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ESTUARINE MUDS MANUAL

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ABSTRACT

This report is an update of the working manual part of 'The hydraulic engineering characteristics of estuarine muds' Report No SR77, December 1986, made in the light of research conducted at Hydraulics Research Ltd (HR) and invited comments received from end users in the industry. A considerable research programme has been undertaken by HR since the publication of Report No SR77 and valuable information has been gained in respect of the behaviour of mud during tidal cycles (Ref 2), the deposition of sediment from flowing water (Ref 20), the consolidation of weak mud beds (Ref 26), the effect of sand on the consolidation and erosion processes (Ref 27) and the response of mud beds under waves (Refs 32 and 33). These findings have been incorporated into this revised manual.

Report No SR77 was widely circulated to consulting engineers, contractors, academics and staff at HR, with a request for their views on the report's technical content, style and usability. Approximately half of the recipients replied with helpful and, in many cases detailed comments. Overall, the general impression was positive and encouraging. This report has been drafted with these comments taken into account wherever possible.

This report 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.

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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 (Ref 1) 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 easy to understand why studies of cohesive sediment have been empirical and site specific rather than of a more fundamental nature.

Most of 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 recently been undertaken at Hydraulics Research (Ref 2) and some of the results are reported herein.

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.

Flocculation of sediment particles 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 elsewhere (Refs 3 and 4).

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. All three of these mechanisms operate in an estuary although it was postulated (Ref 5) 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.

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 shown in Figure 2 (Ref 6). 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 (Ref 7) 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, consolidation and erosion. 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.

This report 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 DEPOSITION

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 imply that laboratory measurements could be an order of magnitude lower than those measured in the field (Ref 8).

- Settling velocity of cohesive sediment is very dependent on the suspended sediment concentration. Settling velocities increase with higher suspended concentrations. (Refs 5, 9, 10 and 11).

- Variation in settling velocities is considerable for sediment from different locations. The data in Figure 5 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 6 (Ref 12).

- 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 7.

- Salinity may have a secondary but inconsistent effect on the settling velocity of cohesive sediment (Ref 12). This is illustrated by the Thames field data in Figure 8.

<u>Procedure</u>

- 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 5 use regression line to find W_{50} against concentration.

or

- estimate W_{50} by

$$W_{50} = 0.001C \qquad (0.05 \leq C \leq 2.0) \qquad (1)$$

where

W_{50} = median settling velocity of flocs (ms^{-1})
C = suspended sediment concentration (kgm^{-3})

- for an estimate of W_n/W_{50} use Figure 6.

2.2 Rate of deposition in still water

Knowledge

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

$$\frac{dm}{dt} = -C.W_{50} \qquad (2)$$

where

$\frac{dm}{dt}$ = mass flux per unit area ($kgm^{-2}s^{-1}$)

C = suspended sediment concentration (kgm^{-3})

W_{50} = median settling velocity of flocs (ms^{-1})

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 series of simple 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 equation 1.

Procedure

- instantaneous rate of deposition can be calculated from equation 2 if the particular variation of W_{50} with C and the near bed concentration of suspended sediment are known.

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.

2.3 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 (Refs 3, 4, 13, 14, 15, 16, 17, 18, 19 and 20).

Recent developments have been made in the modelling of the deposition from flowing water of a distributed sediment (Refs 20 and 21). A distributed sediment is a term which is used to describe a sediment which is not easily characterised by a single settling velocity and critical bed shear stress for deposition. Such a sediment may be better represented by considering the sediment to be divided into a number of classes, each of which has a distinct concentration, settling velocity and critical bed shear stress. On the other hand, a uniform sediment is one which may be reasonably characterised by a single settling velocity and critical bed shear stress for deposition.

Although some of the earlier experimental work was conducted using fairly uniform sediments it is now being recognised that estuarine sediments may more typically behave as a distributed sediment. However, as is discussed in the literature (Ref 20), the application of a distributed sediment model is at present difficult.

Knowledge

- for a given flowing uniform or distributed suspension there exists a bed shear stress below which all of the sediment will eventually deposit. The magnitude of this critical bed shear stress, τ_{cd}, is between 0.06 and 0.10Nm^{-2}.

- the rate of deposition of a uniform sediment at a bed shear stress τ_b, where $0 \leqslant \tau_b \leqslant \tau_{cd}$ may be estimated by

$$\frac{dm}{dt} = - pC.W_{50} \qquad (3)$$

where

p = probability
C = suspended sediment concentration (kg m^{-3})
W_{50} = median settling velocity of flocs (ms^{-1})

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

$$p = (1 - \tau_b/\tau_{cd}) \qquad (4)$$

where

p = probability

τ_b = bed shear stress (Nm^{-2})

τ_{cd} = critical bed shear stress for total deposition (Nm^{-2})

- for a given flowing distributed suspension there exists a high bed shear stress, τ_m, above which none of the sediment will deposit (τ_m is approximately 0.5 to 1 N m^{-2}).

- the amount of a distributed 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 proportion of the suspended sediment which remains in suspension after a few hours at a constant bed shear stress τ_b, may be estimated by (Refs 17 and 20)

$$\frac{C_f}{C_o} \approx \left(\frac{\tau_b - \tau_{cd}}{\tau_m - \tau_{cd}}\right)^{\alpha} \qquad (\tau_{cd} < \tau_b < \tau_m) \qquad (5)$$

where

C_f = final suspended sediment concentration (kgm^{-3})

C_o = initial suspended sediment concentration (kgm^{-3})

τ_b = bed shear stress (Nm^{-2})

τ_{cd} = critical bed shear stress for total deposition ie $C_f/C_o = 0$ (Nm^{-2})

τ_m = critical bed shear stress for no deposition (Nm^{-2})

α = index (approximately equal to 0.5)

Procedure - Uniform sediment

- instantaneous rate of deposition can be calculated 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 $\tau_b \leqslant \tau_{cd}$, 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 $\tau_b \leqslant \tau_{cd}$ 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 depth averaged suspended sediment concentration.

Procedure - Distributed sediment

- for an estimate of the amount of sediment left in suspension at a constant shear stress in the long run (ie approximately 6h) use equation 5.

- to estimate the likely effect of the distributed sediment examine the sensitivity of a uniform sediment calculation with an increased value of τ_{cd} between 0.1 and 0.3 Nm^{-2}

3 CONSOLIDATION

3.1 Bed formation depth

The growth of a loose bed from a suspension of cohesive sediment is depicted diagramatically in Figure 17. From an initial homogeneous 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 (Refs 22, 23, 24, 25 and 26).

<u>Knowledge</u>

- the formation mean density of a mud bed measured in tests in settling columns is largely independent of both the solids concentration of the suspension and the salinity and may be approximated to 80kgm^{-3}.

<u>Procedure</u>

- 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 80kgm^{-3}. This is done in Figure 18.

3.2 Mean density variation with time

Knowledge

- self weight consolidation of loose beds with the accompanying large strains is difficult to model mathematically without the laboratory determination of certain relationships.

- 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 (Refs 5 and 26).

Procedure

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

or

- determine an estimate for the mean density of a bed with time from the data in Figure 19 .

3.3 Density variations with depth and time

Knowledge

- an empirically based numerical model has recently been developed (Ref 26) which enables prediction of the time and depth varying density of a consolidating mud bed.

Procedure

- conduct laboratory settling column tests and measure in-situ density throughout the depth and determine the empirical relationships between effective stress and voids ratio and permeability and voids ratio. Use numerical model to predict the behaviour of a consolidating bed.

or

- the density at a certain depth within a bed may be roughly estimated from the laboratory data presented in Figure 20.

3.4 Effect of sand

Knowledge

- recent experimental work (Ref 27) has indicated that the density of the near surface region of a consolidating mud bed is increased if sand has passed through.

Procedure

- at the present time it is prudent to advise that due attention be given to muddy beds in which small amounts of sand may have been deposited. It should be recognised that this would increase the density of the bed.

4 EROSION

4.1 Threshold of erosion by currents

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 (see for example Refs 2, 3, 6, 28, 29 and 30) and the second category to beds formed from a thick slurry or remoulded with, in some cases, additional compaction.

Knowledge

- a consolidating bed of cohesive sediment has an increasing density with depth (see Fig 20).

- 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 strength, τ_{ce}, which is just insufficient to cause erosion (see Fig 21).

Procedure

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

or

- assume a density profile for the bed and use the relationship shown in Figure 22 to find τ_{ce} against density.

4.2 Rate of erosion by currents

Knowledge

- when the bed shear stress, τ_b, exceeds the critical shear strength, τ_{ce}, the rate of erosion is best described as a function of the difference, $\tau_b - \tau_{ce}$, termed the excess shear stress.
- variation in experimental data is considerable both for a particular cohesive sediment and between different cohesive sediments.
- the erosion constant appears to be dependent to some degree on the rate of increase of bed shear stress (Ref 27) with its value decreasing with decreasing rate of increase of bed shear stress.
- the introduction into the bed of a small quantity of fine sand (~15% by dry weight) can reduce the erosion constant by half (Ref 27).

