations of fluid mud although some experiments on clay suspensions indicated a minimum critical velocity below which the sediment deposited and another critical velocity above which no sediment deposited.

The first report of tests using a rotating annular flume with counter rotating ring came from Partheniades et al. (1966) who studied deposition of mud in a flume with internal and external diameters of 0.72 m and 0.91 m respectively. The channel was rotated at a constant speed and a ring, just in contact with the fluid surface was rotated in the opposite direction. Measurements were taken of the differential velocity between the channel and ring, the shear stress on the ring, the suspended sediment concentration and the temperature of the fluid. The sediment used in all experiments was a commercial kaolinite clay mixed with tap water in the first phase and with tap and distilled water in the second phase.

From plots of sediment concentration against time it was noted that a sharp demarcation occurred when the differential velocity fell below a certain value. Above this velocity an equilibrium concentration would be attained after reducing the speed of rotation from its initial high value, whereas below it the suspended sediment concentration would tend to drop to zero.

For an initial concentration of about 1000 ppm Partheniades found that contrary to Krone's assertion a plot of log concentration versus time did not yield a straight line, even at the very low concentrations of less than 300 ppm. The ratio of equilibrium concentration, C_{eq} , to initial concentration, C_0 , was shown to increase slightly with increasing initial concentration for a differential velocity of 0.644 m/s

but for a differential velocity of 0.810 m/s the ratio was virtually constant. This independence of C_{eq}/C_o with initial concentration is in agreement with the open flume studies of Partheniades (1965). Following on from this finding, Partheniades argued that no interchange of material between the bed particles or flocs and the suspended sediment took place because otherwise the equilibrium concentration would be constant and independent of initial concentration.

In an attempt to determine the controlling variable in the deposition process, Partheniades plotted the equilibrium concentrations versus the average shear stress in the channel, for one value of initial concentration, and found that the points for three depths fell on the same curve. This, however, would hold only when the channel and ring speed were adjusted according to the operating curves, i.e., when there was approximately uniform deposition across the channel.

The introduction of bed shear stress as the controlling parameter, rather than average shear stress in the channel, was later made by Partheniades et al. (1968) reporting on further tests using the annular flume. A power relationship between the bed shear stress at the centerline of the channel and the average shear stress over the channel boundary was given. Partheniades showed that the ratio C_{eq}/C_o plotted against excess shear stress yielded a straight line on a log-normal graph. Below a certain value of bed shear stress the equilibrium concentration was zero.

An explanation of the deposition process in terms of the shear strength of flocs was proposed by Partheniades in which flocs with strong enough bonds are able to withstand the high boundary disruptive stresses and eventually reach and stick to the bed. As already stated, however, this may not be the only explanation for reaching an equilibrium concentration (see Gregory (1981) in section 2.2 on flocculation).

Partheniades conducted another series of experiments to examine whether any exchange of material took place between the suspended sediment and the bed deposit. After an equilibrium concentration had been reached, the suspension was slowly flushed with fresh water until the concentration was reduced from the initial value of 983 ppm to 200 ppm. The rate at which the concentration diminished during the flushing and the quantities of sediment before and after was shown by Partheniades to suggest that no exchange took place.

Limited tests were also carried out to investigate the rate of deposition and results were presented which

showed a power relationship between concentration and time and a linear-log correlation between the relative concentration $(C_0 - C(t))/(C_0 - C_{eq})$ and time.

An extensive study of the depositional behaviour of cohesive sediments was undertaken by Mehta and Partheniades (1973) in which they investigated the rate of deposition of kaolinite and mud in an annular flume. The flume was similar to that used at MIT except that it was larger, having a mean radius of 0.76 m. It also had a false bottom which enabled direct measurement of the bed shear stress. From the early experiments Mehta showed that the ratio C_{eq}/C_0 varied solely with bed shear stress. All data lay on a single straight line on a log-normal plot of C_{eq}/C_0 and the bed shear stress parameter $(\tau_b^* - 1)/(\tau_b^* - 1)^{50}$, where $\tau_b^* = \tau_b/\tau_{bmin}$ and $(\tau_b^* - 1)^{50}$ is the geometric mean. A single value of the standard deviation of $\sigma = 0.49$ characterizes the data.

For a constant ambient water quality Mehta postulated that the physico-chemical properties of different sediment suspensions can be described by the cation exchange capacity (CEC). This is a measure of the cation adsorbing capacity of the clay minerals and it may be considered as a measure of the interparticle forces that bind the clay particles together into flocs. However, the relationship which Mehta shows between CEC and τ_{bmin} for the different sediments, in which τ_{bmin} increases with CEC, must be considered as tentative because the value of CEC of kaolinite was an assumed one.

With respect to the rates of deposition, Mehta presented numerous graphs to show that in many cases all of the deposition phase could be described by a straight line relationship between deposited sediment fraction $[C_0 - C(t)]/(C_0 - C_{eq})$ denoted by C^* , and time, t when plotted on logarithmic - normal axes. The standard deviation, σ_2 and geometric mean, t_{50} were plotted against the bed shear stress parameter, τ_b^* but other than reflecting a generally similar shape of curves provided little further understanding. In discussion, Mehta argued that flocs which are sufficiently large will be able to descend towards the bed countering the upward momentum flux due to turbulent diffusion. Close to the bed, the floc is subjected to the highest drag and hydrodynamic lift forces which are proportional to each other and vary in a stochastic nature. The probability that a floc is able to withstand the high shear stresses and become part of the bed is generally less than unity. That probability is expected to depend on the flow conditions as well as the properties of the floc.

Kusuda et al. (1982) reported on tests carried out in an annular flume identical in concept to that used by Mehta. It had a channel 0.2 m wide, 0.2 m high and 1.00 m in mean radius. No direct measurement of bed shear stress was made either by a false bottom or through the velocity profile near the bed, although the bed shear stress was calculated from the ring shear stress. The size distribution and suspended sediment concentration were measured during deposition tests on a river mud and bay mud. Equilibrium concentrations were obtained which varied consistently in magnitude with bed shear stress. During a deposition test the size distribution of the sediment was found to successively narrow in range as the larger diameter particles deposited.

Preliminary results from a study of the deposition of cohesive sediments in a large annular flume were given by Burt and Game (1985). The 'Carousel' is a 6 m diameter circular flume which has a fixed channel 0.4 m wide and 0.35 m high, and a rotating roof 0.09 m thick which floats on the fluid surface. In agreement with other researchers a critical motor speed was reported below which all the suspended sediment deposited. Furthermore, the ratio of equilibrium to initial concentration at a certain motor speed was shown to be independent of initial concentrations, which varied up to 24000 ppm.

4 CONSOLIDATION

4.1 Introduction

Suspended sediment will deposit from flowing water when the bed shear stress reduces below a certain value and flocs will settle on to the bed. Flocs are thus laid on one another and as additional material accumulates on top, the flocs are brought closer together and the pore water from inside and between the flocs is expelled. Consolidation will occur due to the self weight of the soil particles.

4.2 Consolidation of deposited sediment

Laboratory measurements have been made on consolidating mud by a number of researchers of whom the earliest were probably Work and Kohler (1940). Krone (1962) measured the profile of density after 12 days within a consolidating bed and found that density increased gradually in a linear manner with depth except for slight deviations at the surface and the bed. Krone also measured the shear strength of beds prepared with a uniform density. The consolidation process was reported by Krone to occur in two distinct phases during each of which the density varied linearly with time but at different rates. In

contrast, however, Migniot (1968) deduced a logarithmic density profile with depth and identified three phases of consolidation. The first phase was simply the mud flocs settling into a fairly open lattice and pushing the water through the lattice gaps. During the second phase Migniot considered that the lattice had closed up quite considerably and that the water was escaping relatively slowly. Finally, during the third phase the water is removed from the mud flocs by compression.

Probably the first major study of the properties of a consolidating mud was conducted by Owen (1970). Both the bed formation process during deposition and the consolidation process were studied. Tests were carried out with an initial suspension depth of 10 m in a 92 mm diameter settling column and with suspension concentrations of 1000, 4000, 8000 and 16000 ppm and salinities of 2, 4, 8, 16 and 32 g/l and fresh water. In addition a suspension of 16000 mg/l and salinity of 16 g/l was tested with initial suspension depths of 10, 7, 4.5 and 2 m respectively. The bed thickness was measured at frequent intervals as well as the shear strength of the final bed.

For the mud used by Owen, which was from Avonmouth, salinity was found to have virtually no effect on the properties measured. This was attributed to the high illite content in the mud which is a relatively inert clay mineral. Results from similar bed thicknesses were indistinguishable regardless of whether the bed was formed from a standard depth and varying concentration or a standard concentration and varying depth. During the formation process, the bed thickness increased linearly with time and the mean density of the bed was constant although its value increased with concentration. Also, the surface density of the bed was found to be constant during the formation period but was highly dependent on the bed thickness.

Using the theory given by Kynch (1952), Owen predicted that the density profile was dimensionless and constant during formation and had a wide range of densities from the surface to the bed. During the initial consolidation stage, however, the predicted density profile became more uniform but after about 4000 mins a range in density once again appeared.

At the end of each test the actual density profile was measured and it was found that there was a unique dimensionless density profile for different depths of bed. A comparison of two measured density profiles with Kynch's theory showed moderate agreement, although there was a deviation towards the base of the bed where predicted densities were higher than those

measured. This could not be explained without questioning the validity of the basic assumption of the theory which was that the local settling velocity of the mud was proportional only to the local density.

Considerable improvements were later made to the settling column apparatus used by Owen with the introduction of a Harwell radioactive transmission probe. The probe was mounted on a purpose-built frame which allowed it to be traversed up and down the column. A density-depth profile of the consolidating mud could thus be obtained (see Hydraulics Research Station 1980) without destroying the bed.

Recently, however, a substantial and continuing research program at Oxford University has greatly contributed towards the understanding of the consolidation of soft soils. Laboratory experiments have been conducted in a settling column instrumented with pore pressure transducers at specific points and a total stress transducer at the base of the column. A non-destructive X-ray attenuation technique was used to measure the density throughout the column. This enabled the calculation of effective stresses within consolidating mud to be made and theories relating to self weight consolidation were modified in the light of the empirical results.

Been and Sills (1981) reported on experiments conducted by Been (1980) as well as the large strain consolidation theory from Lee (1979) and Lee and Sills (1981). The experimental observations made by Been and Sills are believed to be unique because of the accuracy and speed of the soil density measurements. Sixteen experiments were run with initial unit weights of 10.0 to 12.0 kN/m³ and heights 643 to 1929 mm. Pore pressure measurements were made by stand pipes to begin with but transducers were used in the latter experiments. The duration of the experiments ranged from one day to one hundred days. Density profiles at instances in time during settling and consolidation were presented by Been and Sills and these illustrated differences which were dependent on the initial concentration.

For an initial unit weight of 10.7 kN/m³ four phases were found to exist for the first few hours. These were water, suspension, a loose soil and dense bed layer. A step change in the density at the suspension soil interface was noted and the density of the suspension decreased slightly as the soil phase increased in both depth and density. After 7 hours the suspension phase no longer existed and the loose soil phase beneath the water started to decrease in depth while increasing in density. Effective stresses

were present in the loose soil which consolidated slowly. On the other hand, for an initial unit weight of 11.2 kN/m^3 the suspension phase did not exist and the density of the loose soil progressively increased with time as its depth reduced.

The distribution of particle sizes within the bed was measured by Been and Sills for experiments with initial unit weights of 10.7 and 12.0 kN/m^3 and 10.2 kN/m^3 dispersed with sodium hexametaphosphate before settling. For the bed settled from the 10.7 kN/m^3 suspension a consistent trend in the particle size distribution was seen in which grading occurred to a certain extent with the coarser particles tending to settle more towards the base of the column. Most striking results were presented for the suspension with an initial unit weight of 12.0 kN/m^3 which showed no segregation of particle sizes from the top to the base of the bed. The effect of the dispersant on the suspension of 10.2 kN/m^3 was to markedly segregate the particle size which indicated that flocculation clearly influenced the settling of the suspension.

Parchure (1980) made an attempt to determine whether sorting of particles occurred in the deposition phase by sampling successive 10 mm thick layers of mud bed. On analysis these layers were each found to contain a wide range of particle sizes although a weak sorting was measured. In the light of the results of Been and Sills, which clearly indicated sorting in depositions, this could imply that the bed analysed by Parchure was perhaps too shallow for the sampling technique employed to show subtle changes in particle sizes.

An analytical solution for the general equation of self weight consolidation developed by Gibson et al. (1967) was presented by Been and Sills. The restrictions of linear relationships between the void ratio/effective stress and void ratio/permeability and a constant coefficient of consolidation were adopted. The requirement of instant deposition in a zero effective stress state was obviously not satisfied but Been and Sills argued that after a few hours the void ratio and pore pressure distributions given by the theory were similar to those of a real mud deposited from a slurry. After modification of the solution by including an imaginary overburden and the determination of the relevant soil parameters from test results the model was used to predict the density profiles during a consolidation test. Reasonable agreement was found between the theory and experiment, although, the assumption of a linear void ratio/permeability relationship was identified as a probable cause of the discrepancies.

Time dependent compression, or creep, was shown by Elder and Sills (1984) to play an important role in primary consolidation, particularly at low densities. This phenomenon was explained by considering a collapse in the soil structure rather than floc spacing decreasing causing interparticle forces to increase. Tests were also performed in a settling column to study the effect of gradual deposition. This was achieved by pumping a dense slurry into the top of a settling column at a constant rate over many hours. A very large difference was seen between the consolidation behaviour of the gradually deposited material and the instantaneously deposited material of comparable masses. The gradually deposited bed was found to take ten times longer to consolidate by a factor of two than the instantaneously deposited bed.

An extension of the work on creep was reported by Elder and Sills (1985) in which a sample of a normally consolidated bed was unloaded and then loaded again. It was seen that the respective consolidation curves were different before and after the unloading and reloading process which illustrated the effect of creep.

Burt and Parker (1984) investigated the effect of progressive deposition on the density of a natural mud bed. Fixed masses of sediment were added at 24 hour intervals to a 10 m high, 92 mm diameter settling column. A total of 7 beds were added and density profiles were measured up to 15 days after the last addition of sediment. It is concluded that a series of deposited beds will tend towards one homogenous bed with density profile similar in form to that of an individual bed.

Although the majority of work on the consolidation of muds has been laboratory orientated some studies have been undertaken to measure the in-situ pore pressures of estuarine mud beds. Field work is currently being undertaken by Sills (1986) in soft muds. As part of a major programme to study the behaviour of the cohesive sediment of the Irish Sea near Sellafield, in-situ measurements have been made of density using a nuclear back scatter probe and pore water pressure using a differential piezometer. Measurement has also been made of the shear strength of cores recovered from the sea bed as well as density and mineralogical determination. A stilling pond at the Royal Portbury Docks, Bristol has been instrumented with total stress transducers, both vertical and horizontal, and pore pressure and water height measurements. Sediment will deposit on and around these instruments and the development of the bed will be monitored. It is intended that in-situ density profiles will be obtained.

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It is important, however, to recognise the value of field work in the understanding of self weight consolidation. Theories which are evolved from theoretical and empirical considerations will be enhanced many times over if their predictions are found to correlate well with actual bed measurements. But, field work in an estuarine mud subject to possible continual erosion and deposition requires considerable effort if reliable data are to be obtained.

5 EROSION

5.1 Introduction

In a muddy estuarine environment there is a portion of the bed which is periodically resuspended. This upper bed is usually very soft with a high water content and is only partially consolidated. It is stratified with respect to cohesion and density variations with depth and is usually too soft to enable the use of standard shear tests for measuring cohesive shear strength. Beneath this upper layer which may have a depth in the order of 0.1 - 1.0 m there is a portion of bed which has comparatively uniform properties. Previous research can also be broadly divided into two categories by the nature of bed investigated. The first category relates to beds deposited from quiescent or low flow conditions and the second category to beds formed from a thick slurry or remoulded with, in some cases, additional compaction. Accordingly, the general form of expressions to describe the rate of erosion differ for the two types of bed.

5.2 Erosion of freshly deposited sediments

Krone (1962) performed experiments in which he measured the concentration and time during the erosion of mud which had previously been deposited from suspension. He suggested that as the concentration increased, the amount of material re-deposited increased, a point supported by his radioactive tracer work. However as previously stated, this phenomena was checked by Partheniades (1962) by replacing the sediment-laden recirculating water with fresh water during an experiment and observing the erosion rates. No difference was found in the rates of erosion before and after changing the water and he could only explain the results of Krone by stating that the respective experiments were not carried out in the same flume.

Critical shear stresses below which no erosion took place, were calculated by Krone by extrapolating the test results and these indicated that a bed deposited from flowing water had a higher critical shear stress

than one deposited from still water. This was attributed to more selective bonding in the case of flowing water as the flocs which settle to the bed will have resisted the high shearing stresses near the bed, and hence, will be stronger than those deposited from still water.

Partheniades conducted erosion tests on two beds which had a macroscopic shear strength in the ratio of 100 to 1. Surprisingly, he found that the minimum velocity at initiation of scour was similar and that the rates of erosion were of the same order of magnitude. He also found that the erosion rates depended on average shear stress, increasing rapidly after a critical value had been exceeded. A theory based on probability was proposed which had the general form

$$\epsilon = K \left\{ 1 - \frac{1}{\sqrt{2\pi}} \int_{-B-C}^{B-C} \exp\left(-\frac{w^2}{2}\right) dw \right\} \quad (7)$$

in which ϵ is the rate of erosion, K , B and C are flow dependent variables and w is a dummy variable.

By analysis of the suspended sediment during an erosion test, Partheniades concluded that the proportion of silt to clay fraction remained the same, which implied that both types of particles were eroded. The striking erosion pattern observed during the tests led Partheniades to deduce that the structure of turbulence must be an important parameter in erosion. The maximum depth of erosion occurred in the centre of the flume with the bed shear stress in the eroded groove lower than the rest of the bed. This could only be explained by the higher turbulence at the centre of the flume.

Erosion studies were performed by Migniot (1968) on beds which had consolidated by different amounts and with muds from a variety of sources. He was primarily interested in the critical shear stress for erosion and he attempted to correlate this with physical properties of the bed. In particular, the initial rigidity of the mud bed, which was measured by recording the torque necessary to move a rotor around which the mud had consolidated, was used by Migniot to give an estimate of the critical shear stress.

Owen (1975) conducted tests in a re-circulating flume to study the erosion of Avonmouth mud beds naturally deposited from quiescent suspensions. The erosion of the bed was examined for muds at two different densities and salinities. In line with other researchers work, Owen also found that a critical shear stress existed. For bed shear stresses below this critical value, erosion ceased after a certain

period which was identified by an equilibrium being attained in the suspended sediment concentration. At bed shear stresses above the critical value erosion was found to continue indefinitely. It appeared that the equilibrium was governed by the strength profile of the bed in that erosion proceeded until a layer of mud was exposed which was sufficiently strong to resist further erosion at that applied shear stress. At shear stresses above the critical value, the rate of erosion increased linearly with applied stress. Although, the values of critical shear stress showed only small differences for the different densities and salinities, the slope of the linear relationships differed substantially, with the rate of erosion being much less both for the beds of higher density and higher salinity.

Laboratory tests were performed by Lonsdale and Southard (1974) in a recirculating flume in which the threshold velocities for erosion were measured for a red clay slurry. Different water contents were investigated and it was found that for water contents above 67.5% erosion was initiated by surface erosion, whereas, at lower water contents the bed failed as the macroscopic shear strength was exceeded. In field tests, Young and Southard (1978) measured the critical shear velocity for erosion of sea bed muds in-situ. Values for the critical shear velocity ranged from 0.32 to 0.84 cm/s, although, muds re-deposited in the laboratory flume had shear velocities greater by a factor of two.

Fukuda and Lick (1980) tested three sediments representative of Lake Erie to determine the influence of water content and mineral size and composition on the initial rate of erosion and equilibrium concentrations. Beds were deposited in quiescent conditions into an annular flume and allowed to consolidate for periods of 1 to 10 days. The authors considered that the equilibrium concentration was due to an equilibrium between the rates of erosion and deposition, although it has been shown by a number of researchers that the bed shear stress required to initiate erosion is high enough to prevent any deposition of sediment. However, the initial rate of erosion was found to increase logarithmically with increasing low values of applied shear stress and linearly with higher values of applied shear stress.

Three different muds were tested by Thorn and Parsons (1980) in the re-circulating flume previously used by Owen (1975), and in a 10 m high settling column also used by Owen (1970). The dimensionless density depth profiles of the three muds (Brisbane, Grangemouth and Belawan) were found to be similar. From the tests, the critical shear stress, τ_c for the initiation of

erosion was measured at various depths through the beds. The relationships between critical shear stress and density of the mud surface were all found to follow similar power laws. Erosion rates were calculated as a function of the excess bed shear stress ($\tau_b - \tau_c$) for time steps of 10, 20 and 30 mins and these were seen to be reasonably similar. However, another mud tested later by Thorn (1981) gave quite a different relationship between critical or equilibrium shear stress and bed surface density compared with the three previous muds. The rates of erosion at various time steps for the Scheldt mud showed significant differences when compared with the group relationship for the earlier three muds.

It is important to realise that in the tests conducted by Owen (1975), Thorn and Parsons (1980) and Thorn (1981) the surface density of the mud sample being eroded was not directly measured, but inferred from an assumed dimensionless density depth profile of the mud settled in the 10 m settling column. There is little evidence to support this assumption and indeed the work of Been and Sills (1981), Hayter and Mehta (1982) and Parchure (1984) add weight to the argument that it may be an invalid assumption.