Procedure

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

or

- instantaneous rate of erosion may be estimated from the data in Figure 23 with E=0.002, ie

$$\frac{dm}{dt} = E\,(\tau_b - \tau_{ce}) \qquad (6)$$

where

$\frac{dm}{dt}$ = mass flux per unit area ($kgm^{-2}s^{-1}$)

E = erosion constant ($kgN^{-1}s^{-1}$)
τ_b = bed shear stress (Nm^{-2})
τ_{ce} = shear strength of mud (Nm^{-2})

- average rate of erosion for the period during the tidal cycle when $\tau_b > \tau_{ce}$ may be calculated by a time step model given known relationships of density against depth, critical shear stress against density and rate of erosion against excess shear stress.

or

- average rate of erosion and depth of erosion for the period during the tidal cycle when $\tau_b > \tau_{ce}$ may be estimated for the assumed relationships of density against depth, critical shear strength against density given in Figure 24, and equation 6, from Figures 25 and 26.

4.3 Erosion by waves

Knowledge

- consideration of the physical processes of waves as an eroding mechanism of mud 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 necessarily be based on the assumption of a rigid bed (Ref 31).

- fluidisation of the upper layer of a mud bed will occur for certain mud characteristics as a result of wave induced orbital velocities (Ref 32)

- the erosion rate of mud from the surface of a mud bed (density $1280 \mathrm{kgm}^{-3}$) was found to be similar to the proportional excess shear stress relationship for current erosion given in equation 6 (Ref 33)

Procedure

- conduct laboratory tests using the specific mud to determine the critical wave shear stress for fluid mud generation and entrainment into suspension of low density beds, ie $< 1200 \mathrm{kgm}^{-3}$ and the erosional characteristics of higher density beds.

or

- for an order of magnitude estimate of erosion rate use equation 6 in which τ_b is replaced by the peak bed shear stress due to the waves.

5 CALCULATION OF FIELD BED SHEAR STRESS

5.1 Current induced 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).

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.within 1m, 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 gradient of the line is $du/d(\log_{10} y)$ and the shear velocity is given by $u_* = 0.174\, du/d(\log_{10} y)$. The bed shear stress is related to the shear velocity by

$$\tau_b = \rho\, u_*^2 \qquad (7)$$

where

τ_b = bed shear stress (Nm^{-2})
ρ = density of fluid (kgm^{-3})
u_* = frictional shear velocity

or

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

  $$u_* = \bar{u} \,.\, n \sqrt{g}/h^{1/6} \quad \text{(m-s units)}$$

  where

  n = Manning's bed roughness coefficient (typically in the range 0.012-0.018 for very soft mud beds or 0.018 to 0.030 for compacted mud beds)

  g = acceleration of gravity
  h = depth of flow.

  The bed shear stress can be calculated using equation 7.

or

- use the smooth turbulent law for very soft mud beds given by

$$\frac{u}{u_*} = 5.75 \log \frac{u_* \, y}{\nu} + 5.5 \qquad (8)$$

where

u = velocity at height y (ms^{-1})
u_* = frictional shear velocity (ms^{-1})
y = height above bed (m)

ν = kinematic viscosity (m^2s^{-1})

Assuming that the mean velocity occurs approximately 0.37 times the depth of the water above the bed and that $\nu \approx 1.0 \times 10^{-6}$ m^2s^{-1} the bed shear stress may be obtained from Figure 27.

5.2 Wave induced bed shear stress

<u>Knowledge</u>

- techniques for calculating the peak orbital velocities are well described elsewhere (for example, Ref 34)

- for given values of wave height and period, and depth of water, the maximum bottom orbital velocity can be calculated using first order linear wave theory from the relationship

$$U_m = \frac{\pi H}{T \sinh (2\pi d/L)} \qquad (9)$$

where

U_m = maximum bottom orbital velocity (ms^{-1})
H = wave height (m)
T = wave period (s)
d = water depth (m)
L = wave length (m)

The magnitude of the wave length is determined iteratively, since

$$\omega^2 = gk \tanh (kd) \qquad (10)$$

where

$\omega = 2\pi/T$ (s^{-1})
g = acceleration due to gravity (ms^{-2})
$k = 2\pi/L$ (m^{-1})

- the peak bed shear stress under a wave can be calculated from

$$\tau_m = \tfrac{1}{2}\rho f_w U_m^2 \tag{11}$$

where

τ_m = peak bed shear stress (Nm^{-2})
ρ = fluid density (kgm^{-3})
f_w = wave friction factor
U_m = maximum bottom orbital velocity

- the wave friction factor is dependent on the wave Reynolds number and the relative roughness, ie

$$R_w = \frac{U_m A}{\nu} \tag{12}$$

where

R_w = wave Reynolds number
U_m = maximum bottom orbital velocity (ms^{-1})
A = semi-orbital excursion length = $U_m T/2\pi$ = (m)
ν = kinematic viscosity (m^2s^{-1})

and

$$r = \frac{A}{k_s} \tag{13}$$

where

r = relative roughness
A = semi-orbital excursion length = $U_m T/2\pi$ (m)
k_s = Nikuradse equivalent sand grain roughness (m)

Procedure

- the maximum bottom oribital velocity can be calculated using equations 9 and 10 or obtained from from a general curve (Ref 34) given in Figure 28.

- the peak bed shear stress can be calculated using equation (11) with f_w being the greater of the smooth (laminar or smooth turbulent) and rough bed friction factors.

- the smooth bed friction factor is calculated from

$$f_{ws} = B\ R_w^{-N} \qquad (14)$$

where

f_{ws} = smooth bed friction factor
R_w = wave Reynolds number

and for $R_w \leqslant 5.10^5$ (laminar)

$B = 2$
$N = 0.5$

or for $R_w \geqslant 5.10^5$ (smooth turbulent)

$B = 0.0521$
$N = 0.187$

- the rough bed friction factor is calculated from

$$f_{wr} = 0.3 \text{ if } A/k_s \leqslant 1.57 \qquad (15)$$

or

$$f_{wr} = 0.00251 \exp\left[5.21 \left(\frac{A}{k_s}\right)^{-0.19}\right] \text{ if } A/k_s \geq 1.57 \quad (16)$$

where

f_{wr} = rough bed friction factor
A = semi-orbital excursion length = $U_m T/2\pi$ (m)
k_s = Nikuradse equivalent sand grain roughness (m)

6 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 ration, or the void 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.

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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 capacity (meq/100g)	20	35	25
% clay minerals	51	50	75-80
Montmorillonite	nil	30	15-20
Kaolinite	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

FIGURES.