The data of the four muds tested by Thorn together with data from erosion tests on a Mersey mud were re-analysed by Puls (1984) working at Hydraulics Research Ltd. Three forms of expressions for the erosion rate versus absolute excess shear stress ($\tau_b - \tau_{cr}$) and normalised excess shear stress $(\tau_b - \tau_{cr})/\tau_{cr}$ were tested against the data. It was found that the best fit was a power law relationship between rate of erosion and excess shear stress which gave regression coefficients in the range 0.73-0.87 for the five muds. Although the index and constant varied considerably for each mud, for all muds taken together the value of the index was 1.00 and the constant was 1.98. Puls also fitted a linear relationship which gave a constant of 4.31 for all the muds which had a much lower regression coefficient of 0.62.

Kusuda et al. (1982) working in conjunction with the University of Florida investigated the erosion of deposited kaolinite beds in the annular flume used by Mehta (1973). The critical shear stress was found to increase as the void ratio decreased and its value was found to be approximately twice that of the Bingham yield stress. A power law relationship was shown to exist between the initial rate of erosion and the normalised excess shear stress $(\tau_b/\tau_c - 1)$.

Work carried out at the University of Florida on the study of erosion was first reported by Mehta and

Partheniades (1979). Following on from this, Yeh (1979), Parchure (1980), Dixit (1982) and Parchure (1984) have all reported studies on the erosional behaviour of kaolinite and mud in both an annular flume and a re-circulating flume. Virtually all the beds used in the tests had been deposited from a suspension in static or slow flowing water. The exception was a placed bed used by Mehta and Partheniades. The tests showed that erosion continued indefinitely in a uniform bed, whereas, in a deposited stratified bed erosion ceased when the bed surface could resist the bed shear stress and not because of an equilibrium between erosion and deposition.

Similar trends were also seen for deposited kaolinite beds in a long recirculating flume by Yeh (1979). A device for measuring the in-situ density of a deposited bed was described by Parchure (1980). Tests conducted by Dixit (1982) in a long flume showed that the characteristic bed shear stress increased with increasing time of consolidation up to 120 hours after which increasing the consolidation to 240 hours gave no further change. The relationship between erosion rate and the normalised excess shear stress was expressed as an exponential function

$$\varepsilon = \varepsilon_0 \exp \left(\alpha (\tau_b - \tau_s) / \tau_s \right) \quad (8)$$

in which the two coefficients, α and ε_0 , were found to be independent of the consolidation time.

An extensive series of tests were undertaken to study the erosion of kaolinite and a lake mud in an annular flume by Parchure (1984). The effects of salinity and micro-organisms on the critical shear strength and the rates of erosion were investigated for beds deposited from suspension. The density depth profiles of the beds were measured and were found to follow exponential relationships. The profiles of the different beds did not, however, have similar magnitudes even when expressed in dimensionless terms of mean-bed density and initial thickness.

Unlike the approach followed by Migniot (1968), Lambermont and Lebon (1978), and Thorn and Parsons (1980) which consisted of using a correlation between bed density and the bed shear strength, Parchure considered that the results of Krone (1962), Partheniades (1962), and Christensen and Das (1973) showed that it was not reliable to make such a correlation.

Measurements were taken by Parchure of the critical shear strength of the beds which were found to vary in the range 0.04 - 0.17 N/m². Salinity increased this shear strength rapidly for salinities in the range 0

to 2 ppt, but above 10 ppt the effect was negligible. The critical shear stress of the top layer of mud was found to be constant for consolidation times of 1 day to 10 days, although lower layers were found to increase. This was explained by the lack of overburden on the surface which prevented the flocs from crumbling and reducing their order aggregation and increasing their shear strength. It is interesting to compare this with the approach of Been and Sills (1981) who added an imaginary overburden to the surface of the soil in their theoretical analysis to take account of the increase in density of the surface during consolidation.

From the shear strength - depth profiles of the beds, Parchure proposed a three zoned structure common to the beds tested. The three zones have the upper boundaries of the critical shear stress, the characteristic shear stress and the maximum shear stress respectively. The depth at which the characteristic shear stress occurs was identified by a sharp reduction in the rate of increase in shear strength with depth.

Parchure carried out a flushing experiment in which the suspension was very slowly replaced with fresh water while the flume was rotating after an equilibrium concentration had been attained during an erosion test. The subsequent minimal increase in the concentration of the fresh water gave further support to the argument that the equilibrium concentration is not an equilibrium between the rate of deposition and the rate of erosion.

Consideration of all the results of the erosion tests led Parchure to express the rate of erosion as an exponential function of the square root of excess shear stress. This had the form

$$\epsilon = \epsilon_f \exp [\theta (\tau_b - \tau_s)^{\frac{1}{2}}] \quad (9)$$

where ϵ_f is the average floc erosion rate which is defined as the rate of erosion after the major erosion has ceased and is a result of a stochastic nature of the erosion process. The factor θ is shown to be inversely proportional to absolute temperature, and by analogy with the rate process expressions Parchure regarded θ to also be proportional to $(\tau_b - \tau_s)^{\frac{1}{2}}$. However, the data were widely scattered for this relationship with some data lying an order of magnitude off the line in terms of erosion rate. Other researchers' data were reanalysed by Parchure but considerable differences in the floc erosion rate, ϵ_f and the factor θ were found.

Some experiments using micro-organisms in two kaolinite beds in tap water were also conducted by Parchure. These tests showed that the critical shear stress was substantially increased and the rate of erosion reduced with the introduction of micro-organisms.

It is perhaps worth mentioning however that some of the differences in rates of erosion of muds given by researchers may be attributed in part to the different approaches taken in evaluating the bed shear stress, τ_b .

With the exception of direct velocity measurements by Burt and Game (1985) in the Carousel mud flume, other researchers have derived the bed shear stress from energy slopes in recirculating flumes or total shear stress in annular flumes. Measurement of the bed shear stress through a false floor by Parchure (1984) in the annular flume is still not totally satisfactory. It is becoming more generally accepted that non destructive measurement of the velocity field is important if the correct interpretation of experimental data is to be made.

5.3 Erosion of mud beds by waves

The importance of waves as an eroding mechanism of soft soils has long been appreciated. However, consideration of the physical processes is complicated by the complexity of the mud bed response. Changes in the characteristics of surface waves due to mud motion, wave energy dissipated in the mud and the erosion of the mud are all interlinked. Hence, the estimation of shear stress at the bed surface for the purpose of correlation with the rate of erosion should not be based on the assumption of a rigid bed. Further complexities arise out of the influences of the physico-chemical properties of the sediment and the fluid, the non-Newtonian rheological behaviour of mud and the effects of wave loading and consolidation on the structure of the bed.

In a recent review of wave resuspension of muds, Maa and Mehta (1985) described four types of mud behaviour which have been considered by researchers; viscous fluid, elastic, viscoelastic and viscoplastic.

Dalrymple and Liu (1978) used an approach in which both the fluid and mud were assumed to be viscous fluids. Their linearized analytic solutions to the equations of motion were compared with the experimental results of Gade (1958) and found to give good agreement.

Models based on the principle of the elastic behaviour of mud have been considered by Mallard and Dalrymple (1977) and, in a modified form to include a soil inertia term, by Dawson (1978). This method led to the prediction that water wave length decreases relative to the rigid bed solution due to the elastic nature of the bed, although as Maa and Mehta state, this was contrary to the laboratory data of Nagai et al. (1983). Also, due to the assumed elastic behaviour of the mud, wave dissipation could not be taken into account in this analysis.

Kolsky (1963) presented linearized equations of motion for a small disturbance in an incompressible viscoelastic material based on the analogy of the spring-dashpot system. A theoretical study of wave attenuation in a two layer system in which the viscosity of the upper layer is ignored and the lower layer, i.e. mud, is treated as viscoelastic, was given by Macpherson (1980). Through transformation of Kolsky's equations, Macpherson derived an expression similar to the Navier-Stokes equations of motion but with a complex viscosity term. The same assumptions with respect to the behaviour of the water and mud were made by Hsiao and Shemdin (1980) but they solved Kolsky's equations directly by assuming the existence of a stream function for the mud bed.

A viscoplastic or Bingham plastic material is characterised by a yield strength. Such a material can withstand a shear stress up to a critical value, above which it is a fluid and the viscous shear stress is proportional to the excess shear above the yield strength. However, at low rates of deformation many muds show a marked difference from the Bingham plastic behaviour. A mud tested by Faas (1981), for example, gave viscosities in the range 1-10% of its initial value as the rate of shear was increased, as opposed to a constant viscosity characteristic of the Bingham plastic behaviour. Williams and James (1978) also found similar pseudoplastic behaviour in two muds tested for the Hydraulics Research Station.

Maa and Mehta reported that few researchers have studied in detail the motion of a mud bed under the action of waves. Migniot (1968) showed that the maximum horizontal and vertical displacements in the mud decreased rapidly with depth and with the degree of consolidation. The results of both Shuckman and Yamamoto (1982) and Nagai et al (1983) are in agreement, at least in qualitative terms, with those of Migniot.

Two long term, time dependent characteristics of bed behaviour were noted by Maa and Mehta; degradation of shear strength or 'soil softening' (Thiers and Seed

(1968) and Schuckman and Yamamoto (1982)), and the potential for mud liquefaction (Turcotte et al, (1984)).

Alishahi and Krone (1964) probably conducted the first experimental study of waves over mud. The waves were wind generated and the mud was from San Francisco Bay. They demonstrated the existence of critical wave-induced shear for suspension of the bed surface. Jackson (1973) conducted tests on a mixture of clay, silt and some fine sand on a sloping beach. For small orbital velocities, in the range 0.12-0.15m/s, Jackson observed that there was little erosion, whereas, at orbital velocities greater than 0.20 m/s mass erosion occurred.

A time-concentration variation in which the concentrations asymptotically approached a certain value was reported by Thimakorn (1980) from tests with mechanically generated progressive waves over an estuarial mud bed.

Maa and Mehta also presented a theoretical model in which the upper layer was considered as a viscous (Newtonian) fluid and the lower layer to be viscoelastic. The model was applicable to cases in which the strains can be assumed to be small in the mud layer. A comparison between measurements in the mud layer by Nagai et al. (1983) and the prediction of the model, although being somewhat simplistic, appeared to give a reasonable prediction of the characteristics of mud motion. The purpose behind the development of the model was to use it, in conjunction with a laboratory study of resuspension by waves, to estimate the interfacial stress and to evaluate wave attenuation.

5.4 Erosion of remoulded soils

Christensen and Das (1973) conducted tests on remoulded kaolinite and grundite samples to investigate the effect on the rate of erosion of test duration, tractive stress, moisture content and temperature of the water. The experimental method adopted involved lining a 102mm long, 25.4mm diameter brass tube with a clay sample 3mm thick. Water was passed through the centre of the tube at Reynolds numbers of 4000-8000.

The rate of erosion varied with time during each of the tests but followed a consistent trend which had three stages. In the first stage the erosion rate decreased with time, then it became constant during the second stage, and finally, in the third stage the rate of erosion rapidly increased as the clay surface quickly deteriorated. This entire process was likened by Christensen and Das to the creep behaviour of

cohesive soils at stress levels large enough to eventually cause failure. Curves showing the steady state rate of erosion against tractive shear stress demonstrated that the rate of erosion rapidly increased beyond a certain critical shear stress for each soil. Stresses above the critical value lead to severe erosion of the clay surface in a short period of time.

Variations in density of the samples produced results which illustrated that decreasing the density of the samples reduced the erosion rates. This is contrary to many other researchers conclusions but was attributed to the greater surface smoothness of the less dense samples due to their higher moisture content.

Temperature effects were found to be significant with the erosion rate increasing considerably with increasing temperature. For example, an increase in temperature of 30°C is seen to increase the rate of erosion for the kaolinite sample by more than an order of magnitude. Following Mitchell (1969), who considered bonding mechanisms and the strength of soils in terms of rate process theory, expressions were given by Christensen and Das based on the assumption that the mechanism for erosion is similar to that of creep. Allowing for the differences in shear strength between the experiments, the authors concluded that the rate process theory is applicable to erosion. However, the values of the experimental activation are substantially lower than those obtained for creep, although some of this discrepancy may be accounted for by the accuracy of temperature control and the crude method for the calculation of experimental activation.

Lambermont and Lebon (1978) obtained the solution for the stationary erosion flux under a constant shear stress. Empirical relationships between the density and yield shear stress after Migniot (1968), and density profile through the sediment layer after Fujita (1962) were used. Also, the assumptions that the critical shear stress is uniquely related to the yield stress and that the settling velocity in viscous sublayer becomes negligible because the particles are deflocculated, were necessary for the solution. To apply the equations, two experimental values of erosion flux and shear stress were required. Unfortunately, the example given in which the solutions were compared with data from experiments by Partheniades (1965) apparently depict the graph of only the original experimental data points and fitted curves.

Sargunam et al. (1973) reported tests performed on 76mm diameter specimens at various applied fluid shear stresses in a rotating cylinder apparatus. The erosion rates were shown to vary linearly with shear stress. Further tests using the same apparatus by Ariathurai and Arulanandan (1978) lead to the adoption of an expression for the rate of erosion in terms of the normalized excess shear stress. Graphs were presented which depicted the effect on the coefficient in the erosion expression of cation exchange capacity, concentration at low sodium adsorption ratio, sodium adsorption ratio and temperature. For over 200 tests, and with few exceptions, the value of the coefficient was in the range 0.003-0.03 g/cm²/mm.

Raudkivi and Hutchinson (1974) carried out a study in a flume to evaluate the effects of salinity and temperature on erosion of kaolinite. Although their data showed considerable scatter, the plots of erosion rate versus temperature were 'U' shaped. In an attempt to explain this unusual shape the authors decided to draw upon the rate process theory as an analogy.

Kelly and Gularte (1981) also applied the rate process theory to the erosion of a cohesive soil. Following Mitchell (1964 and 1968), and Andersland and Douglas (1970) expressions for the experimental activation energy E, and the experimental flow volume V_f, were given as

$$E = \frac{RT_2T_1}{T_2 - T_1} \ln \left(\frac{\epsilon_2 T_1}{\epsilon_1 T_2} \right) \quad (10)$$

and

$$V_f = \frac{2kT}{(\tau_2 - \tau_1)} \ln \left(\frac{\epsilon_2}{\epsilon_1} \right) \quad (11)$$

These expressions are completed analogous to those used in studies of soil creep, except that the stress τ is the average bed shear stress and the rate ϵ is the erosion rate. Experiments were conducted in a refrigerated recirculating water tunnel which had a working section 3m long and 152mm square in cross section. Results were presented which illustrated linear relationships between erosion rate, inverse of absolute temperature, and erosion rate and shear stress. The critical shear stress was shown to significantly increase with increasing salinity (2.5 - 10ppt), and to decrease slightly with increasing moisture content. Kelly and Gularte compared their results with earlier studies and concluded that the rate process theory could be applied qualitatively to describe surface erosion, although the values of

experimental activation energies for erosion were lower than those for soil creep.

Gularte et al. (1979) compared the results of the erosion tests with the Bingham yield stress obtained from vane and standard viscometer tests for an illitic silt material. The effects of water content and salinity on the critical shear stress for erosion and the Bingham yield stress were determined. A reduction in the water content increased both the critical and yield stresses. However, the size of this increase was measured in orders of magnitude for the Bingham yield stress, whereas, the critical shear stress changed by only a factor of two for the range of water content examined. Increasing salinity was found to increase the critical shear stress, although, it had no effect on the Bingham yield stress.

A direct comparison of critical shear stress and Bingham yield stress for four values of salinity in the range of 2.5 to 10.0 ppt showed four straight lines of increasing gradients from 1.0×10^{-4} to 2.8×10^{-4} . For a deposited bed, Kusuda (1982) quoted on average a gradient of 2. This difference may be attributed to the differences in the Bingham yield stresses which were up to four orders of magnitude greater in Gularte's tests.

Consolidated cohesive sediments, with unconfined compressive strengths up to 70 kPa, were eroded in a unidirectional flow generated in a flume tunnel by Kamphuis and Hali (1983). The critical shear stress, although only measured when erosion had been visually determined to have commenced, is shown to vary linearly with unconfined compressive strength, vane shear strength and consolidation pressure.

6 FUTURE RESEARCH NEEDS

From the work presented in the literature review and summarised in the engineering guide it is evident that there exists gaps in the present level of knowledge in certain areas of cohesive sediment behaviour. These are identified below together with a brief outline of the necessary work which should be undertaken to improve the level of knowledge.

6.1 Deposition

It is apparent that even though deposition of sediment from a suspension does occur at bed shear stresses greater than the critical stress, τ_{cd} , below which all the sediment eventually deposits, the equation used in determining the rate of deposition in flowing water (see Section 2.2.3) does not take this into account. The probability, p , in the equation

$$\frac{dm}{dt} = -p C w_{50}$$

takes the values between 0 and 1 according to the equation

$$p = (1 - \tau_b / \tau_{cr}) \text{ for } 0 < \tau_b < \tau_{cr}$$

At bed shear stresses greater than τ_{cr} no deposition is assumed to take place.

It is important, therefore, to study the amount and rate of deposition in relation to the bed shear stress more closely and to formulate a better equation to describe the rate of deposition in flowing water.

Furthermore, the rate of deposition during a time-varying bed shear stress pattern warrants urgent consideration as this would more closely represent the real behaviour of suspended sediment in a tidal environment.

6.2 Consolidation

There is a strong need for a better understanding of the initial consolidation of relatively small deposited beds (typically 50mm thick) in relation to the increase in density over the first couple of days. Equally as important is the lack of information on the consolidation of successive deposits of sediment from suspension.

Both of these areas of need would benefit from a series of tests conducted in a laboratory settling column with the facility for the non-destructive measurement of density throughout the bed.

6.3 Erosion

The erosion of a recently deposited sediment in relation to the tidal cycle and time-varying bed shear stress is an important area which is in need of research. In an estuary there may be a continual cycle of deposition, partial consolidation and re-erosion of cohesive sediment. It is thus crucial that experiments are conducted which may enable the erosion of partially consolidated beds to be more thoroughly understood and to some extent quantified.

6.4 Sand fraction

The behaviour of cohesive sediment in respect of deposition, consolidation and erosion will be influenced by the amount of sand present in the sediment. It would be useful from an engineering viewpoint if some understanding of the likely behaviour of cohesive sediment containing a proportion of sand could be realised.

7 REFERENCES

1. Alishahi M R and Krone R B. "Suspension of Cohesive Sediment by Wind-generated Waves", Technical Report HEL-2-9, Hydraulic Engineering Laboratory, University of California, Berkeley, California, August, 1964.
2. Andersland O B and Douglas A G. "Soil Deformation Rates and Activation Energies", *Geotechnique*, Vol 20, No 1, 1970, pp 1-16.
3. Allersma E. "Mud in Estuaries and along coasts", *International symposium of River sedimentation*, Beijing, China, March 1980.
4. Ariathurai R and Arulanandan K. "Erosion of Cohesive Soils", *Journal of the Hydraulics Division, ASCE*, Vol 104, No HY2, February, 1978, pp 279-283.
5. Been K and Sills G C. "Self-weight Consolidation of Soft Soils: An Experimental and Theoretical Study", *Geotechnique*, Vol 31, No 4, pp 519-535. 1981.
6. Burt T N and Game A C. "The Carousel: commissioning of a circular flume for sediment transport Research", *Hydraulics Research*, Wallingford, England, Report No SR 33, January 1985.
7. Burt T N and Game A C. "Deposition of fine sediment from flowing water: An investigation of dependence on concentration", *Hydraulics Research*, Wallingford, England. Report No SR 27, February 1985.
8. Burt T N and Stevenson J R. "Field settling velocity of Thames mud," *Hydraulics Research Ltd*, Wallingford, England. Report No IT 251, August 1983.
9. Burt T N and Parker W R. "Settlement and density in beds of natural mud during successive sedimentation", *Hydraulics Research Ltd*, Wallingford, England. Report No IT 262. March 1984.
10. Christensen R W and Das D M. "Hydraulic Erosion of Remolded Cohesive Soils" Special Report 145, Highway Research Board, Washington, DC, 1973, pp 8-19.
11. Dalrymple R A and Liu P L-F. "Waves over Soft Muds : A two-layer Fluid Model", *Journal of*

Physical Oceanography, Vol 8, Nov 1978,
pp 61-82.

12. Dawson T H. "Wave Propagation over a Deformable Sea Floor", Ocean Engineering, Vol 5, 1978, pp 227-234.
13. DSIR. "Estuary of the River Mersey", Water Pollution Research, Tech - Paper No 7, HMSO, London, 1938.
14. Dixit J G, Mehta A J, and Partheniades E. "Redepositional Properties of Cohesive Sediments Deposited in a Long Flume", Report No UFL/COEL-82/002, Coastal and Oceanographic Engineering Department, University of Florida, Gainesville (FL), August 1982.
15. Einstein H A and Krone R B. "Estuarial sediment transport patterns", Journal of the Hydraulics Division. Proceedings of the American Society of Civil Engineers. HY2 March 1961. pp 51-59.
16. Einstein H A and Krone R B. "Experiments to determine Modes of Cohesive Sediment Transport in Salt Water", Journal of the Geophysical Research, Vol 67, No 4, April 1962, pp 1451-1461.
17. Elder D McG and Sills G C. "Time and stress dependant compression in soft sediments", ASLE Symposium on prediction of validation of consolidation, October 1984.
18. Elder D McG and Sills G C. "Thickness and Consolidation of sediment due to selfweight", Engineering Foundation Conference. Sea Island G A February 1985.
19. Etter R J, Hoyer R P, Partheniades E and Kennedy J F. "Depositional behaviour of Kaolinite in turbulent flow", Journal of the Hydraulics Division, Proceedings of the American Society of the Civil Engineers, Vol 94, No HY6, November 1968.
20. Faas R W. "Rheological characteristics of Rappahannock Estuary Muds, South Eastern Virginia, USA, " in : Holocene Marine Sedimentation in the North Sea Basin, IAS Special publication, Vol 5, 1981, pp 505-515.
21. Fuchs N A. "The Mechanics of Aerosols", Pergamon, New York, 1964.
22. Fujita H. "Mathematical Theory of Sedimentation Analysis", Academic Press, New York, 1962.

23. Fukuda M K and Lick W. "The Entrainment of Cohesive Sediments in Freshwater", Journal of Geophysical Research, Vol 85, No C5, May 1980, pp 2813-2824.
24. Gade H G. "Effects of Nonrigid, Impermeable Bottom on Plane Surface Waves in Shallow Water", Journal of Marine Research, Vol 16, December, 1958, pp 61-82.
25. Gibson R E, England G L and Hussey M J L. "The Theory of One Dimensional Consolidation of Saturated Clays. I. Finite non-linear Consolidation of thin homogenous layers", Geotechnique 17, No 3, 1967, pp 261-273.
26. Gregory J. "Flocculation in Laminar Tube Flow", Chemical Engineering Science, Vol 36, No 11, 1981, pp 1789-1794.
27. Gularte R C, Kelly W E and Nacci V A. "Rheological Methods for Predicting Cohesive Erosion", 15th Annual Conference of the Marine Technology Society, New Orleans USA Ocean Energy, 1979.
28. Harrison A J M and Owen M W. "Siltation of fine sediments in Estuaries", 14th Conference. Paris 1971.
29. Hayter E J and Mehta A J. "Modelling of Estuarial Fine Sediment Transport for Tracking Pollutant Movement", Final Report No UFL/COEL-82/009. Coastal and Oceanographic Engineering Department, University of Florida, December 1982.
30. Hsiao S V and Shemdin O H. "Interaction of Ocean Waves with a Soft Bottom", Journal of Physical Oceanography, Vol 10, No 4, April 1980, pp 605-610.
31. Hydraulics Research Station. "River Scheldt surge barrier", Report No EX 928. November 1980.
32. Jackson J R. "A model Study of the Effects of Small Amplitude Waves on Resuspension of Fine-grain Cohesive Sediments", M.S Thesis, University of New Hampshire, Durham, New Hampshire, 1973.
33. Kamphius J W K and Hall K R. "Cohesive material Erosion by Unidirectional Current", Journal of Hydraulic Engineering, Vol 109, No 1, January 1983.

34. Kelly W E and Gularte R C. "Erosion Resistance of Cohesive Soils", Journal of the Hydraulics Division, ASCE, Vol 107, No HY10, October 1981, pp 1211-1224.
35. Kolsky H. "Stress waves in Solids", Dover Publications, New York, 1963.
36. Kranck K. "Experiments on the significance of flocculation in the settling of fine-grained sediment in still water", Canadian Journal of Earth Science, 17, pp 1517-1526, 1980.
37. Kranck K. "Particulate matter grain-size characteristics and flocculation in a partially mixed estuary", Sedimentology. 1981, 28, pp 107-114.
38. Krone R B. "Flume Studies of the Transport of Sediment in Estuarial Shoaling Processes", Final Report. Hydraulic Engineering and Sanitary Engineering Research Laboratory, University of California, Berkeley (CA), 1962.
39. Krone R B. "A study of Rheologic Properties of Estuarial Sediments", Technical Bulletin No 7, Hydraulic Engineering and Sanitary Engineering Research Laboratory, University of California, Berkeley (CA), September 1963.
40. Krone R B. "A Field Study of Flocculation as a Factor in Estuarial Shoaling processes", U.S Army Corps of Engineering, Comm. Tidal Hydraulics, Technical Bulletin, No 19, 1972.
41. Krone R B. In discussion on "Laboratory experiments on the settling velocity of mud flocs", by Van Leussen. 1986.
42. Kuenen, Ph H. "Experiments in Connection with Turbidity Currents and Clay Suspensions", 17th Symp. Colston. Res. Soc. Proc. University of Bristol, Butterworths, London. 1965, pp 47-74.
43. Kusuda T, Koga K, Yorozu H and Awaya Y. "Density and settling velocity of flocs", Reprint from the memoirs of the Faculty of Engineering, Kgushu University, Vol 41, No 3, 1981.
44. Kusuda T, Urnita T, Koga K, Yorozu H and Awaya Y. "Depositional process of fine sediments", Wat. Sci. Tech. Vol. 14, Capetown, 1982, pp 175-184.
45. Kynch G J. "A theory of Sedimentation", Trans. Faraday Soc. 48, 1952, pp 166-176.

46. Lambermont J and Lebon G. "Erosion of Cohesive Soils," Journal of Hydraulic Research, Vol 16, No 1, 1978, pp 27-44.
47. Lee D Y. "Resuspension and Deposition of Lake Erie Sediments," Thesis presented to the Case Western Reserve University, Cleveland Ohio, in 1979, in partial fulfilment of the requirements for the degree of Master of Science.
48. Lee K and Sills G C. "The Consolidation of a Soil Stratum, including self-weight effects and large-strains", Numerical and Analytical Meth. Geomec. In press. 1981.
49. van Leussen W. "Laboratory experiments on the settling velocity of mud flocs". Third International Symposium on River Sedimentation, Jackson, Mississippi, USA. March 1986.
50. Lonsdale P and Southard J B. "Experimental Erosion of North Pacific Red Clay", Marine Geology, Vol 7, 1974, pp 51-60.
51. Maa P T and Mehta A J. "Considerations on Bed Response on Wave Resuspension of Muds", Paper Presented at the Symposium on Circulation Patterns in Estuaries, Virginia Institute of Marine Science, Gloucester Point, Virginia, January 1985.
52. Macpherson H. "The Attenuation of Water Waves over a Non-rigid Bed", Journal of Fluid Mechanics, Vol 98, Part 4, 1980, pp 721-742.
53. McLaughlin R T. "The settling Properties of Suspensions", Proc. ASCE, Vol 85, HY 12, December 1959, pp 9-41.
54. Mallard W W and Dalrymple R A. "Water Waves Propagating over a Deformable Bottom", Proceedings of the 9th Offshore Technology Conference, Vol 3, Houston, Texas, May 1977, pp 141-146.
55. Mehta A J. "Characterization of cohesive sediment properties and transport processes in Estuaries", Proceedings workshop. Cohesive sediment dynamics. Springer-Verlag, USA, 1985.
56. Mehta A J and Chung-Po Lin. "Sediment driven density fronts in closed-end canals." Paper presented at the symposium on physics of shallow water estuaries, University of Miami, Florida, Sept 1984.

57. Mehta A J and Partheniades E. "Depositional Behaviour of Cohesive Sediments", Technical Report No 16, Coastal and Oceanographic Engineering Laboratory, University of Florida, Gainesville (FL), March 1973.
58. Mehta A J and Partheniades E. "An Investigation of the Depositional Properties of Flocculated Fine Sediments", Journal of Hydraulic Research, Vol 13, No 4, December 1975, pp 361-381.
59. Mehta A J and Partheniades E. "Kaolinite Resuspension Properties", Journal of the Hydraulic Division, ASCE, Vol 105, No HY4, April 1979, pp 409-416.
60. Mehta A J and Partheniades E, "Resuspension of deposited cohesive sediment beds", Proceedings of Eighteenth Coastal Engineering Conference, South Africa, Nov 1982, pp 1569-1588.
61. Mehta A J, Partheniades E, Dixit J G and McAnally W H. "Properties of deposited kaolinite in a long flume", Applying research to Hydraulic Practice. Proc ASCE speciality conference. Jackson, Miss. August 1982.
62. Migniot C. "A study of the physical properties of various very fine sediments and their behaviour under hydrodynamic action", La Houille Blanche, 23, 7, (59-620), 1968.
63. Mitchell J K. "Shearing Resistance of Soil as a Rate Process", Journal of Soil Mechanics and Foundation Division, ASCE, Vol 90, No SM 1, January 1964, pp 29-61.
64. Mitchell J K. "Temperature Effects on the Engineering Properties and Behaviour of Soils", Highway Research Board, Special Report No 103, 1969, pp 9-38.
65. Mitchell J K, Campanella R G and Singh A. "Soil Creep as a Rate Process", Journal of Soil Mechanics and Foundation Division, ASCE, Vol 94, No SM 1. January 1968, pp 231-253.
66. Nagai T, Figueroa J L and Yamamoto T. "Non-linear Mechanics of Sea-bed Interactions, Part III - Wave Tank Experiments on Soil Mass Transport in Clay Beds Associated with Wave Damping", Report, Rosenstiel School of Marine and Atmospheric Science, University of Miami, Florida, February 1983.

67. Nudaillac G D. "Parametrization of physical phenomena in a mud transport numerical model", IFREMER, Brest, France.
68. Odd N V M and Owen M W. "A two layer model of mud transport in the Thames Estuary", Proc ICE, 1972.
69. Owen M W. "A Detailed Study of the Settling Velocities of an Estuary Mud", Hydraulics Research Station, Wallingford, England, Report No INT 78, September 1960.
70. Owen M W. "A study of the properties and behaviour of muds", Hydraulics Research, Wallingford, England, Report No INT 61, November 1966.
71. Owen M W. "Properties of a consolidating mud", Hydraulics Research, Wallingford, England, Report No INT 83, December 1970.
72. Owen M W. "The effect of Turbulence on the settling velocities of silt flocs", Hydraulics Research, Wallingford, England, 1971.
73. Owen M W. "The effect of temperature on the settling velocities of an estuary mud", Hydraulics Research, Wallingford, England, Report No 106. July 1972.
74. Owen M W. "Erosion of Avonmouth Mud", Report No INT 150, Hydraulics Research Station, Wallingford, England, September 1975, (Second Impression, November 1977).
75. Parchure T M. "Effect of Bed Shear Stress on the Erosional Characteristics of Kaolinite", Thesis presented to the University of Florida, Gainesville (FL), in 1980, in partial fulfillment of the requirements for the degree of Master of Science.
76. Parchure T M. "Erosional Behaviour of Deposited Cohesive Sediments", Dissertation presented to the University of Florida, in 1982, in partial fulfillment of the requirements for the degree of Doctor of Philosophy.
77. Parchure T M. "Erosional Behaviour of Deposited Cohesive Sediments", PhD Thesis, University of Florida, 1984.
78. Parchure T M and Mehta A J. "Erosion of soft cohesive sediment deposits", Paper to appear in ASCE, Hydraulics Division Journal in 1985-1986.

79. Partheniades E. "A study of Erosion and Deposition of Cohesive Soils in Salt Water", Thesis presented to the University of California, Berkeley (CA) in 1962, in partial fulfillment of the requirements for the degree of Doctor of Philosophy.
80. Partheniades E. "Erosion and Deposition of Cohesive Soils", Journal of the Hydraulic Division, ASCE, Vol 19, No HY1, January, 1965, pp 105-139.
81. Partheniades E, Cross R H and Ayora A. "Further results on the deposition of cohesive sediments", Second Conference on Coastal Engineering Vol 1, Ch 47 London, September 1968.
82. Partheniades E and Kennedy J F. "Depositional behaviour of fine sediment in a turbulent Fluid Motion", Proceedings of the 10th Conference on Coastal Engineering, ASCE, Tokyo, Japan, 1966, pp 707-729.
83. Partheniades E, Kennedy J F, Etter R J and Hoyer R P. "Investigations of the depositional behaviour of fine cohesive sediments in an annular rotating channel", Hydrodynamics Laboratory Report No 96, 1966.
84. Partheniades E and Paaswell R E. "Erodibility of Channels with Cohesive Boundaries", Journal of the Hydraulics Division, ASCE, Vol 96, No HY3, March 1970, p 755.
85. Partheniades E, and Mehta A J. "Rates of deposition of fine cohesive sediments in turbulent flow", International Association for Hydraulic Research, 14th Conference, Paris 1971.
86. Peijiu Y. "A Preliminary Study of Flocculation Formed by Cohesive Sediment and its influence on Rheological Properties of Slurry", Institute of Hydraulic Research, Yellow River Conservancy Commission (1982).
87. Peirce T J and Williams O J. "Experiments on Certain Aspects of Sedimentation of Estuarine Muds", Proc. Inst. Civ. Engineers, Vol 34, July 1966, pp 391 - 402.
88. Peng, Yeh H Y, Maa P Y and Mehta A J. "Considerations of bed response in wave resuspension of muds", Paper presented at the symposium on Circulation in Estuaries, Virginia, Institutes of Marine Science, Gloucester Point, UH, January 1985.

89. Postma H. Sediment, in Demerara coastal Investigation : Delft, Netherlands, Hydrodynamics Laboratory, 1962, pp 105-164.
90. Puls W and Kuehl H. "Field measurements of the settling velocity of estuarine flocs". Third International Symposium on River Sedimentation, Jackson, Mississippi, USA. March 1986.
91. Pulus W. "Erosion characteristics of estuarine muds". Hydraulics Research, Wallingford, England, Report No 265, February 1984.
92. Raudkivi A J and Hutchison D L. "Erosion of kaolinite clay by flowing water". Proc R Soc London, A 337, 1974, pp 537-554.
93. Richardson J F and Zaki W N. "The Sedimentation of a suspension of Uniform Spheres under Conditions of Viscous Flow", Chem. Eng. Sci. 1954, pp 65-73.
94. Sargunam A, Riley P, Arulanandan A and Krone R B. "Physico-chemical Factors in Erosion of Cohesive Soils", Journal of the Hydraulics Division ASCE, Vol 99, HY3, March 1973, pp 555-558.
95. Schuckman B and Yamamoto T. "Non-linear Mechanics of Sea-Bed Interactions, Part II - Wave Tank Experiments on Water Wave Damping by Motion of Clay Beds", Technical Report TR 82-1, Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, Florida, March 1982.
96. Sills G C. Private communication. 1986.
97. Sills G C and Elder D Mc G. "The transition from sediment suspension to settling bed", NSF workshop on Cohesive sediment Dynamics. October 1984.
98. Smoluchawski M, 2 Phy. Chem. 1917, 92 55.
99. Stevenson J R and Burt T N. "Further studies of the field settling velocities of Thames mud", Hydraulics Research Ltd, Wallingford, England. Report SR 10. March 1985.
100. Task Committee. "Shoaling Processes in Navigable waters", Journal of Waterway, Port, Coastal and Ocean Engineering, Vol 109, No 2, May 1983.
101. Thiers G R and Seed H B. "Cyclic Stress-Strain Characteristics of Clays", Journal of the Soil

Mechanics and Foundations Division, ASCE, Vol 94, No SM 2, March 1968, pp 555-564.

102. Thimakorn P. "An Experiment on clay suspension under Water Waves", Proceedings of the 17th Coastal Engineering Conference, ASCE, Vol 3, Sydney Australia, March 1980, pp 2894-2906.
103. Thorn M F C. "Physical Processes of Siltation in Tidal Channels", in Hydraulic Modelling Applied to Maritime Engineering Problems, ICE, London, 1981, pp 47-55.
104. Thorn M F C and Parsons J G. "Erosion of Cohesive Sediment in Estuaries: An Engineering Guide", Proceedings of the Third International Symposium on Dredging Technology, Paper F1, 1980, pp 349-358.
105. Turcotte B R, Liu P L - F and Kuthawy F H. "Laboratory Evaluation of Wave Tank Parameters for Wave-Sediment Interaction", Joseph H. De Frees Hydraulics Laboratory, Report 84-1 and Geotechnical Engineering Report 84-6, School of Civil and Environmental Engineering, Cornell University, Ithacu, New York, August 1984.
106. van de Ven T G and Mason S G. Colloid Polymer Science. 1977, 255 468.
107. Williams D J A and James A F. "Rheology of Brisbane and Rotterdam Mud", Report to Hydraulics Research Station, Wallingford, UK, Department of Chemical Engineering, University College Swansea, UK. 1978.
108. Work L T and Kohler A S. "Sedimentation of suspensions", Ind. Engng Chem. 32. 1940.
109. Yeh H Y. "Resuspension Properties of Flow Deposited Cohesive Sediment Beds", Thesis presented to the University of Florida, Gainesville (FL) in 1979, in partial fulfillment of the requirements for the degree of Master of Science.
110. Young R A and Southard J B. "Erosion of fine-grained marine sediments : Sea-floor and laboratory experiments", Geological Society of American Bulletin, V 89, May 1978, pp 663-672.

TABLES

TABLE 1 Characterisation of sediment

1. Type of material

(a) Clay Minerals

- (i) Clay mineral alone
- (ii) Mixture of clay minerals in varying proportions
- (iii) Mixture of clay-mineral and non-clay-mineral, both in the fine sediment range

(b) Soils, Muds and Clay Material

- (i) Mixture of cohesive and non-cohesive (such as sand) sediments
- (ii) Mixture of clay material and organic matter or organic compounds
- (iii) Sediments from natural environment (unclassified)
- (iv) Sediments from natural environment (classified according to Soil Classification System)

(c) Non-sediment Fine Materials

2. Nature of clay structure

(a) Electrical forces acting between particles

- (i) Net energy of attraction
- (ii) Double layer thickness

(b) Particle arrangement or fabric consisting of texture and particle orientation

3. Particle Size Distribution

- (a) Median diameter
- (b) Effective size
- (c) Uniformity coefficient
- (d) Curvature coefficient

4. Cation Exchange Capacity

5. Exchangeable Sodium Percentage

6. Sodium Adsorption Ratio of Clay

7. Dielectric Constant

8. Silica-sesquioxide Ratio

9. Chemical Composition

10. Specific Gravity

11. Hydration or Adsorbed Water

12. Antecedent Water

13. Aging

TABLE 2 Mineralogy and cation exchange of three muds

Mud Source	Grangemouth	Brisbane	Belawan
Cation exchange (meg/100g)	20	35	25
% clay minerals	51	50	75-80
Montmorillonite	nil	30	15-20
Kaolin	17	15	30
Illite/mica	17	(5)	30
Chlorite	17	nil	trace
% non-clay minerals	39	50	20
% organics and minor constituents	10	nil	traces

TABLE 3 Erosion threshold stresses of four muds

Belawan mud :	0.10N/m^2
Brisbane mud :	0.07N/m^2
Grangemouth mud :	0.10N/m^2
Scheldt mud :	0.07N/m^2