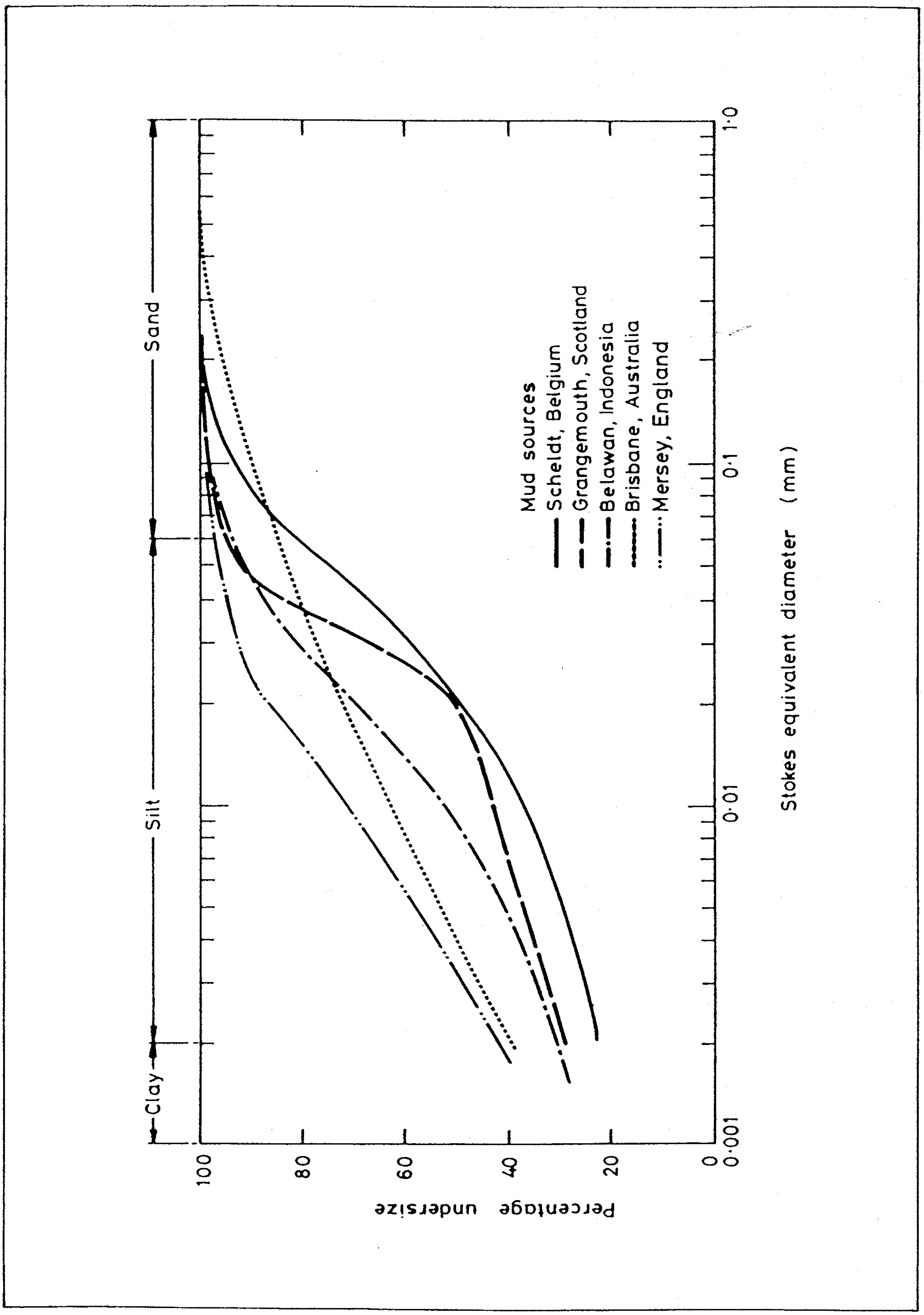


Fig 1 Particle size distribution of fine muds

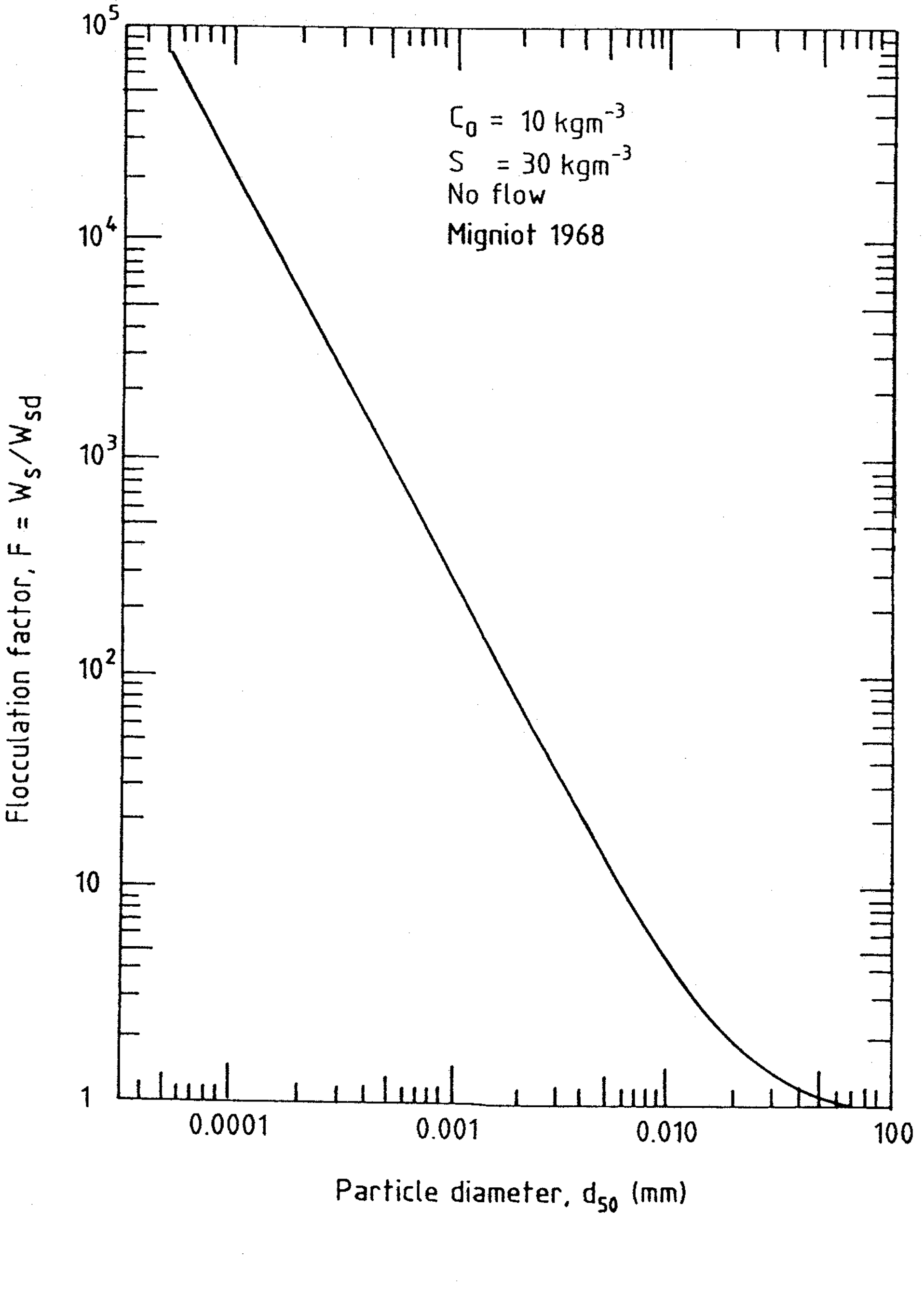


Fig 2 Flocculation factor, F, as a function of median particle diameter

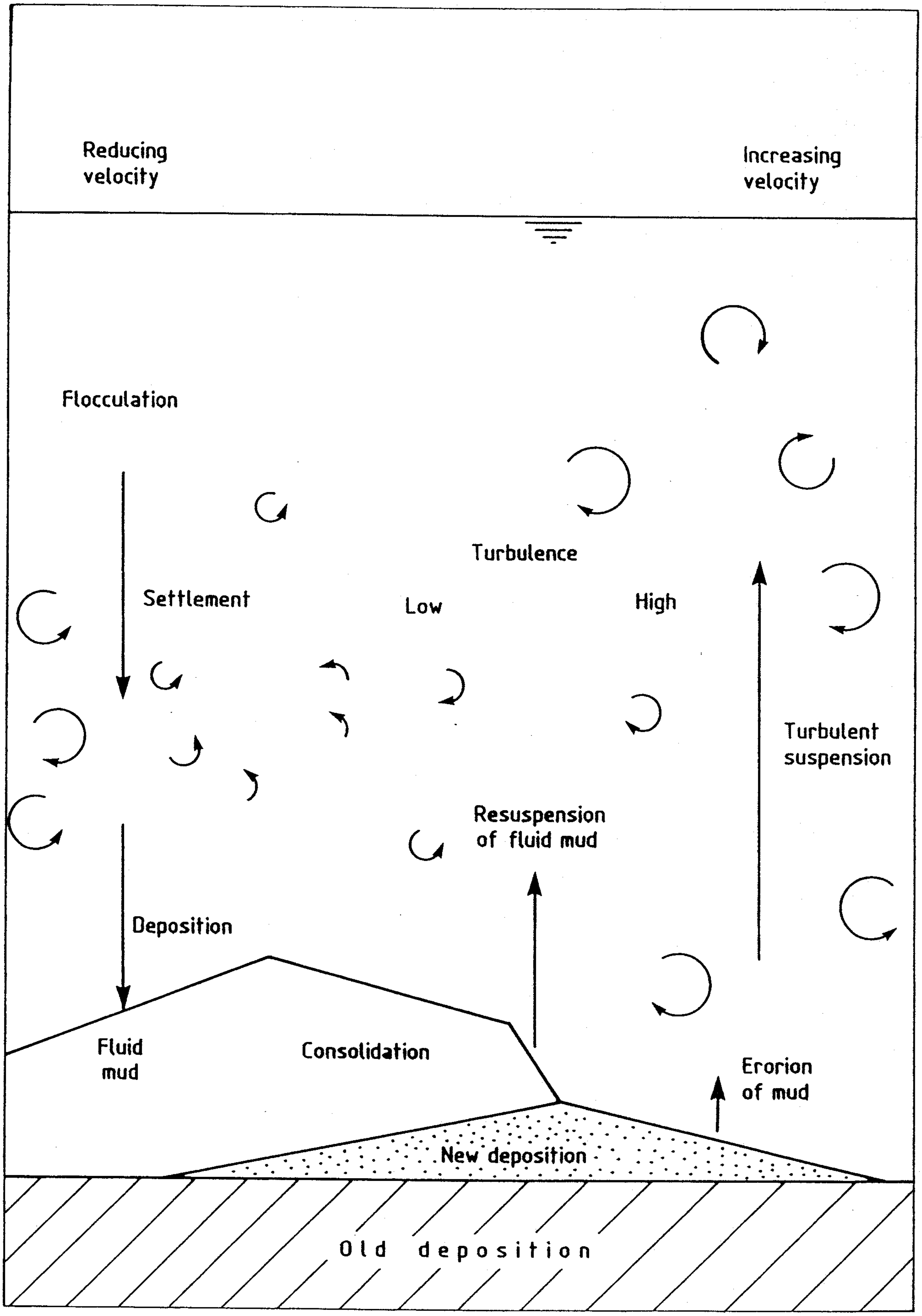


Fig 3 States of cohesive sediments

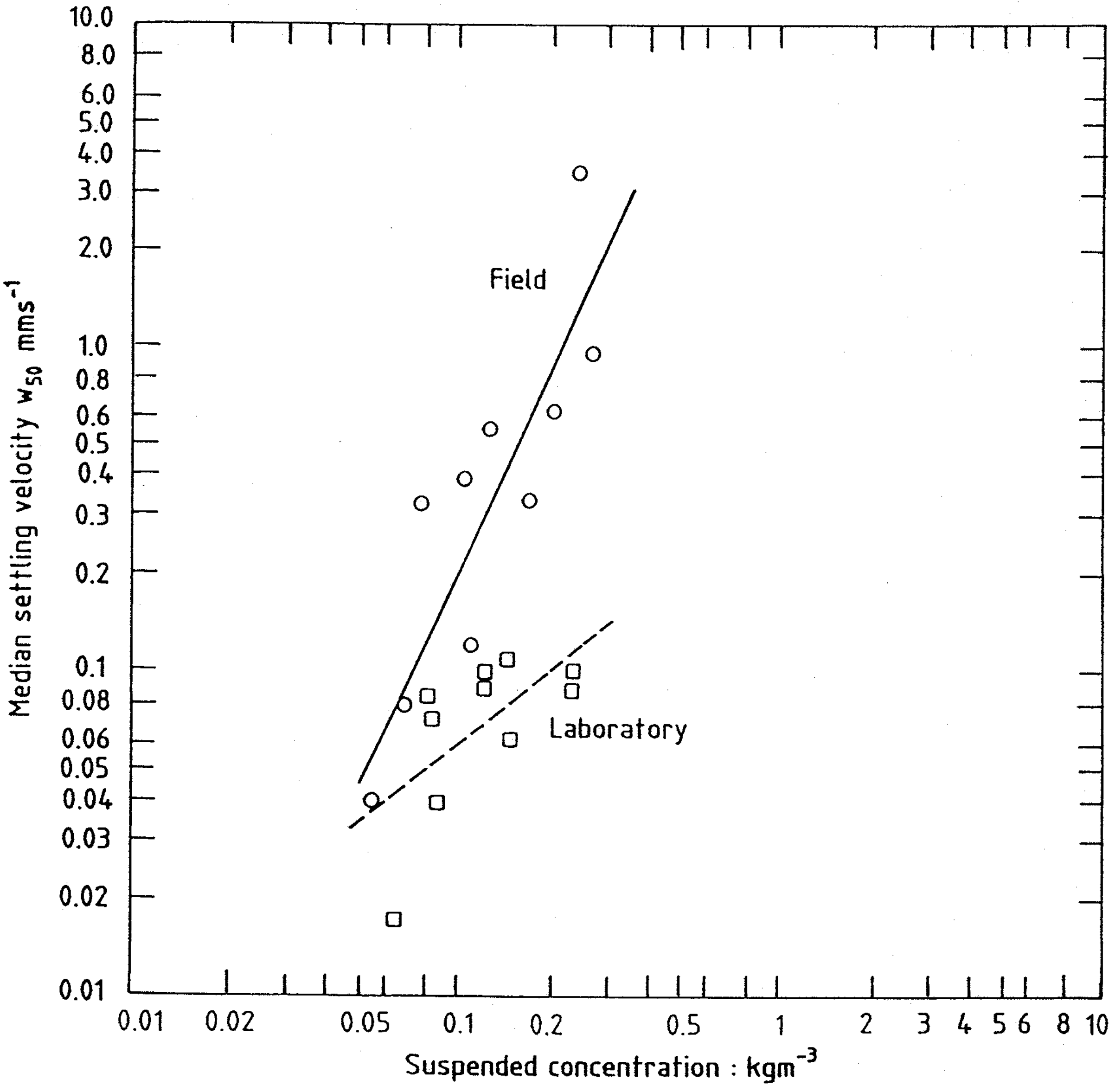


Fig 4 Median settling velocity against suspended concentration : field and laboratory

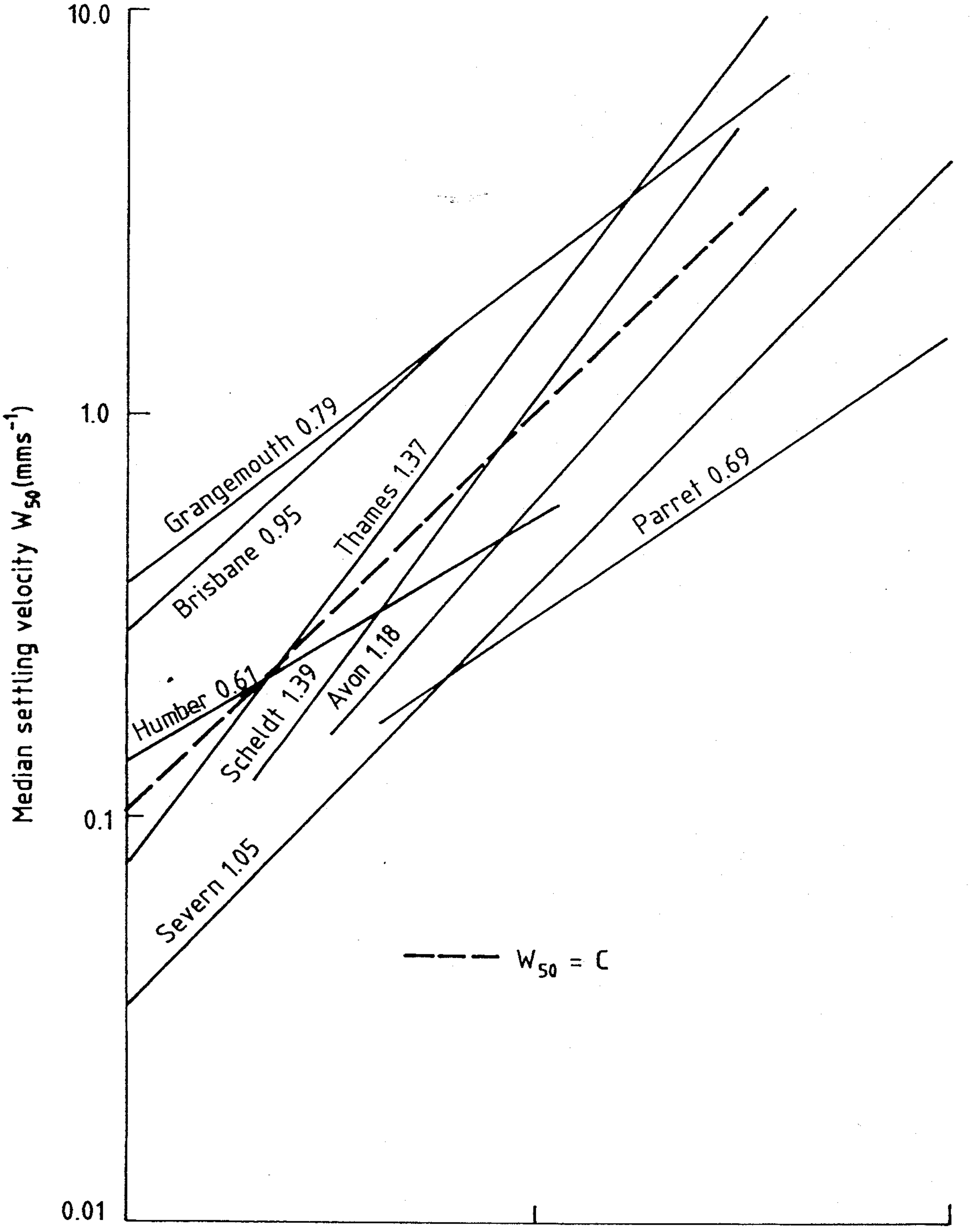


Fig 5 Median settling velocity against suspended concentration : comparison of eight estuaries