FIGURES

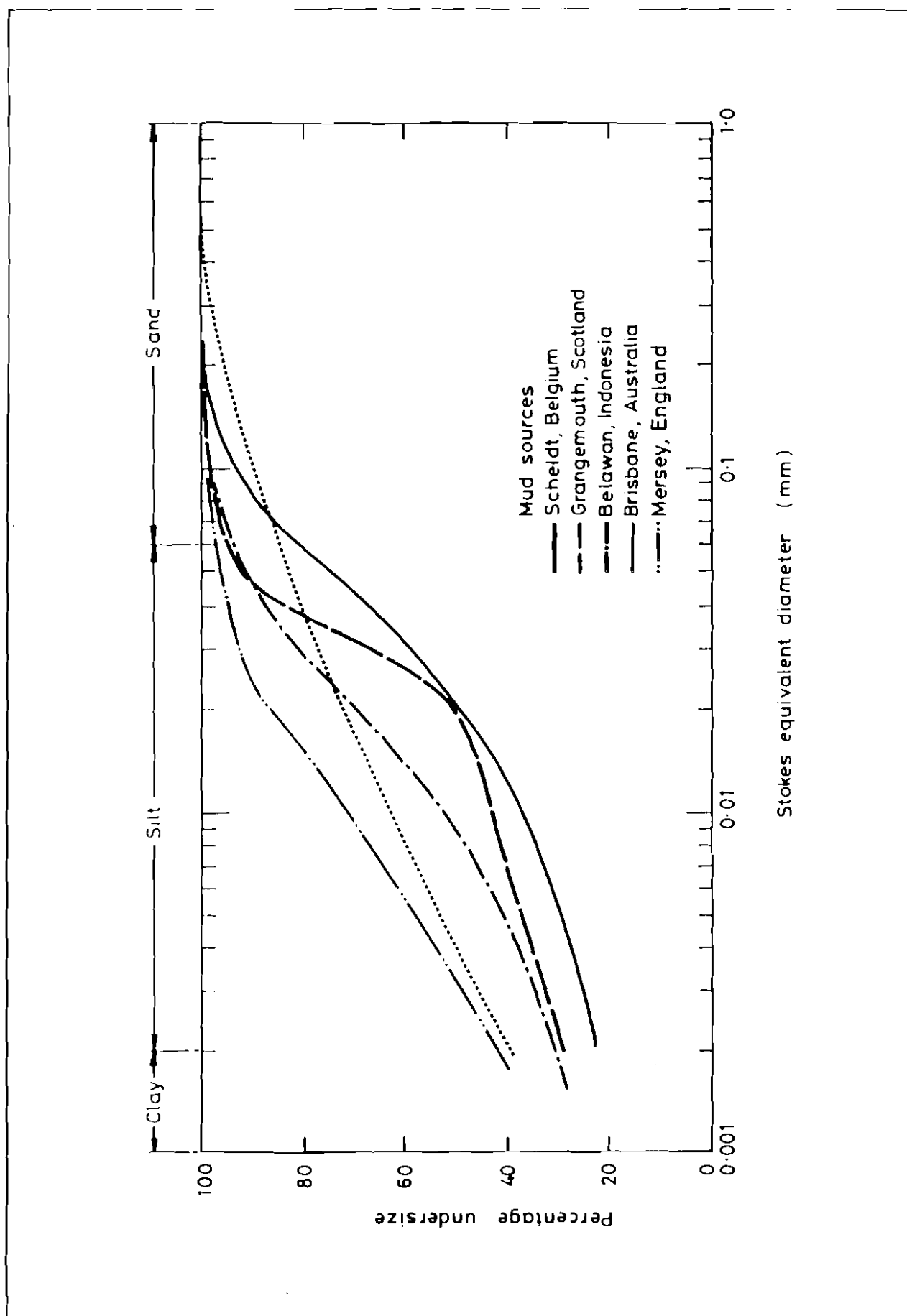


Fig 1 Particle size distribution of fine muds

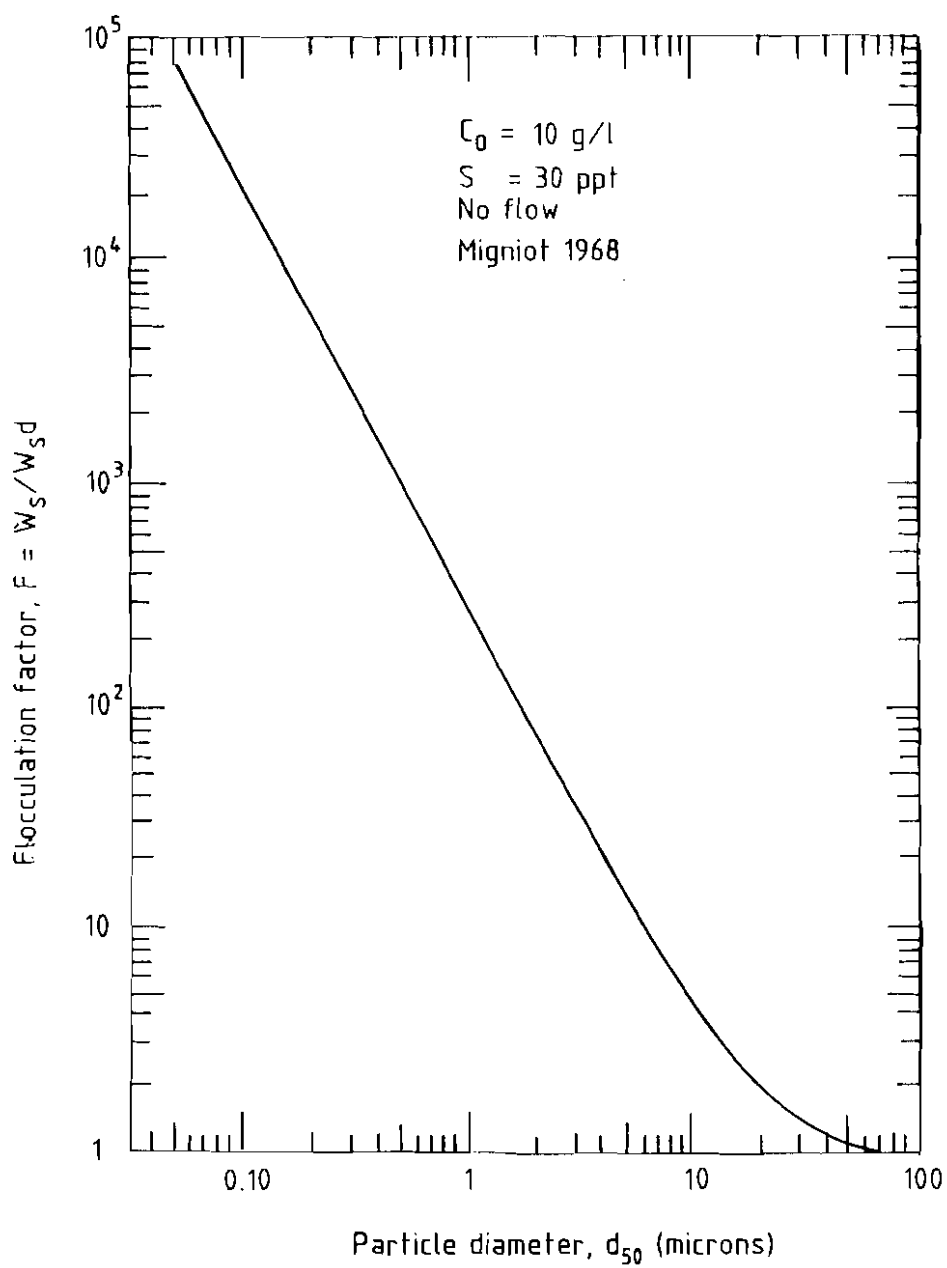


Fig 2 Flocculation factor, F , as a function of median particle diameter

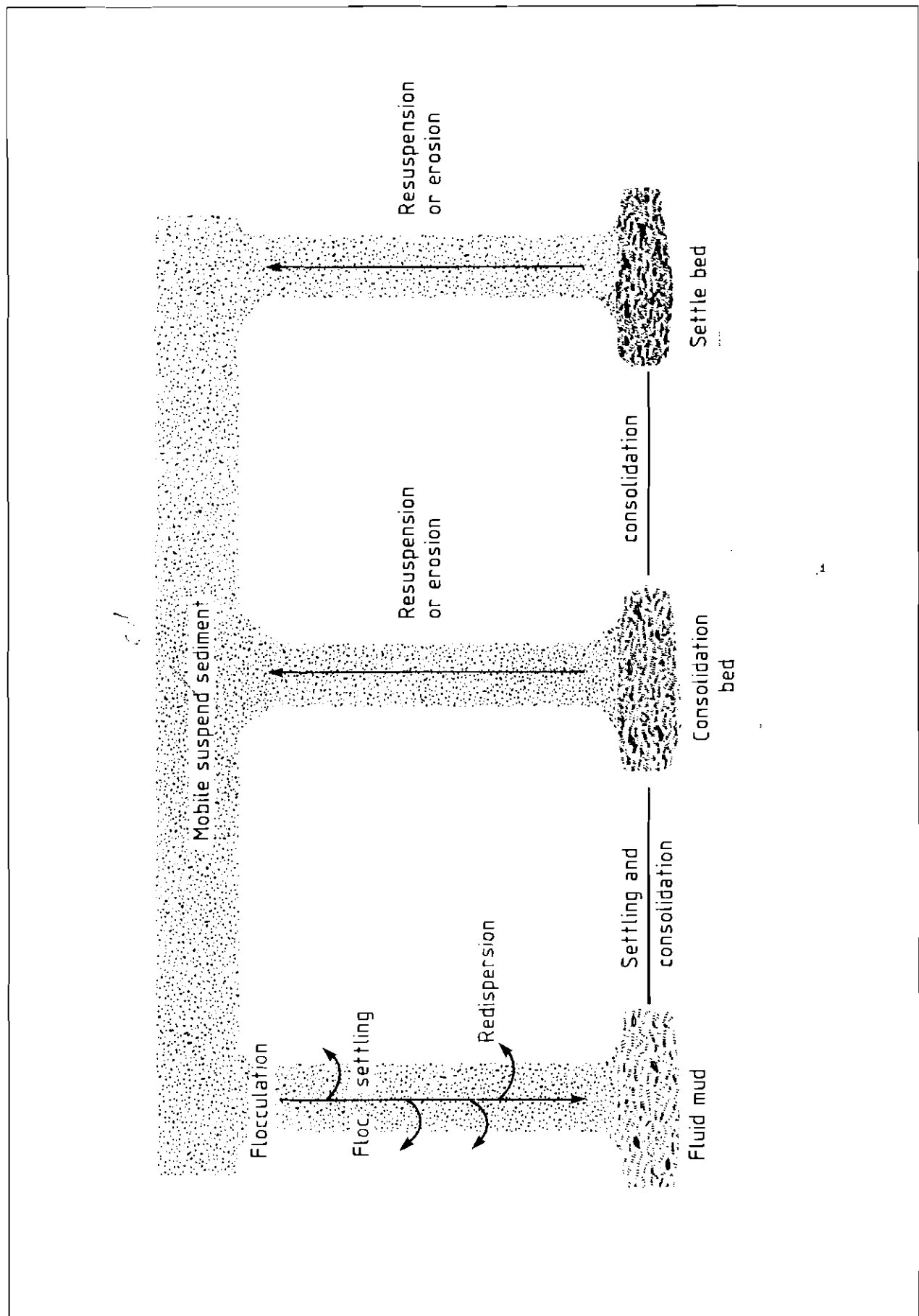


Fig 3 States of cohesive sediments

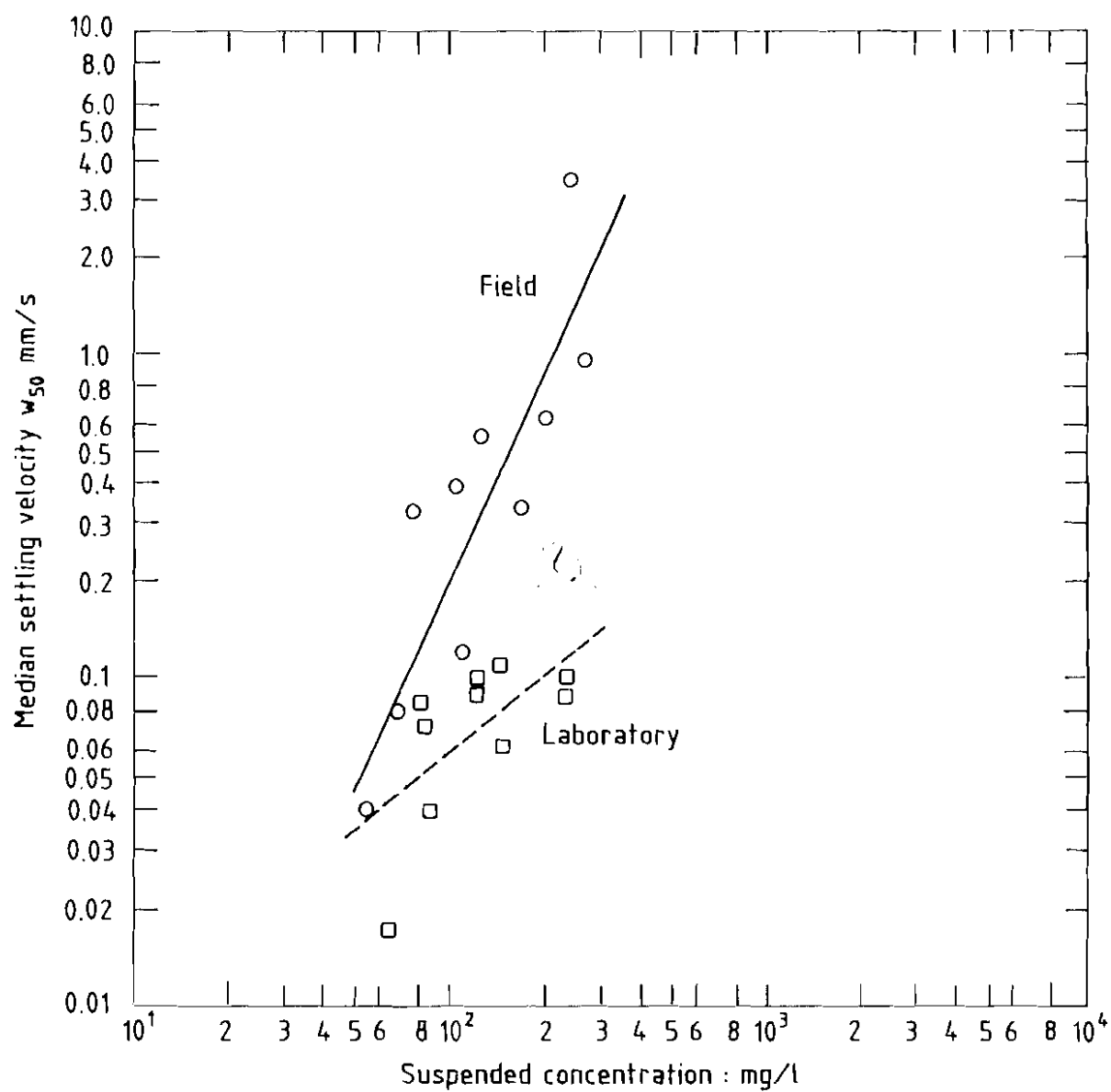


Fig 4 Median settling velocity against suspended concentration : field and laboratory

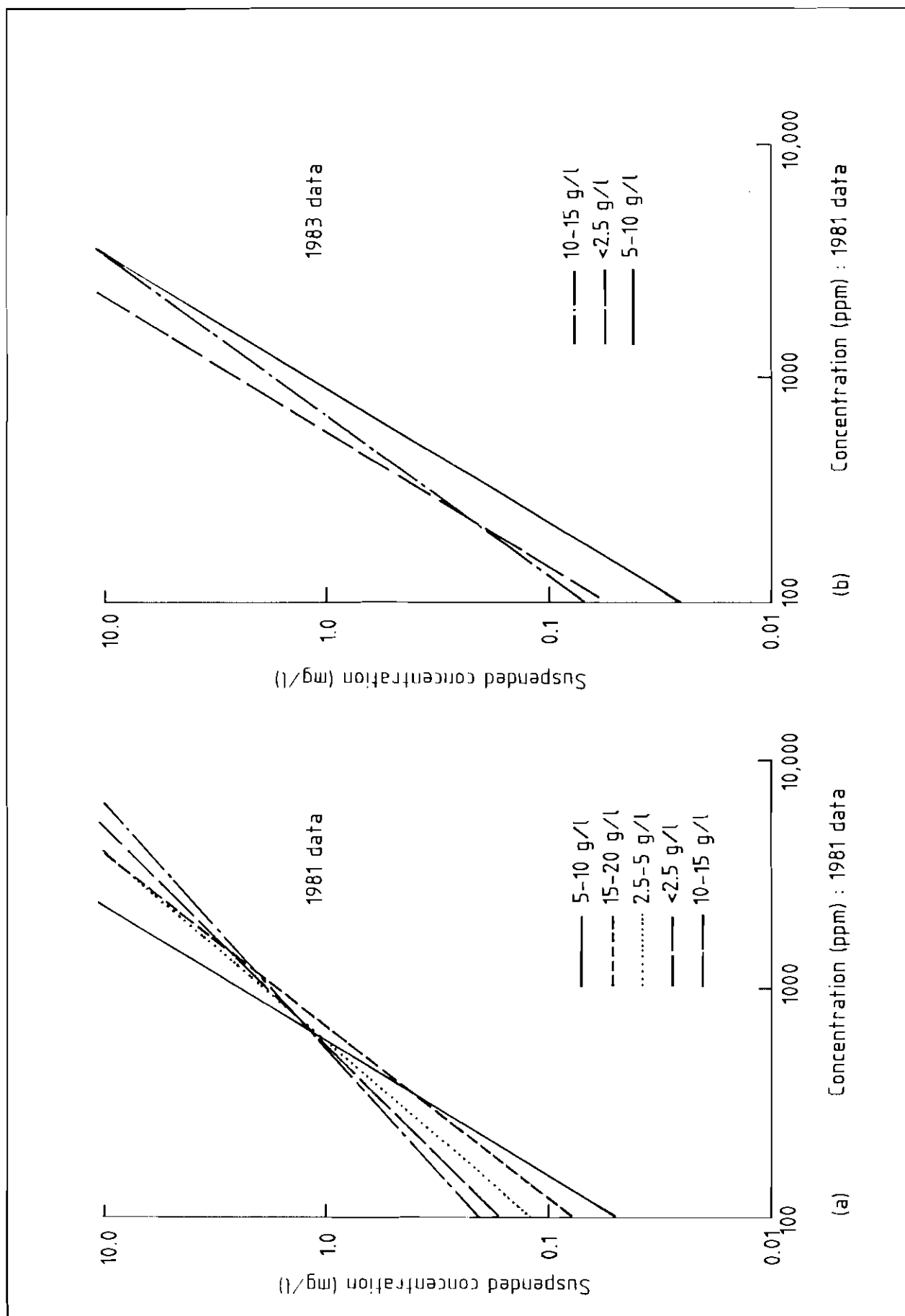


Fig 5 Effect of salinity on median settling velocity

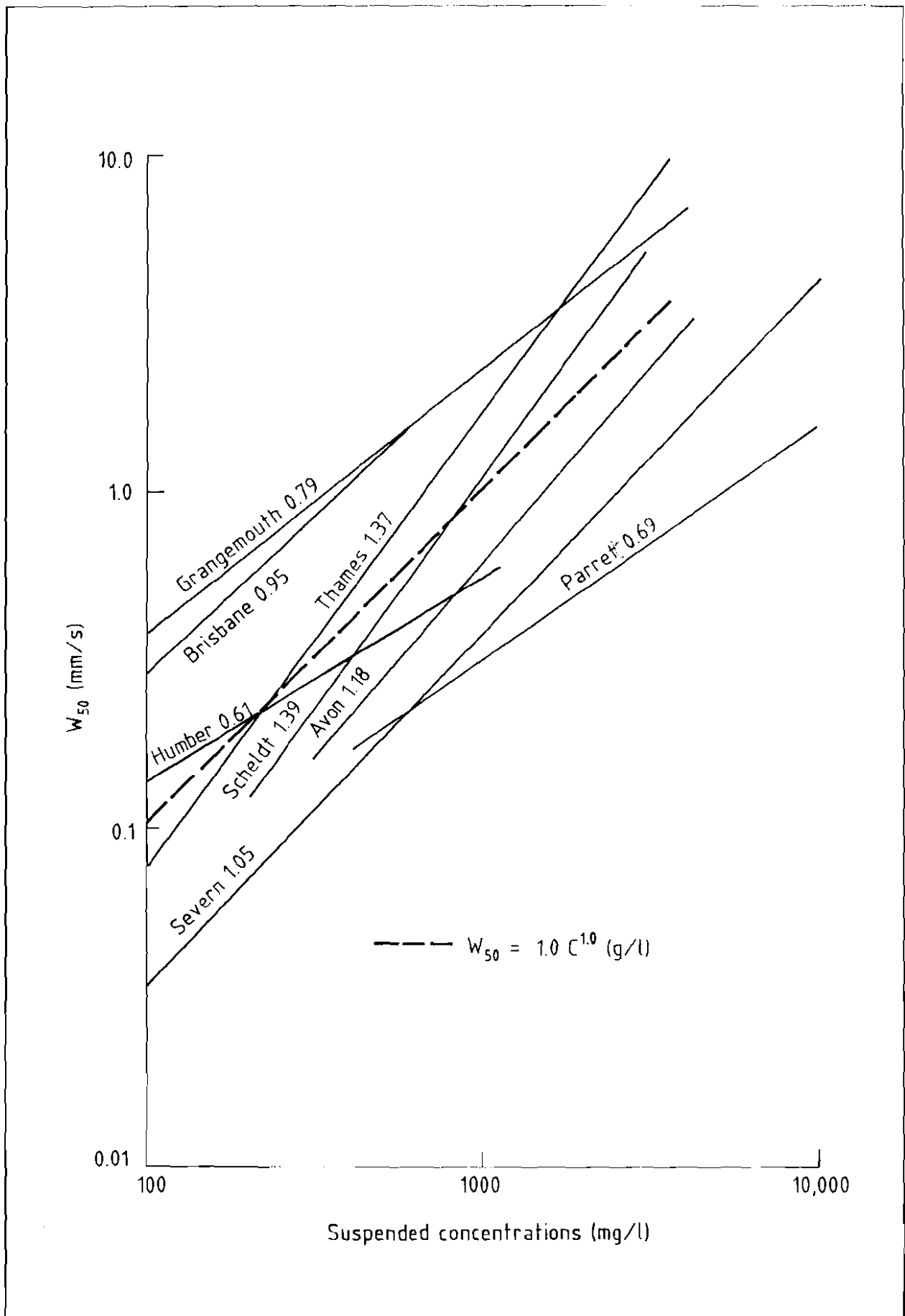


Fig 6 Median settling velocity against suspended concentration : comparison of eight estuaries