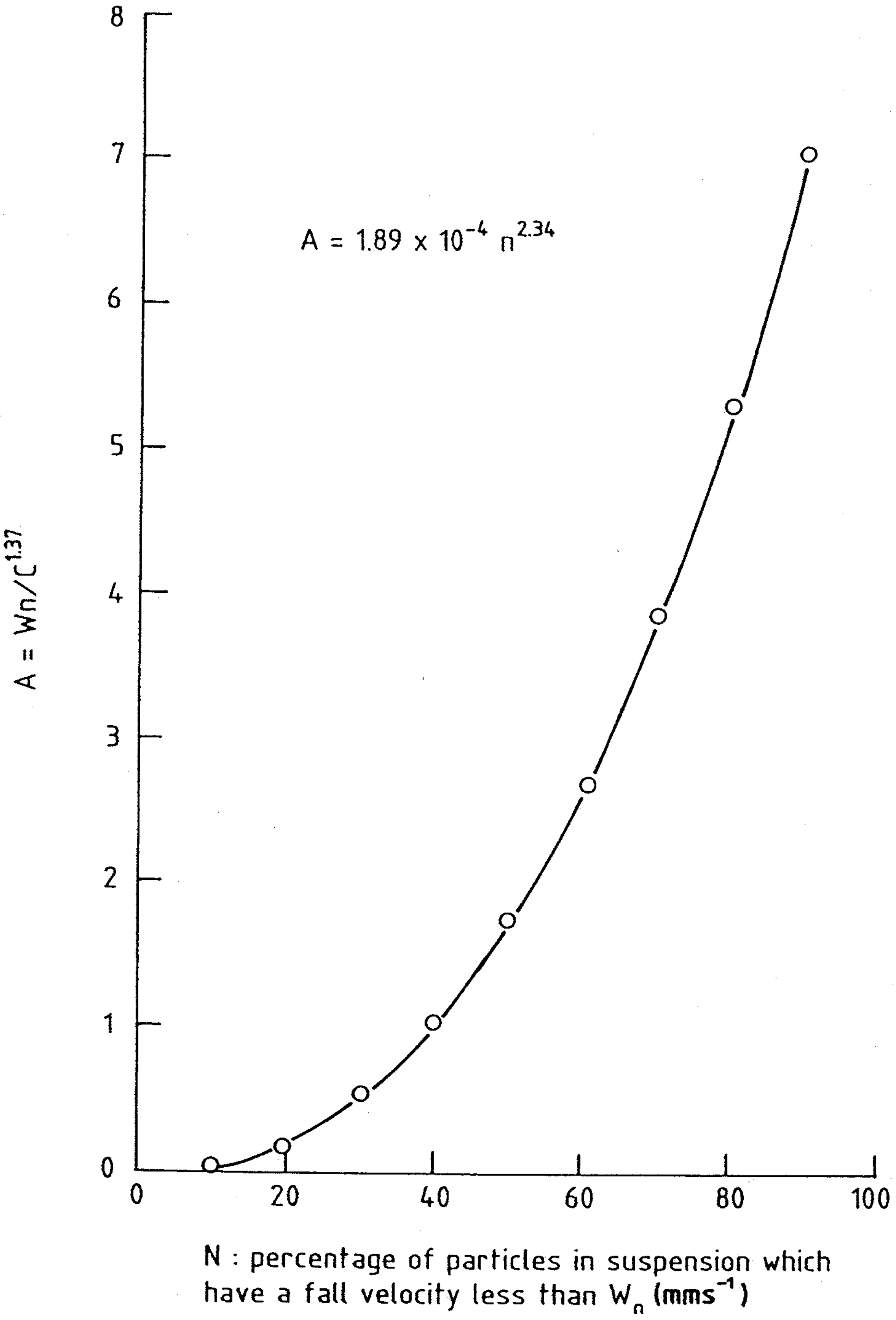


Fig 6 General equation for Thames settling velocity data

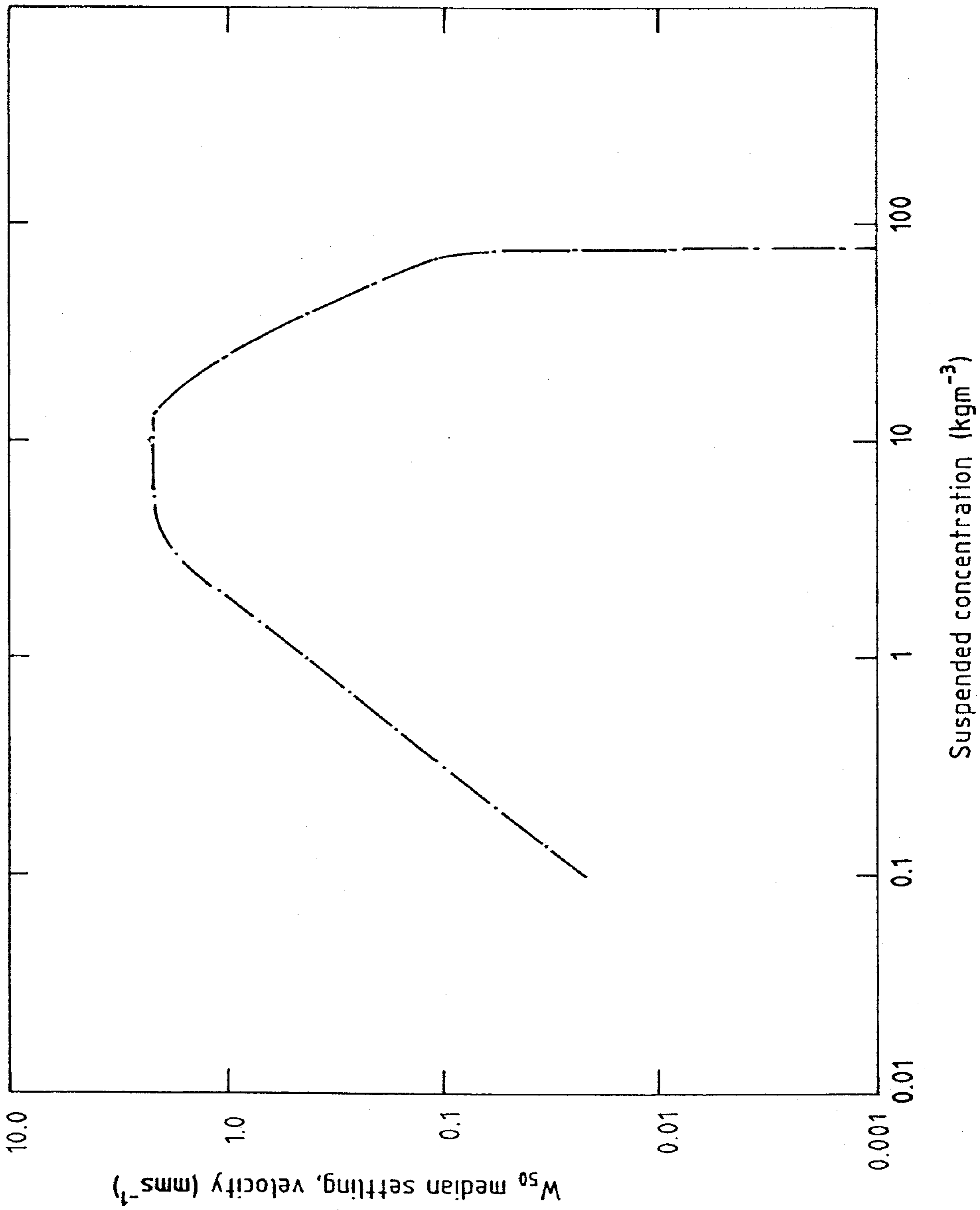


Fig 7 Median settling velocity against suspended concentration for Severn Estuary

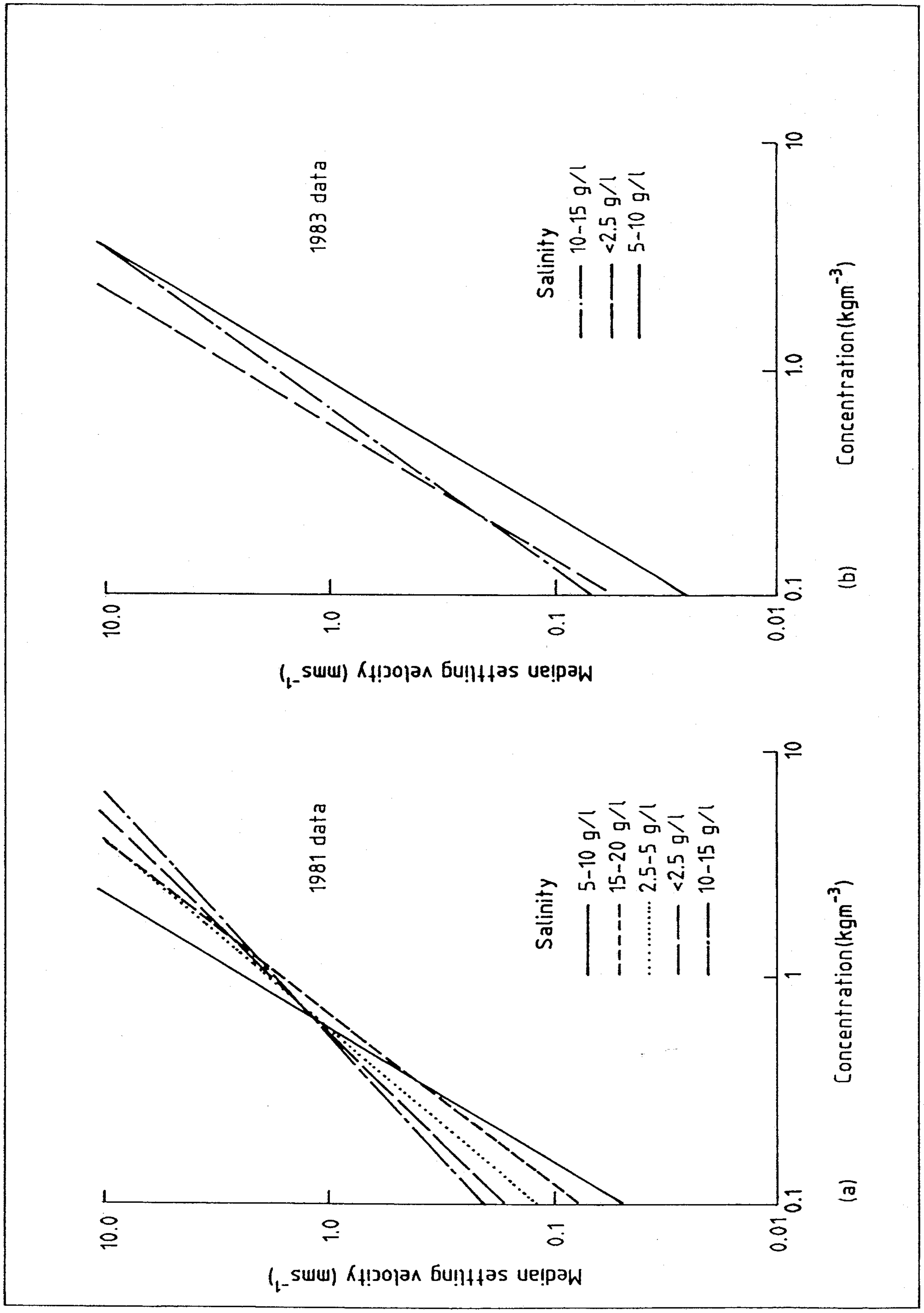


Fig 8 Effect of salinity on median settling velocity

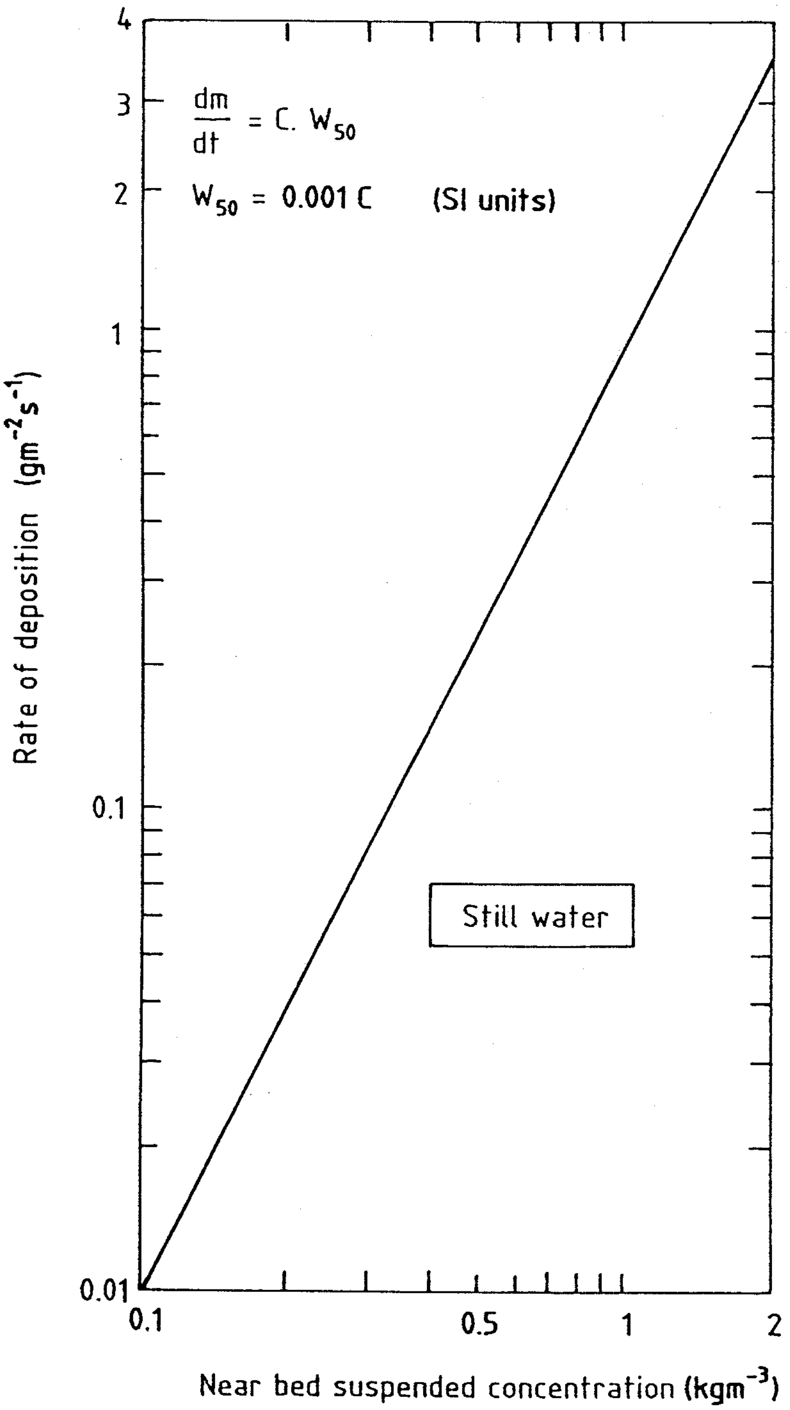


Fig 9 Rate of deposition against near bed suspended concentration

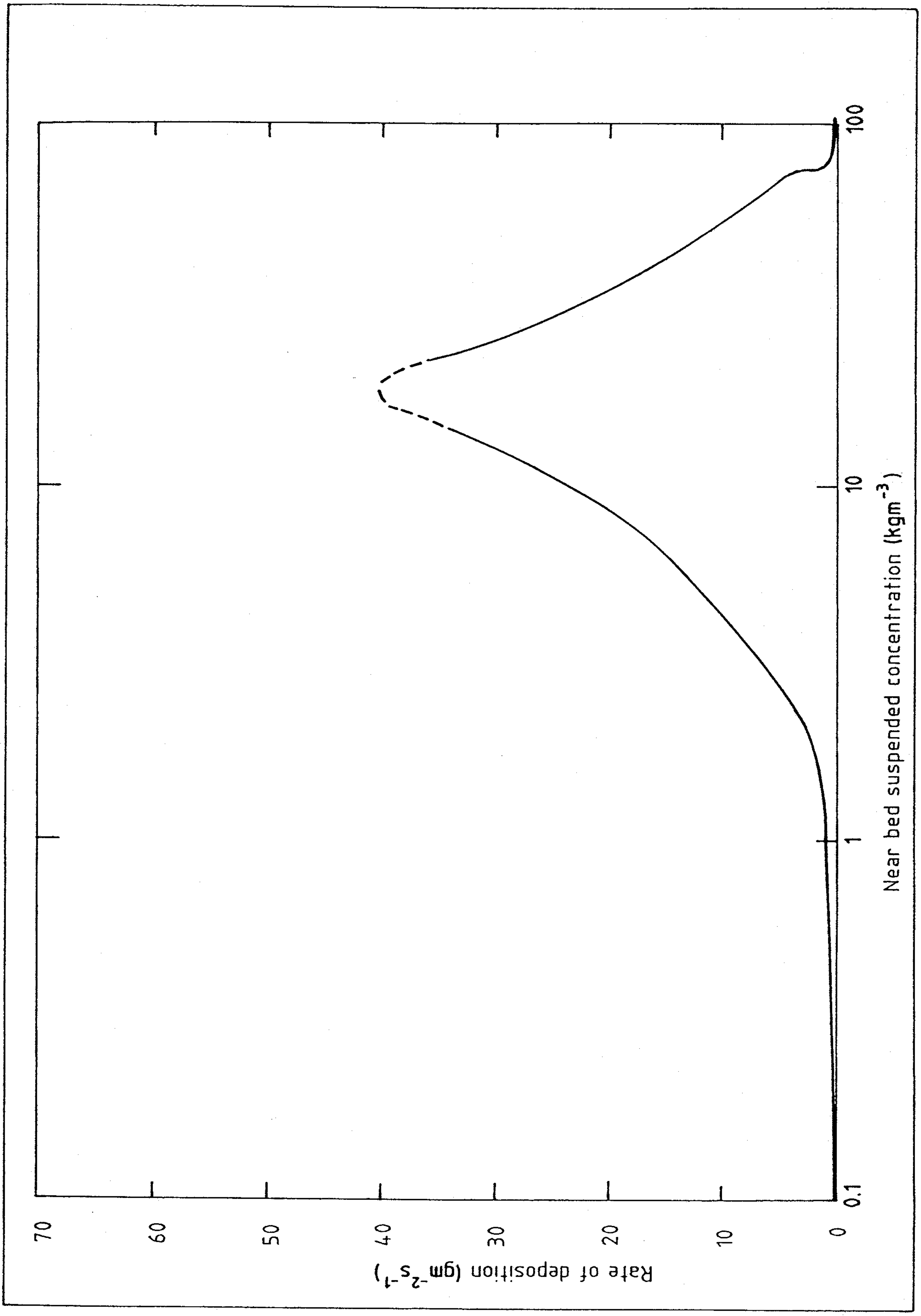


Fig 10 Rate of deposition against near bed suspended concentration : high concentration