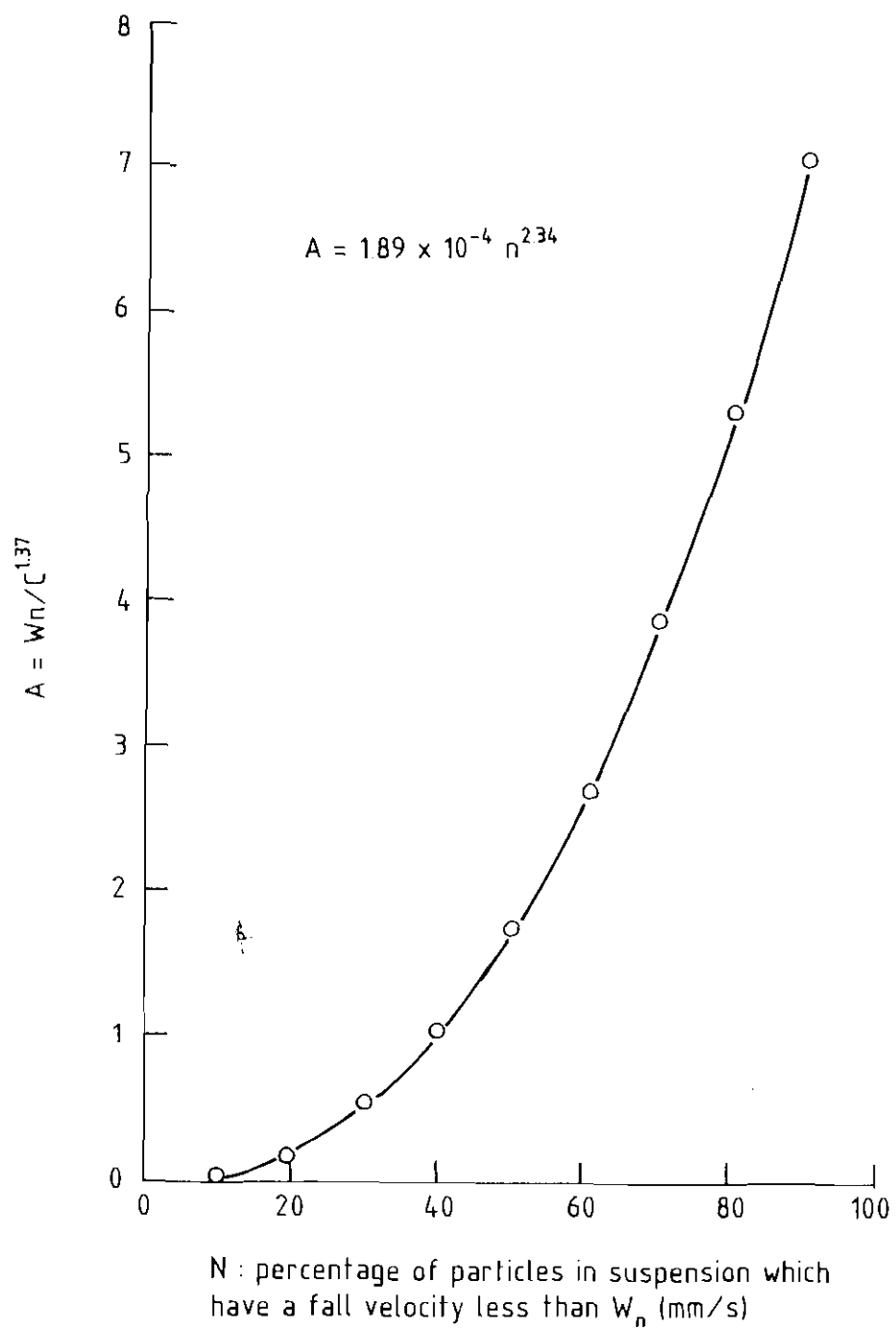


Fig 7 General equation for Thames settling velocity data

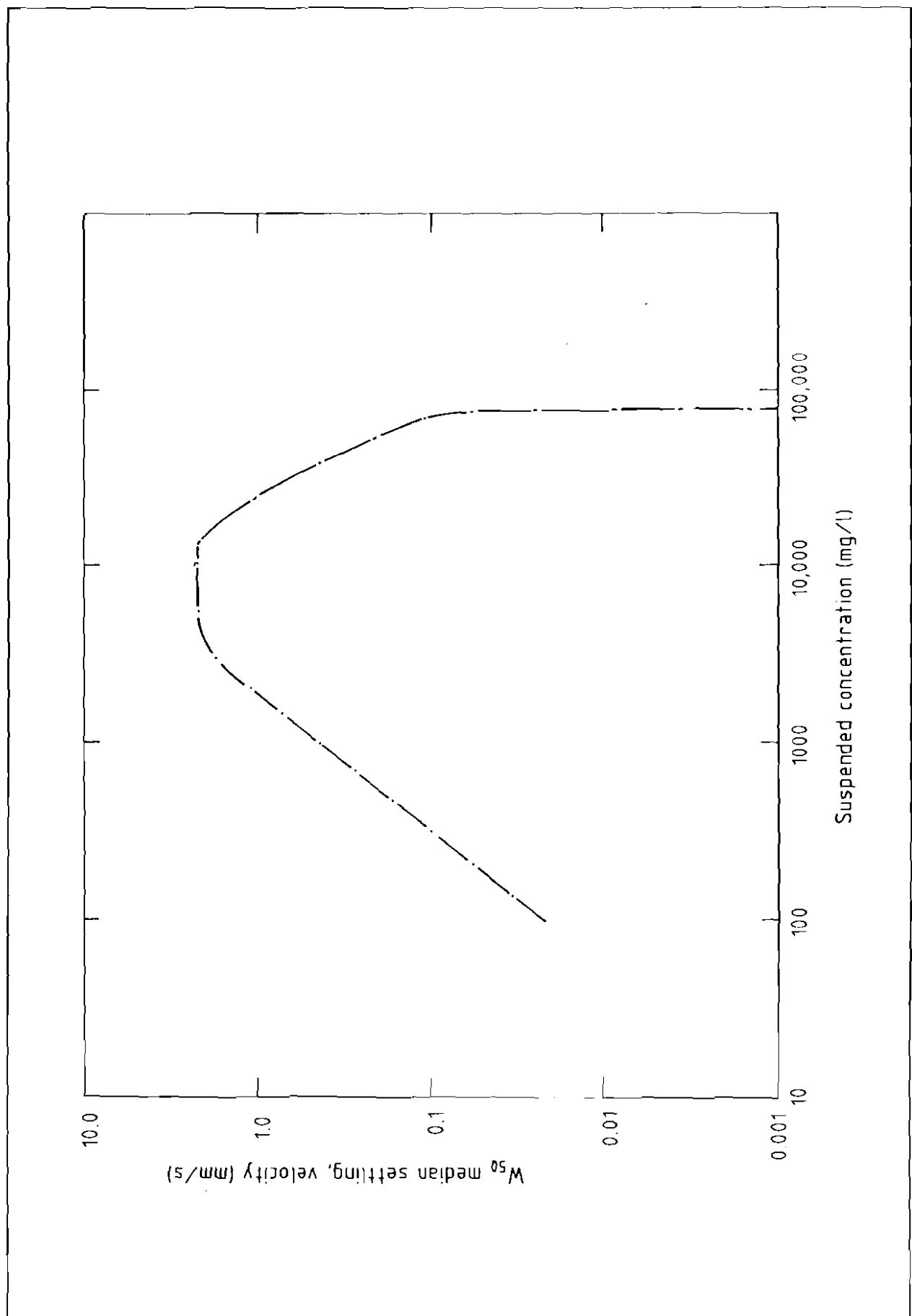


Fig 8 Median settling velocity against suspended concentration for Severn Estuary

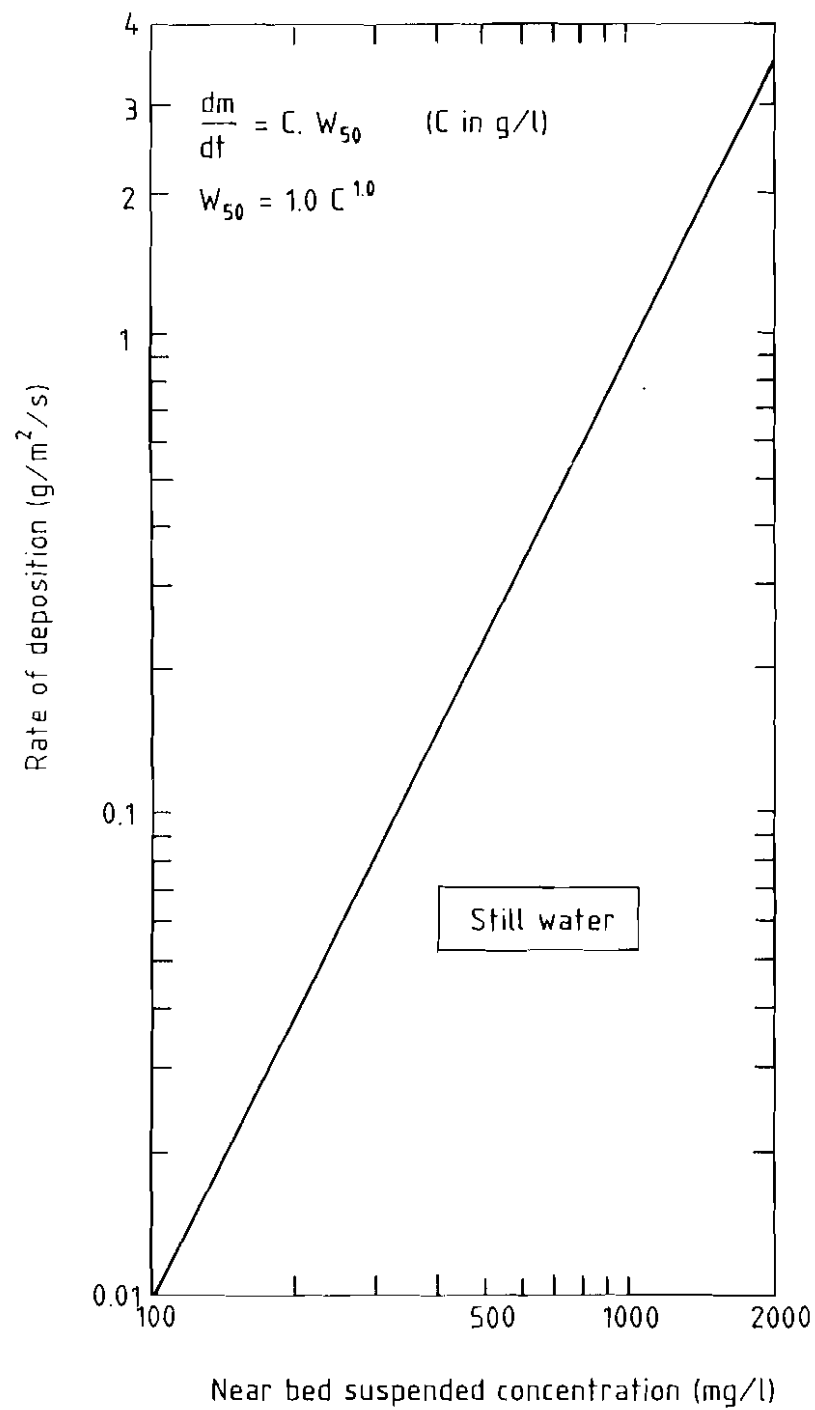


Fig 9 Rate of deposition against near bed suspended concentration

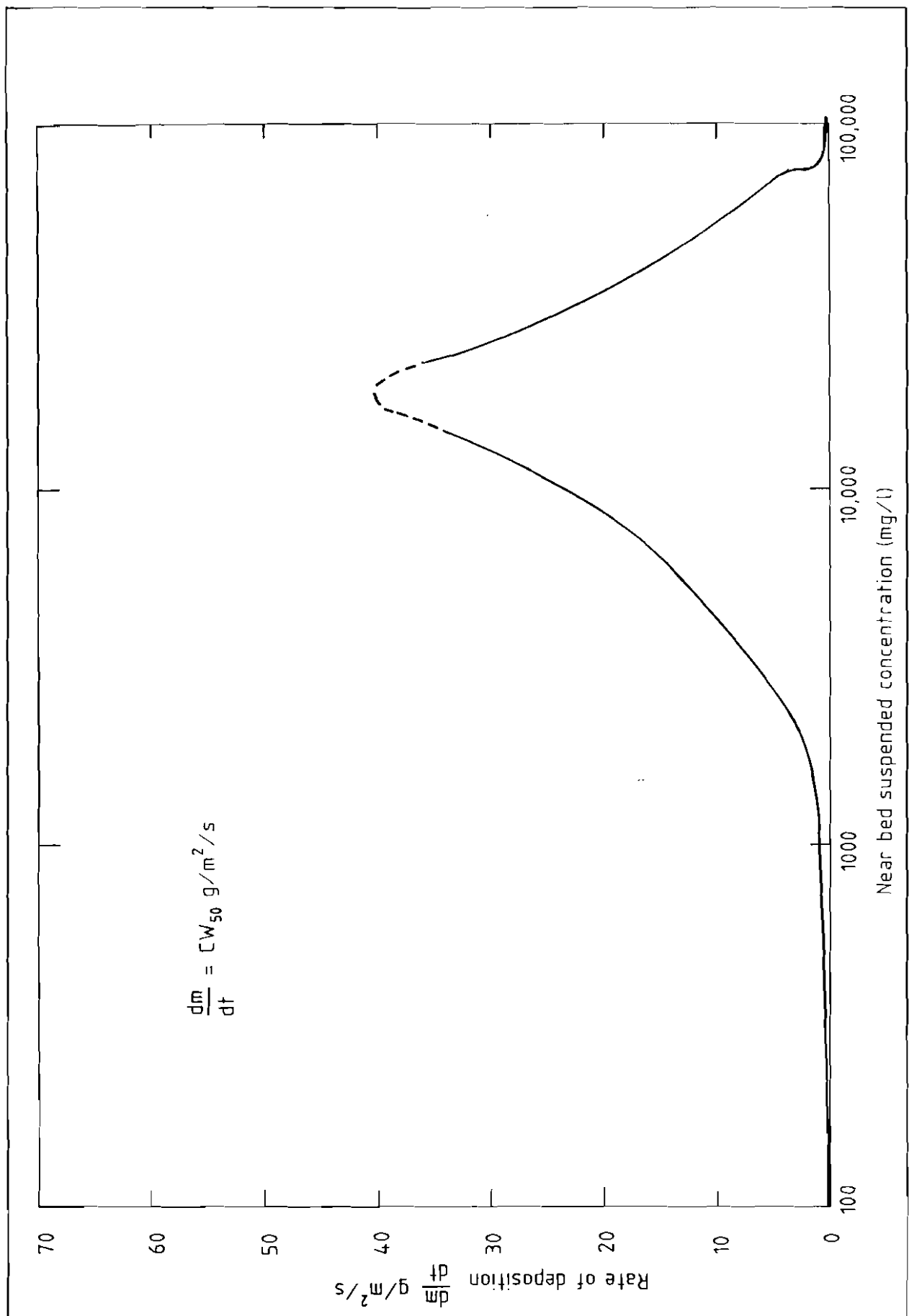


Fig 10 Rate of deposition against near bed suspended concentration : high concentration

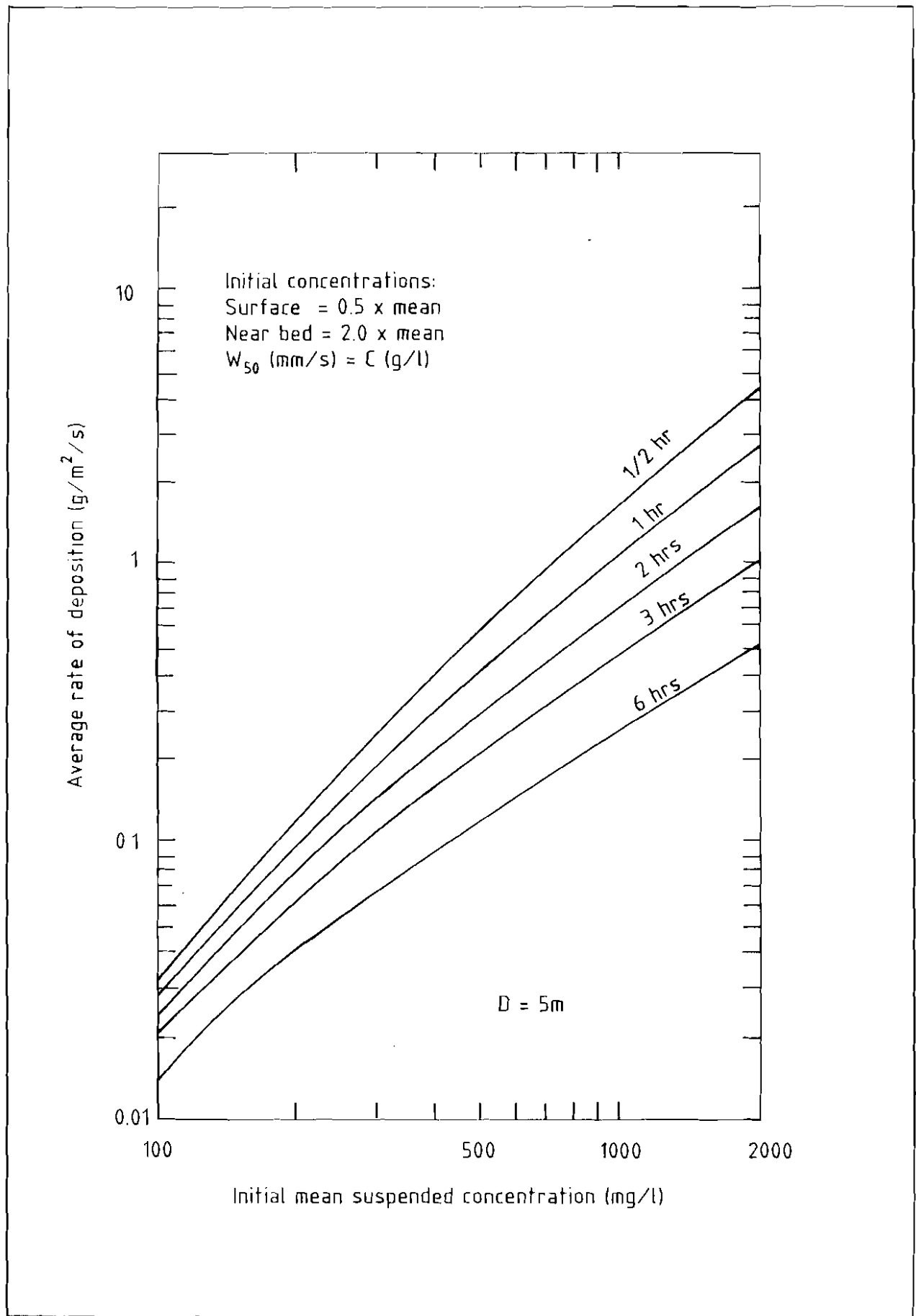


Fig 11 Average rate of deposition against initial mean suspended concentration and time $D = 5\text{m}$

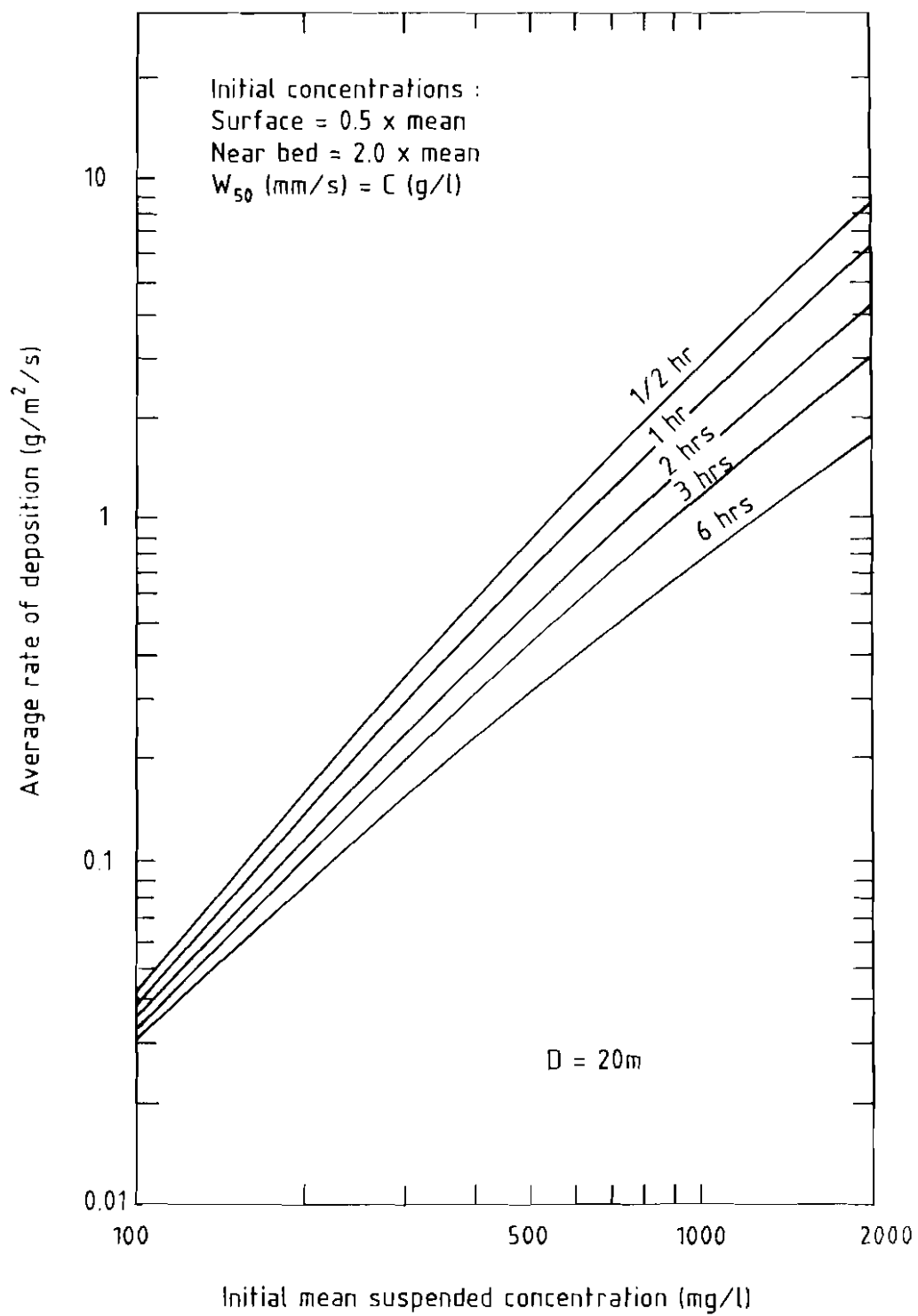


Fig 12 Average rate of deposition against initial mean suspended concentration and time $D = 20\text{m}$