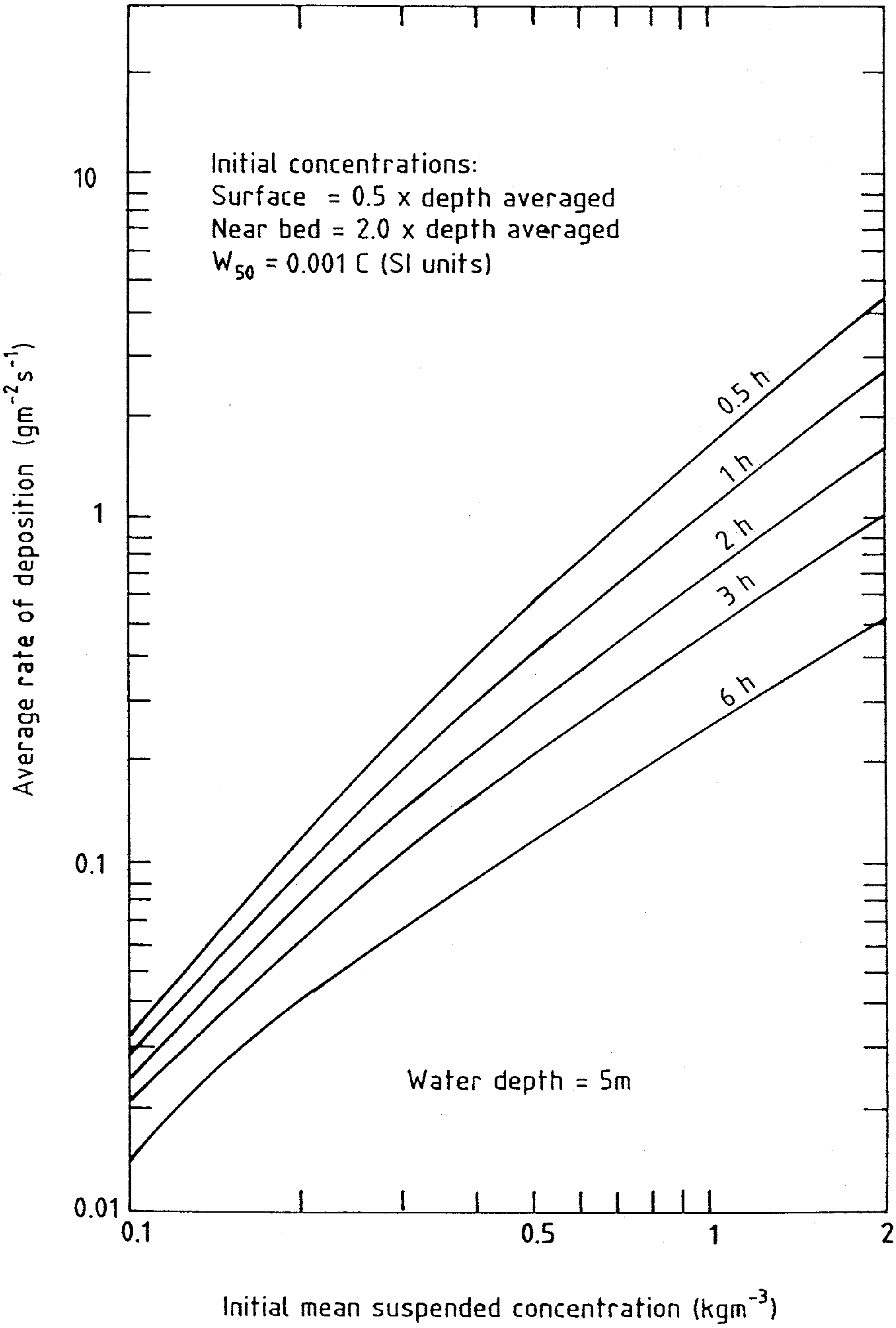


Fig 11 Average rate of deposition against initial mean suspended concentration and time, D = 5m

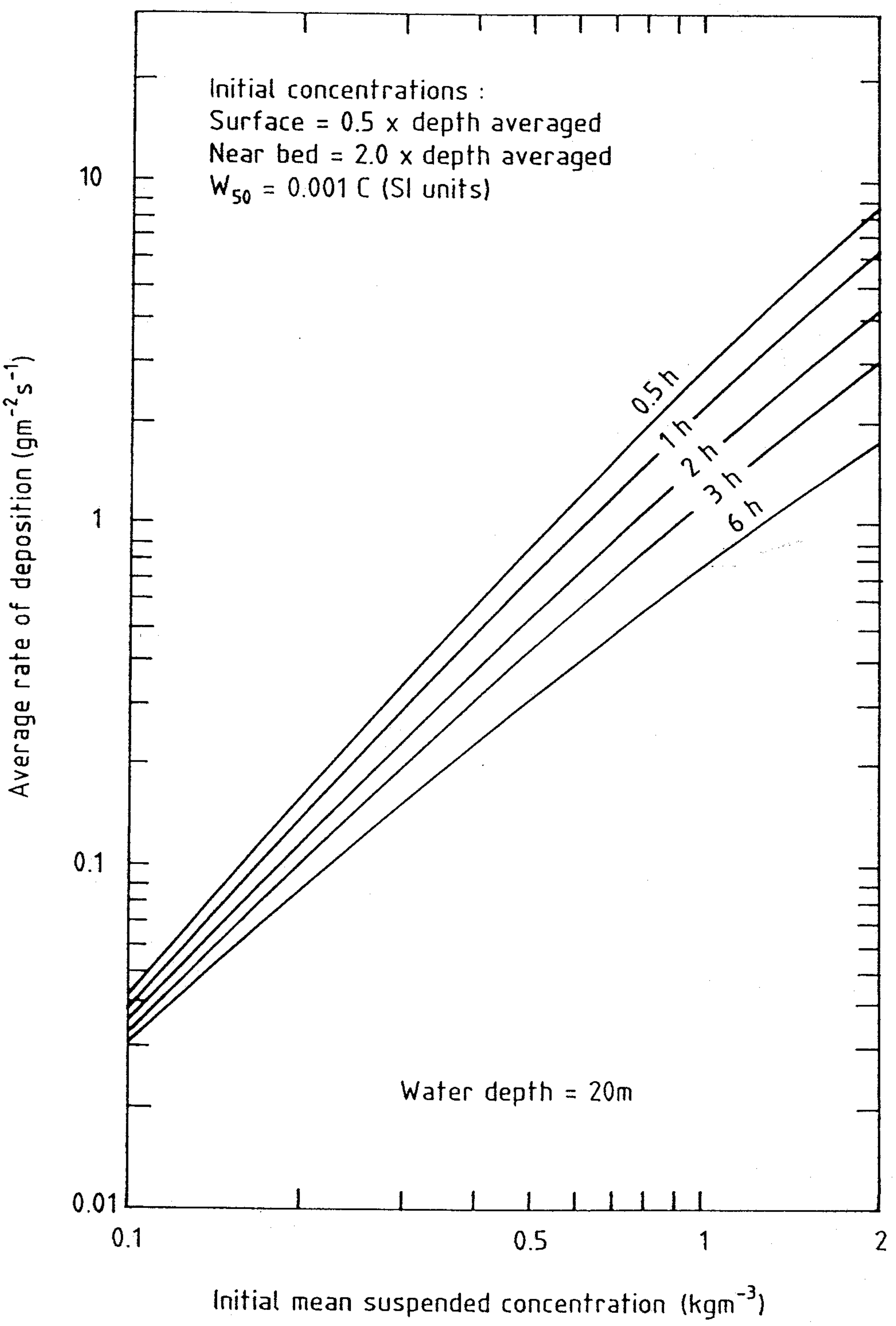


Fig 12 Average rate of deposition against initial mean suspended concentration and time, D = 20m