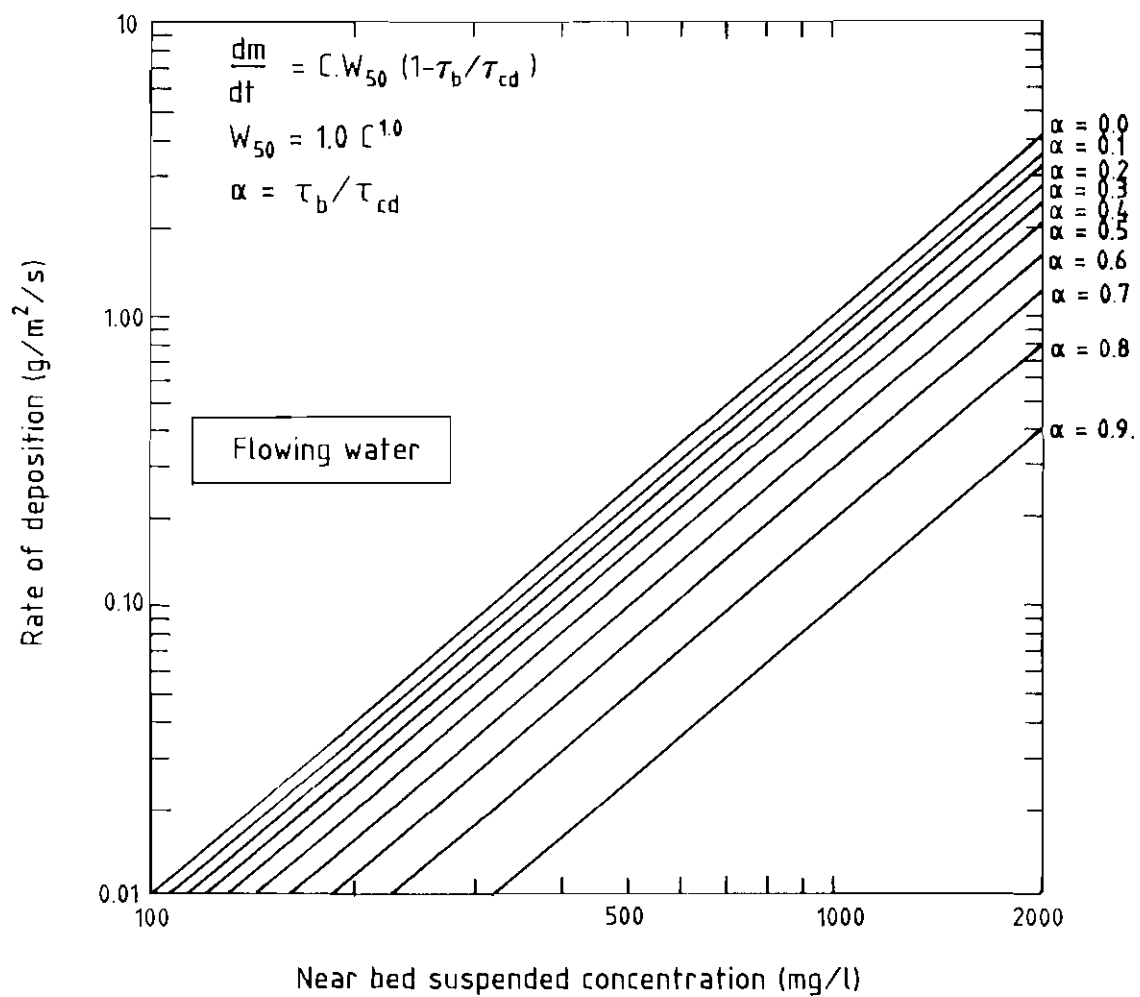


Fig 13 Rate of deposition in flowing water against near bed suspended concentration

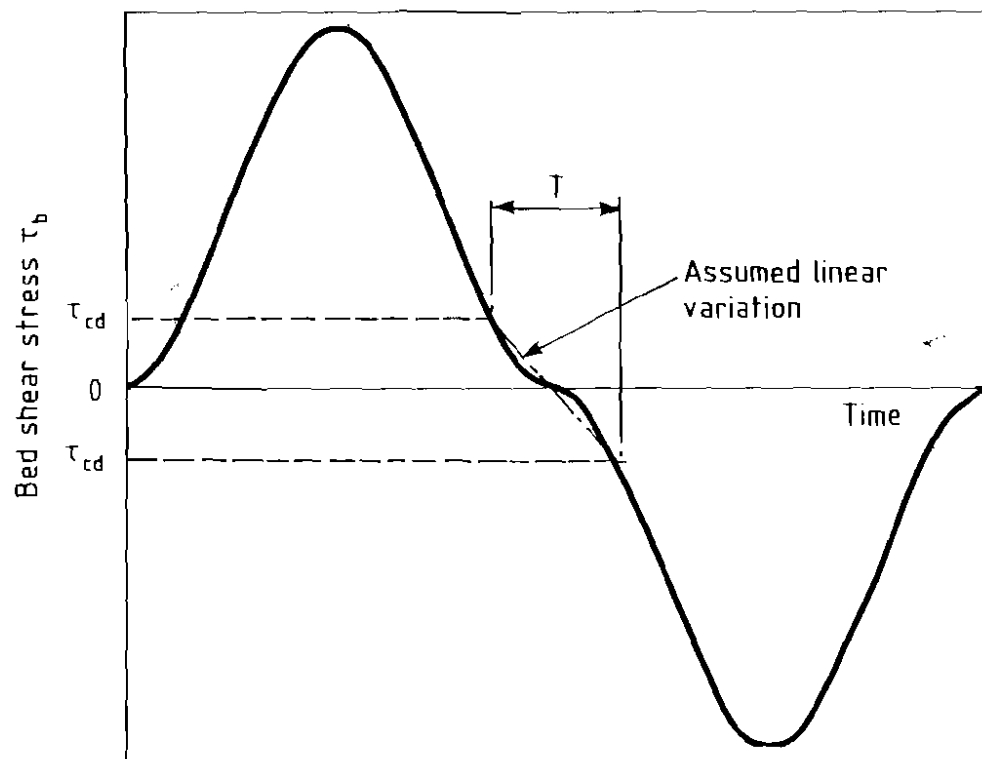
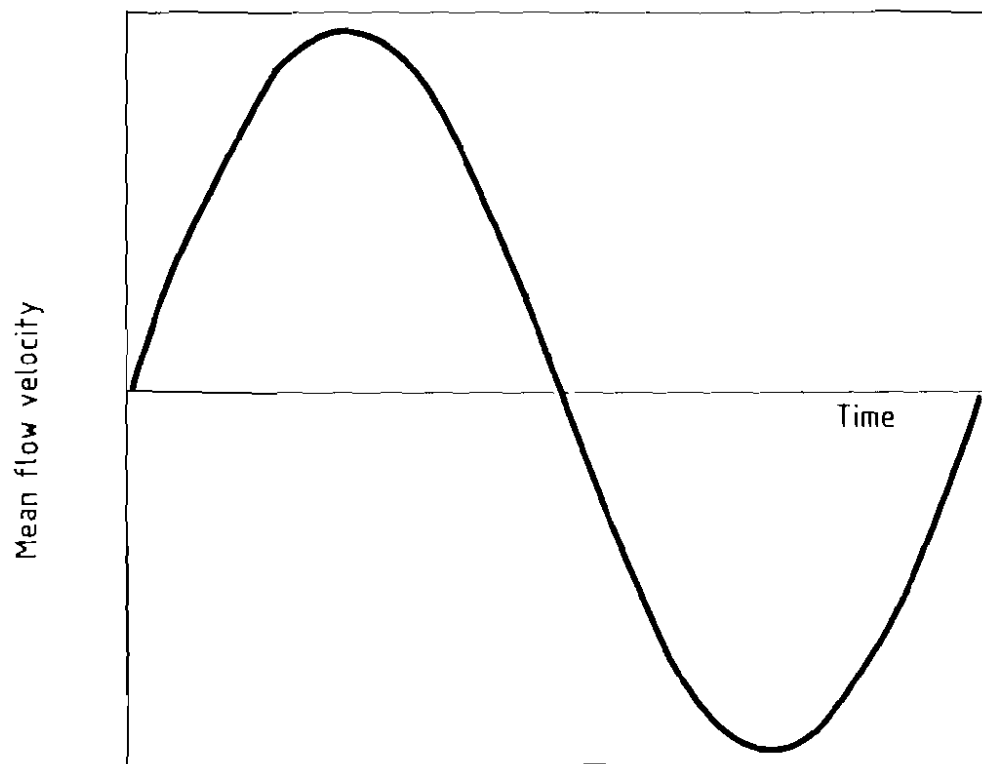


Fig 14 Periods of deposition in a tidal cycle

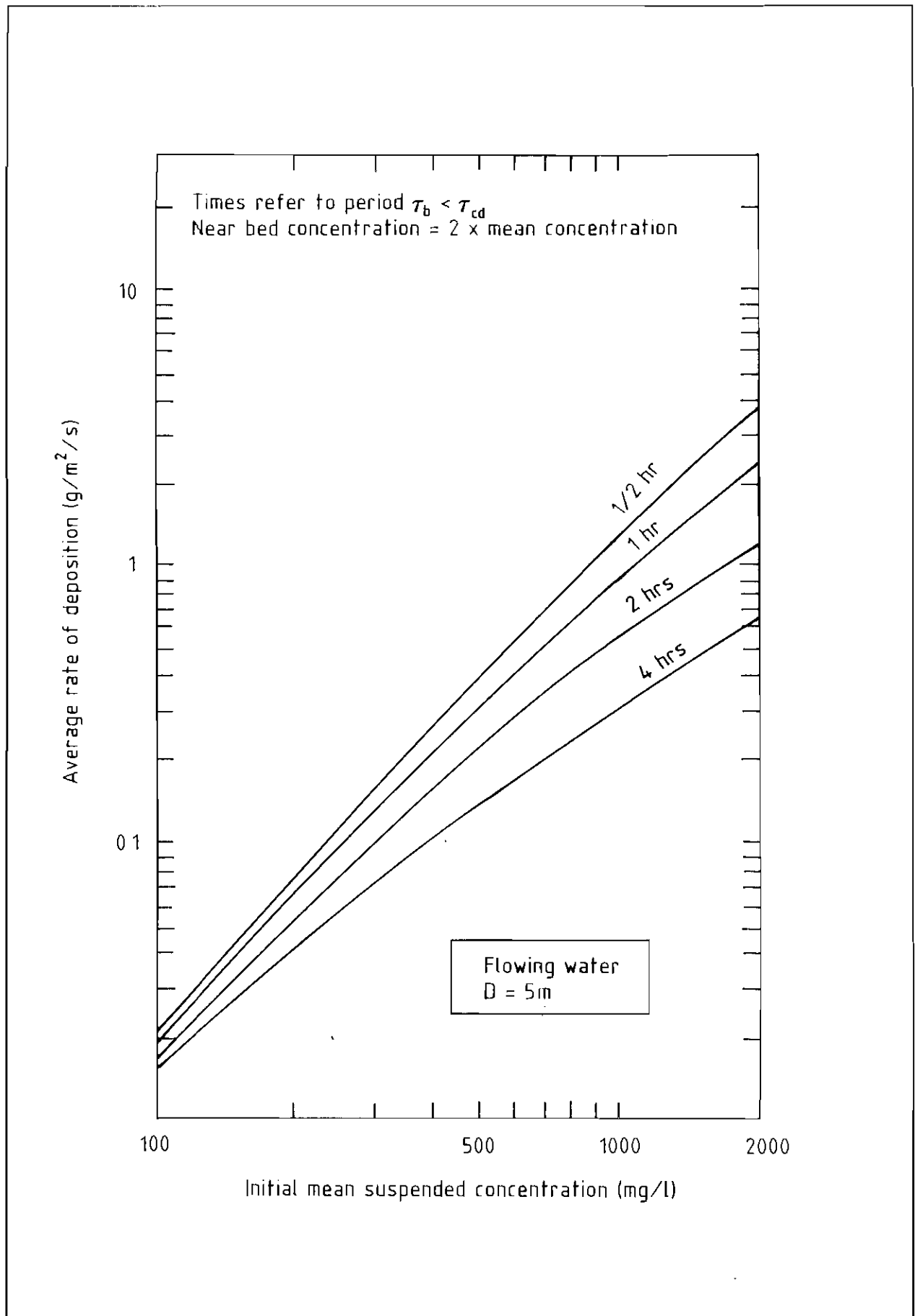


Fig 15 Average rate of deposition in flowing water against mean suspended concentration and time $D = 5\text{m}$

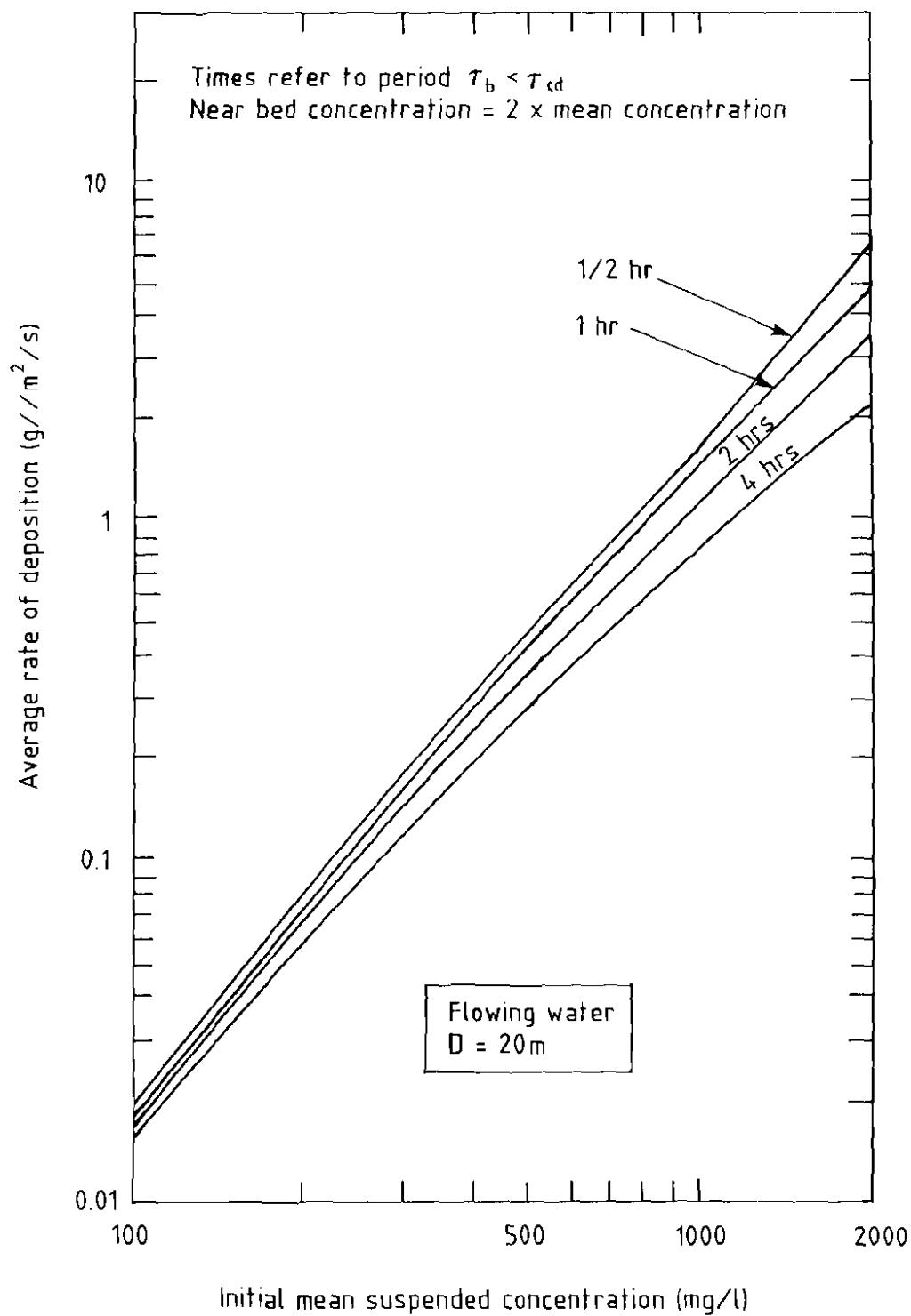
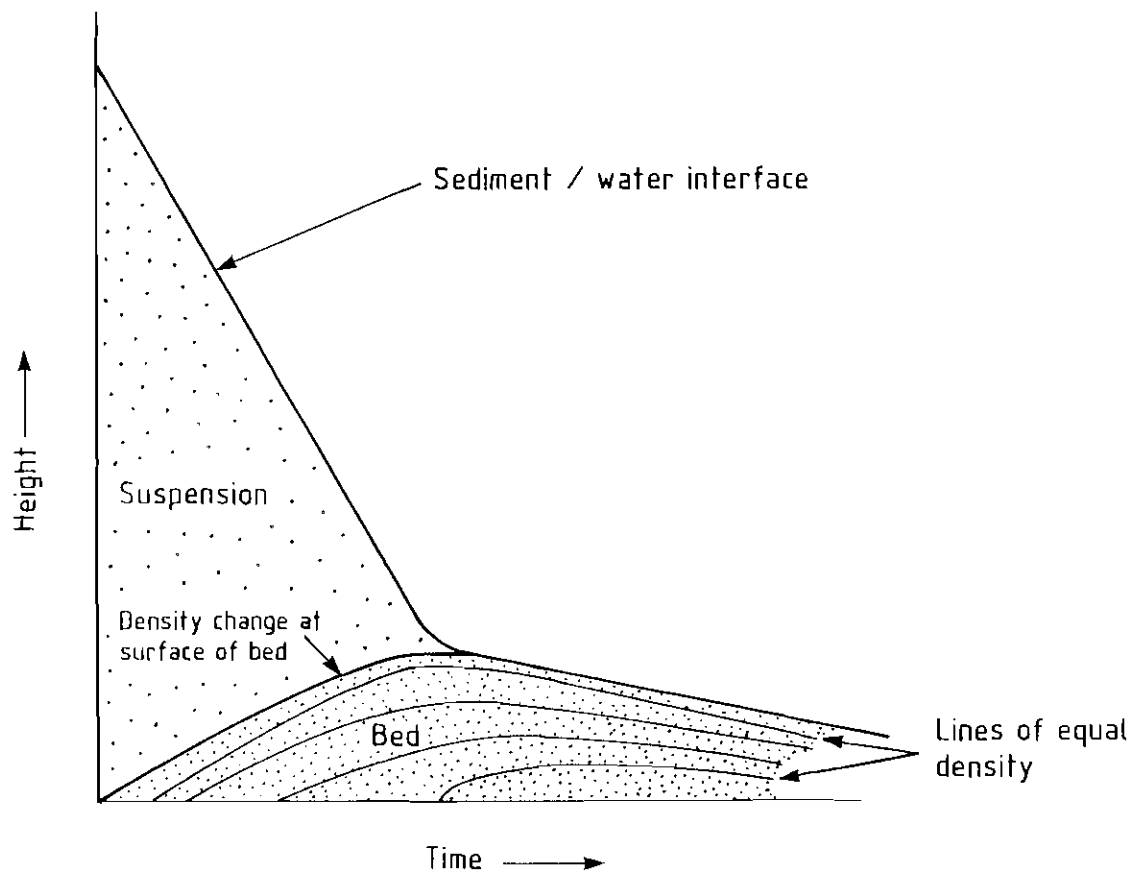


Fig 16 Average rate of deposition in flowing water against mean suspended concentration and time $D = 20\text{m}$



Notes

The bed surface rises to intersect settling sediment / water interface after which it falls due to continued consolidation

Fig 17 Growth of the bed in a settling suspension

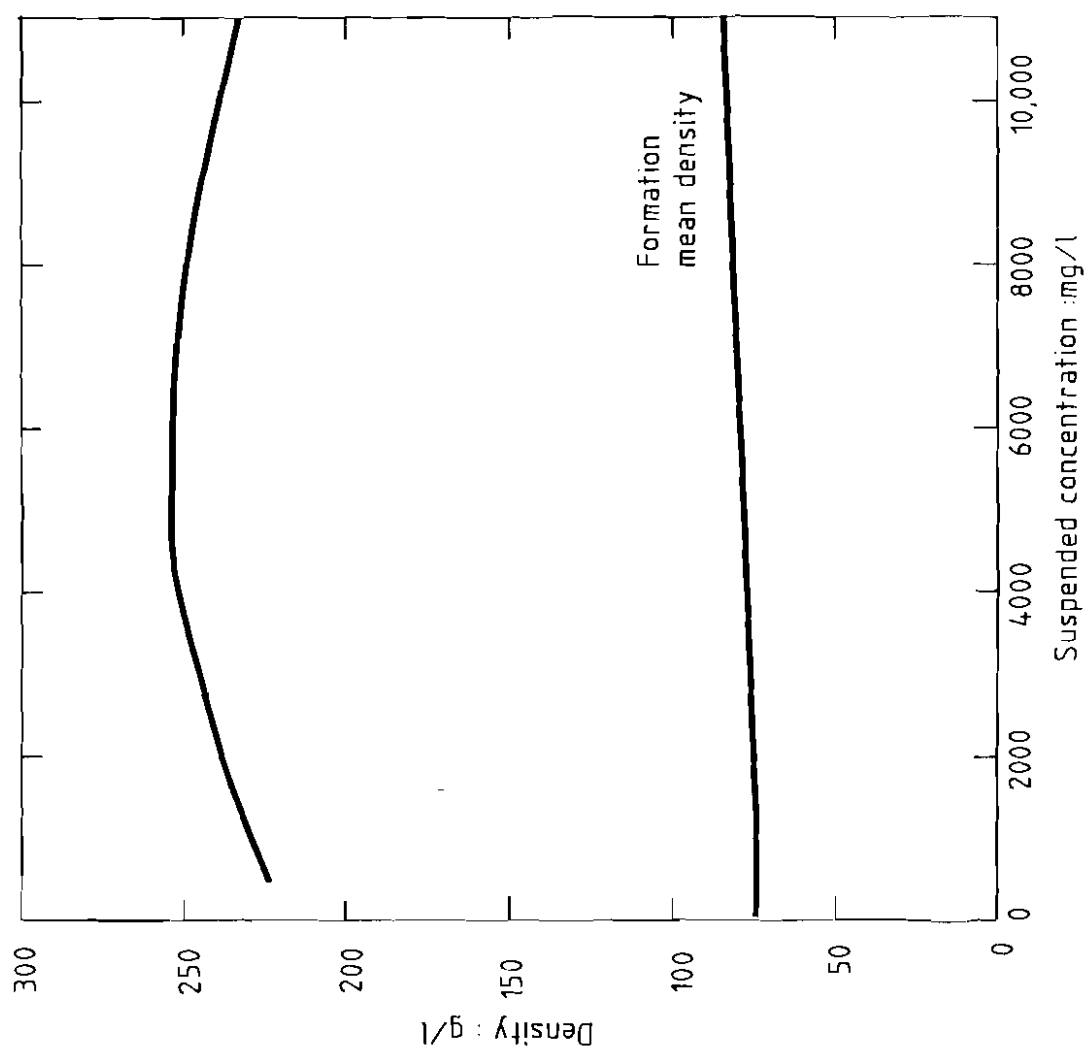


Fig 18 Formation and final mean densities against suspended concentration

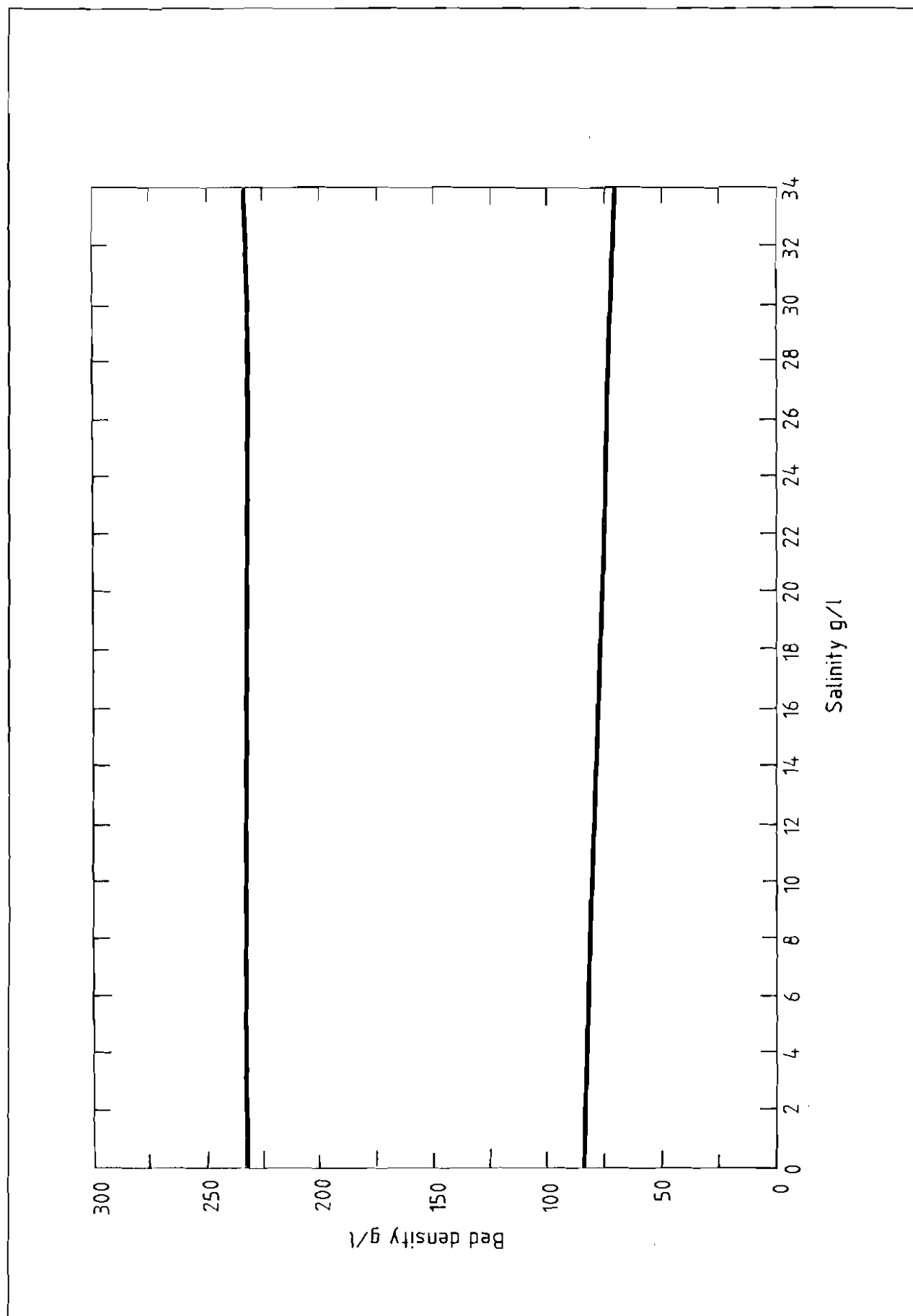


Fig 19 Formation of final mean densities against suspended salinity

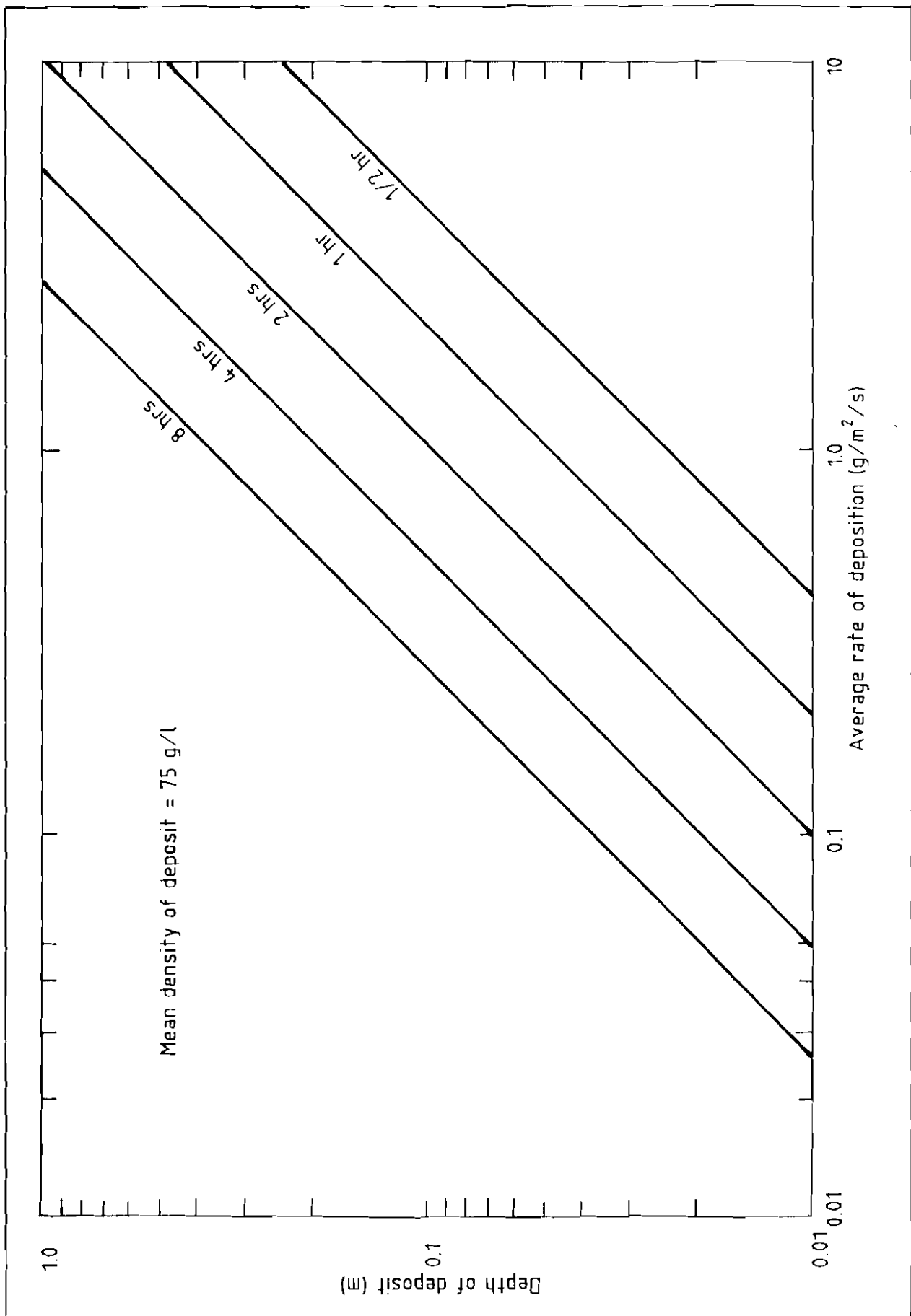


Fig 20 Depth of deposit against average rate of deposition and time

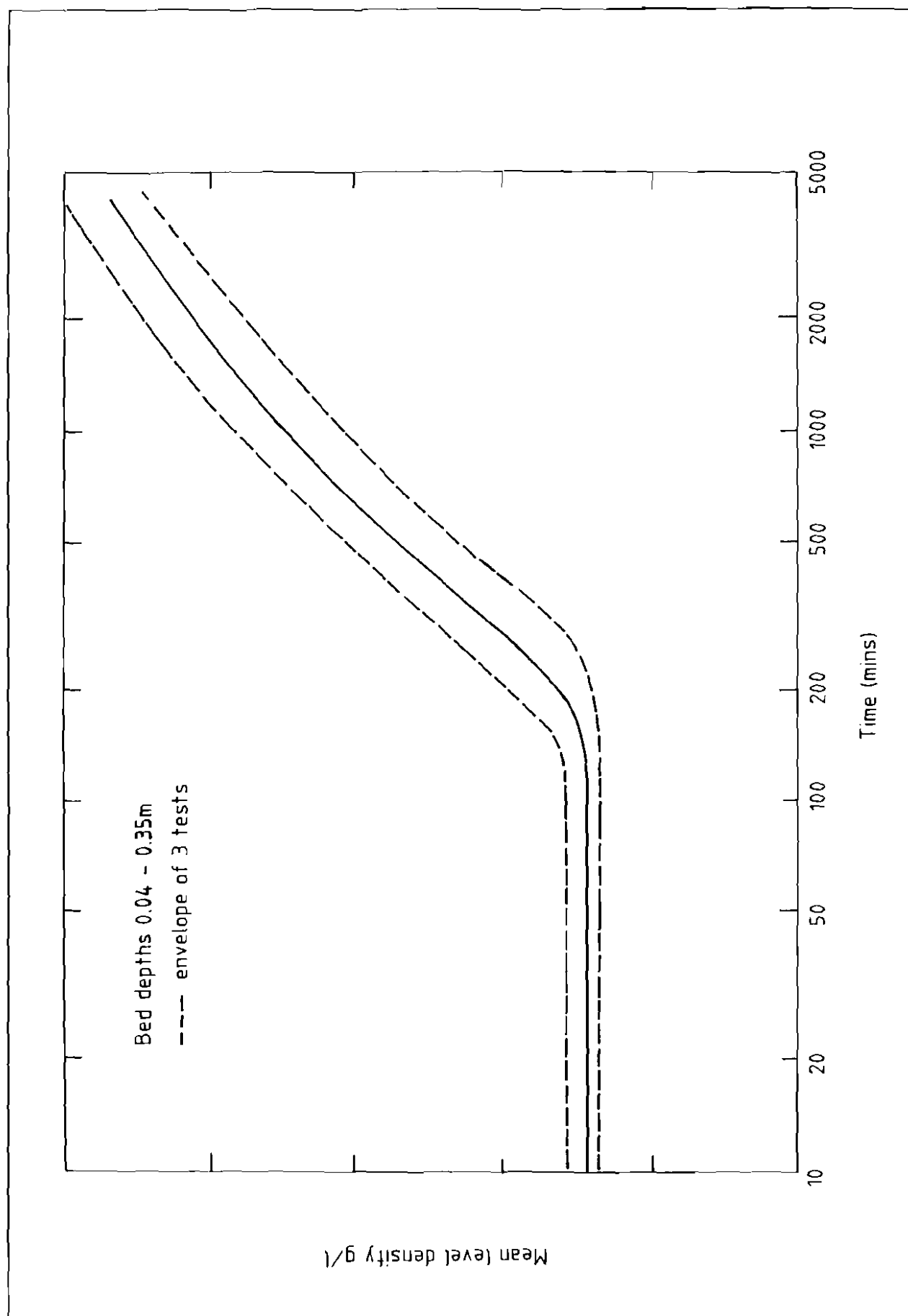


Fig 21 Rate of increase of mean density with time of a consolidating bed

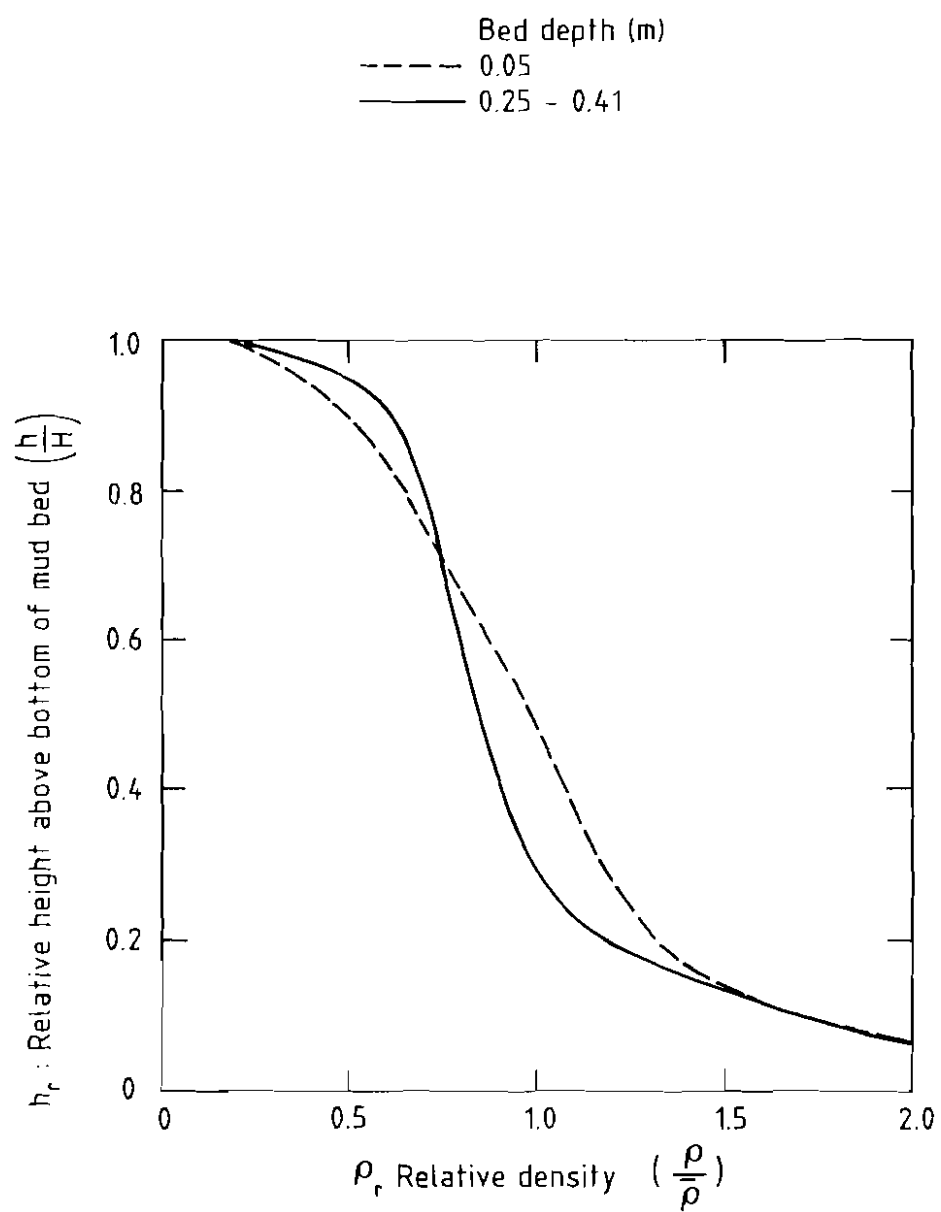


Fig 22 Dimensionless density-depth profiles of mud beds

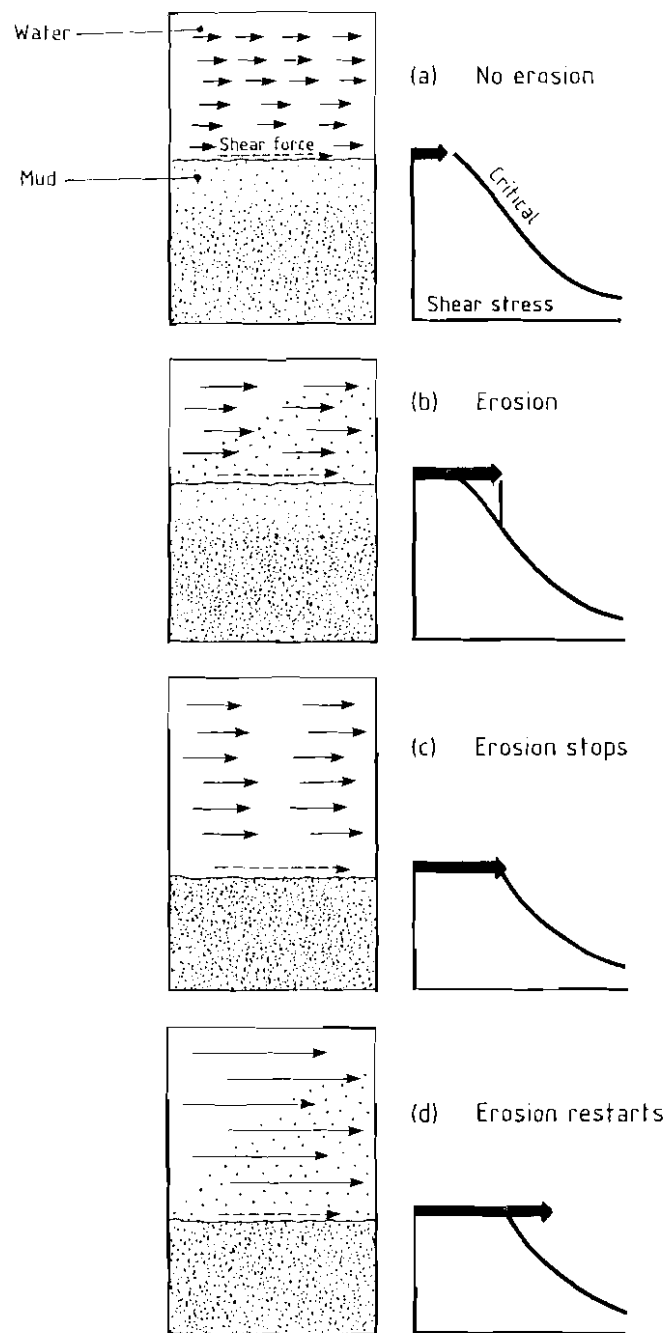


Fig 23 The cohesive sediment erosion process

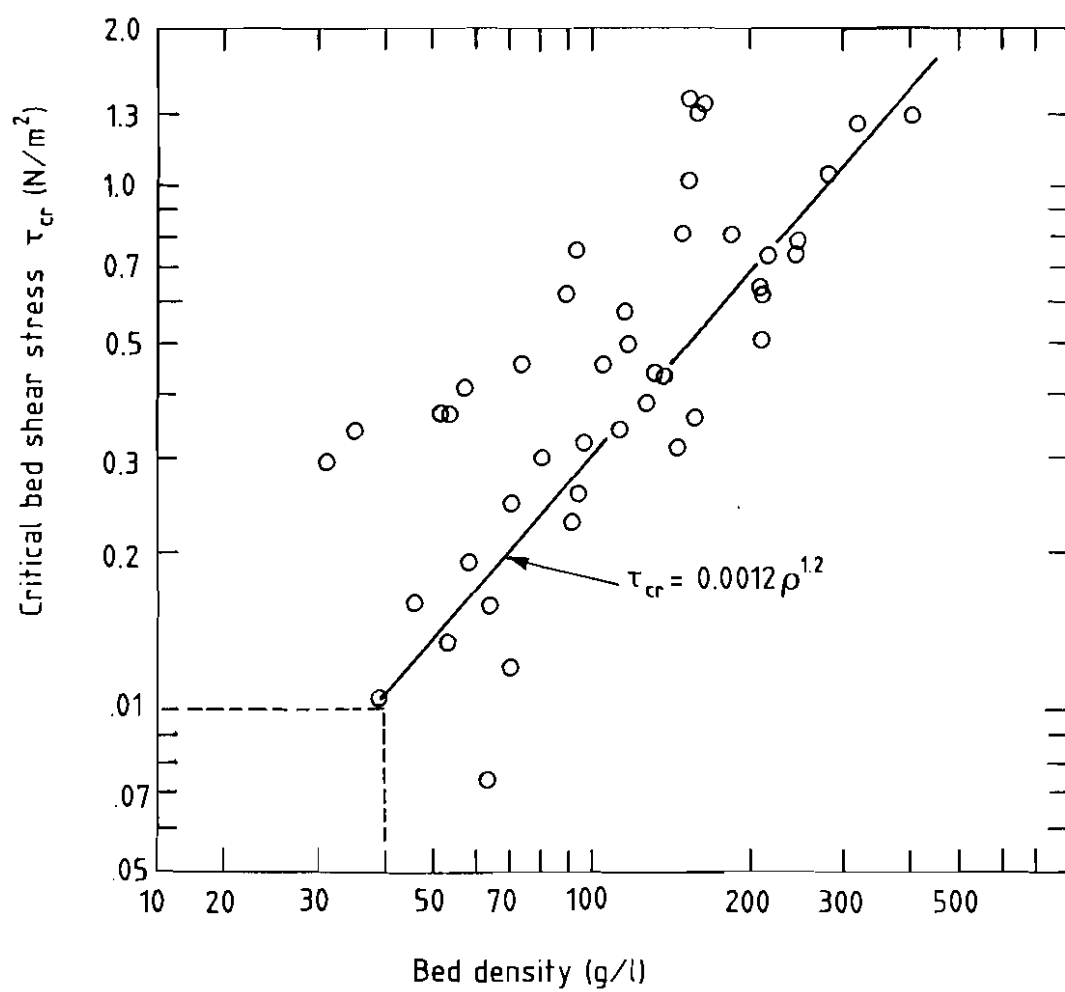


Fig 24 Erosion threshold stress against bed density

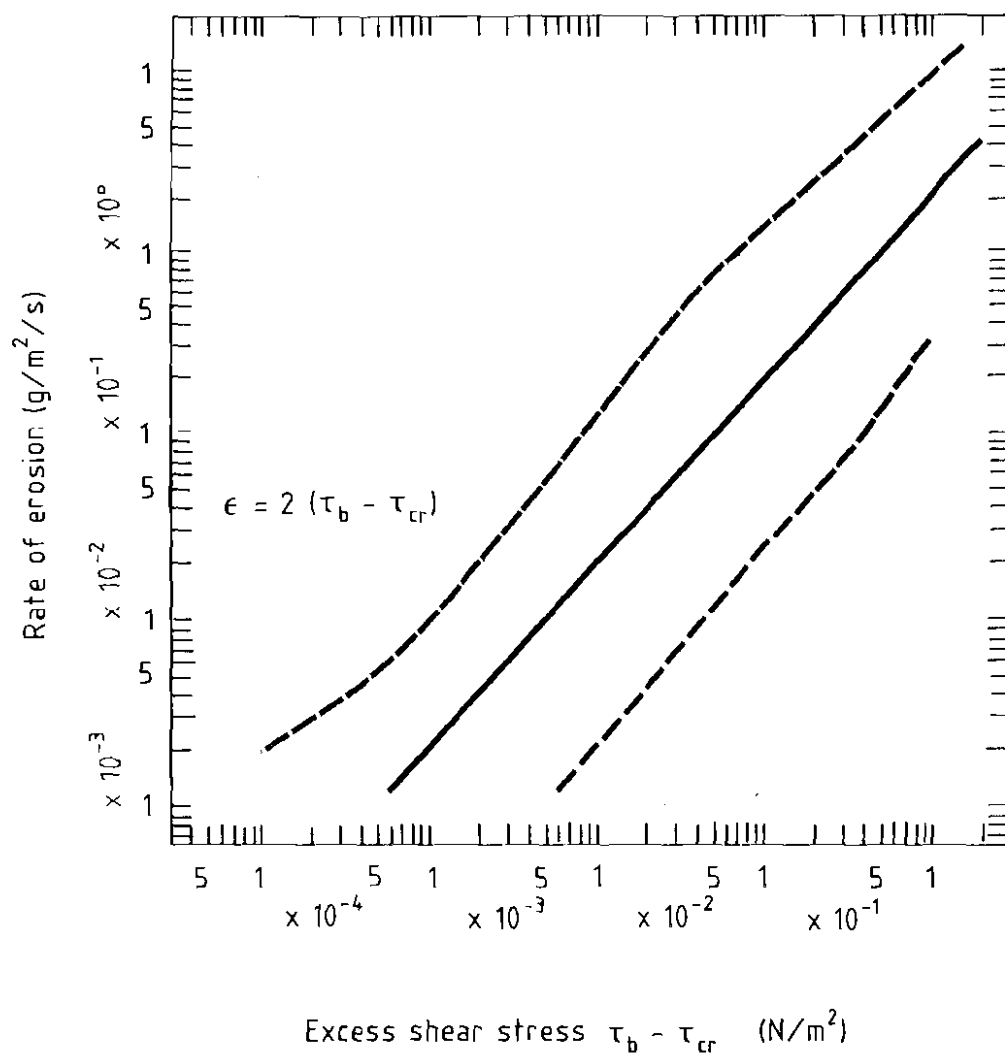


Fig 25 Rate of erosion against excess bed shear stress

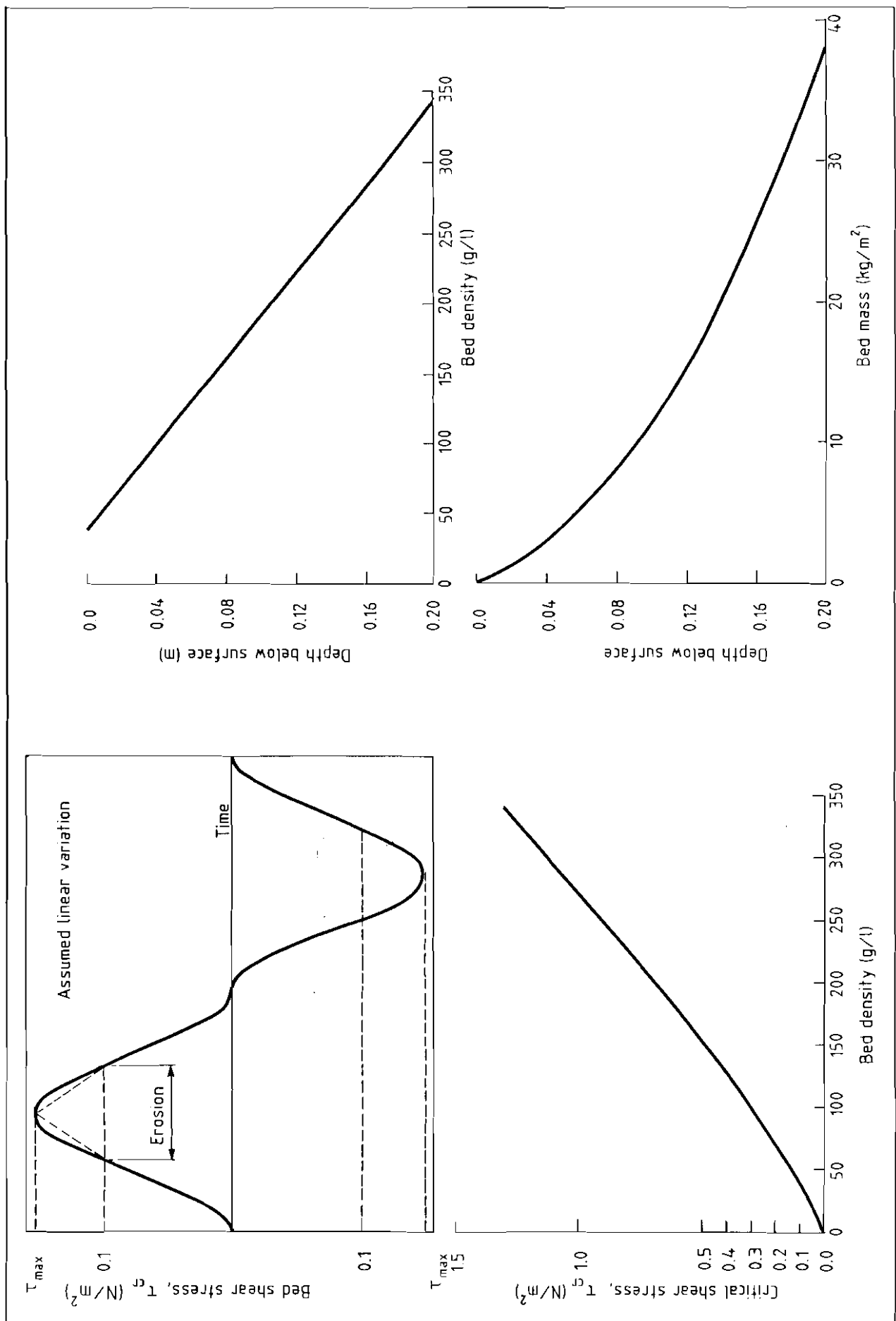


Fig 26 Periods of erosion in a tidal cycle and assumed bed characteristics

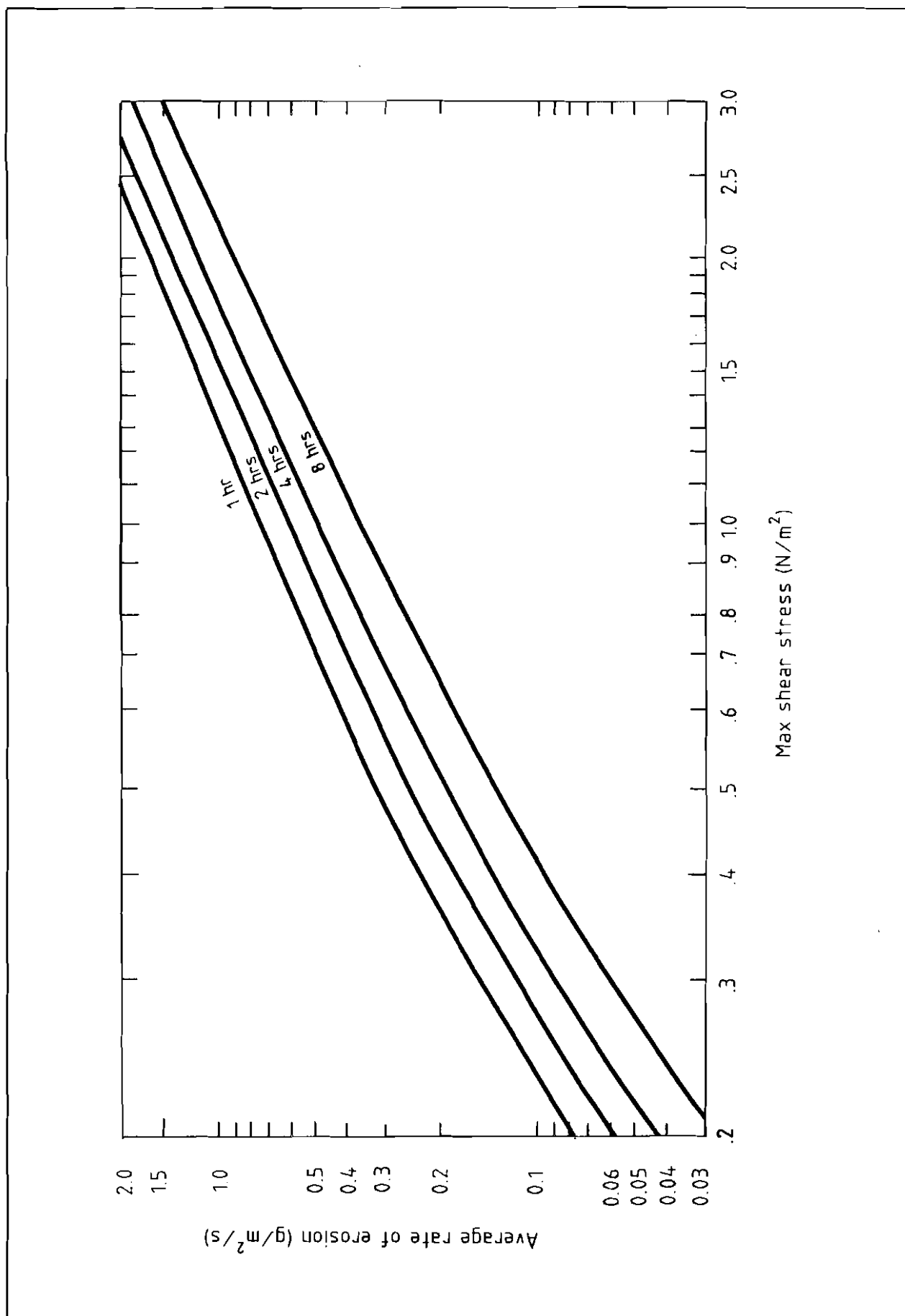


Fig 27 Average rate of erosion against maximum shear stress and time

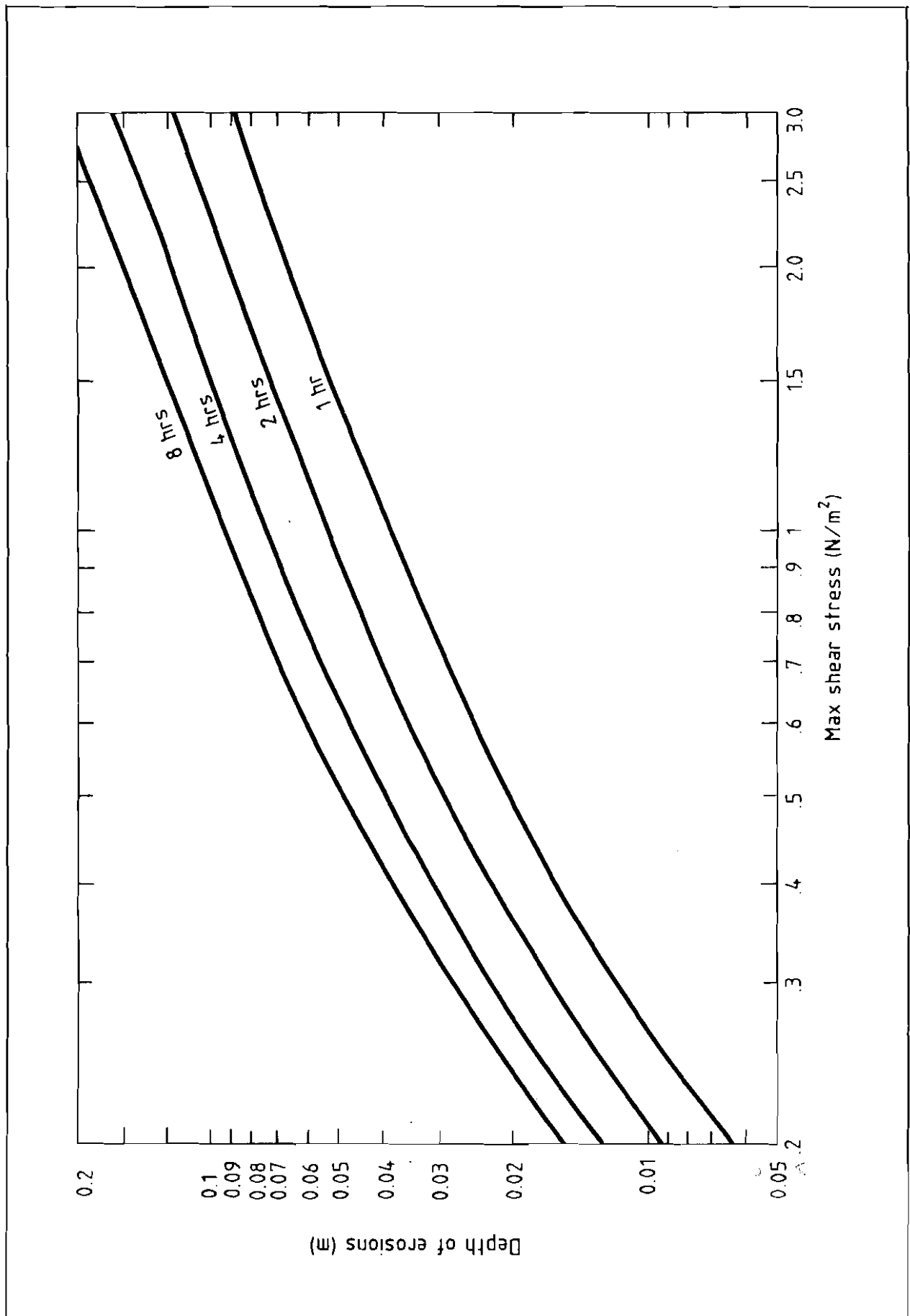
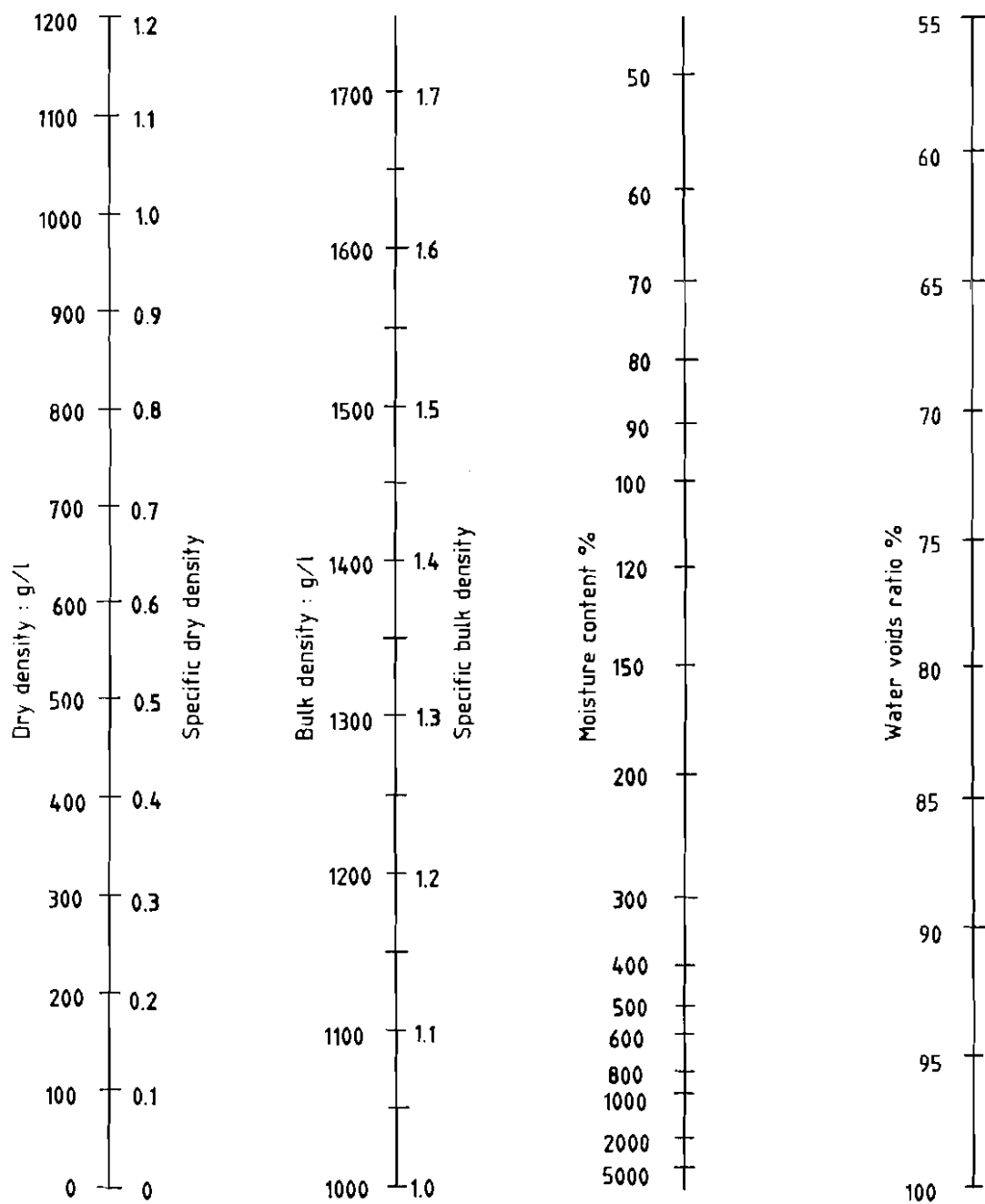


Fig 28 Depth of erosion against maximum shear stress and time



Note : For sediment specific gravity of 2.65
 Conversions between dry density, bulk density,
 moisture content and water voids ratio

Fig 29 Conversions between dry density, bulk density,
 moisture content, and water voids ratio