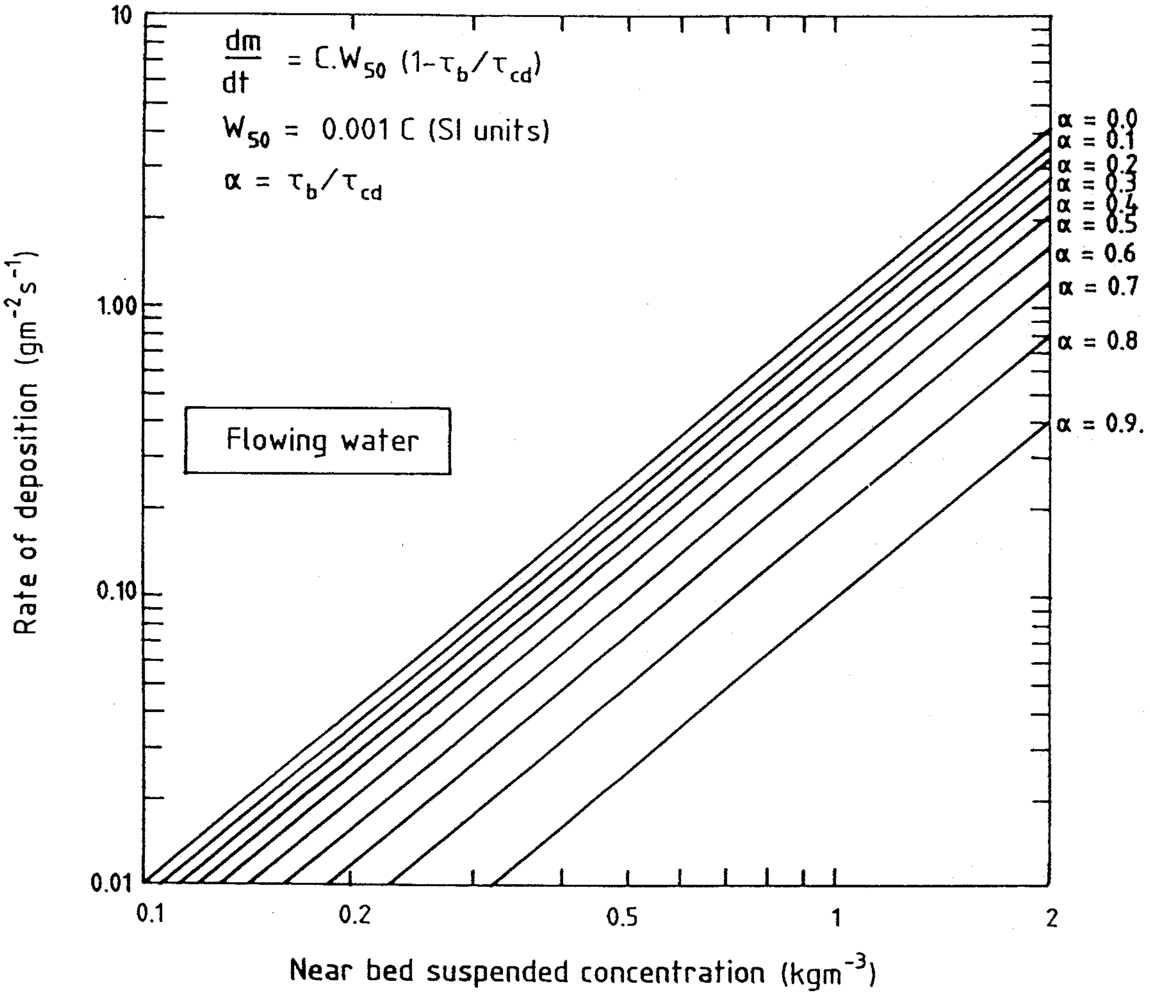


Fig 13 Rate of deposition in flowing water against near bed suspended concentration

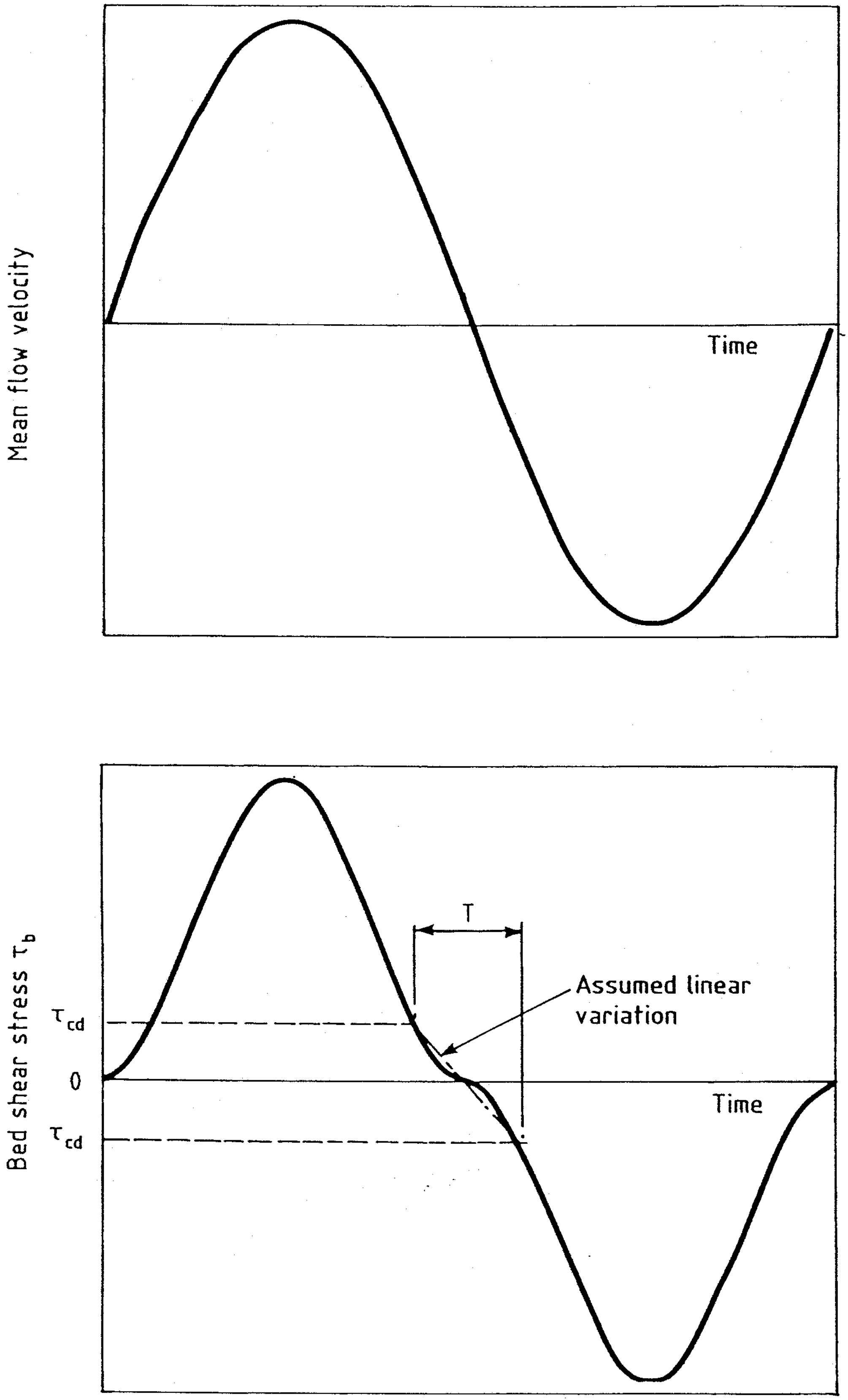


Fig 14 Periods of deposition in a tidal cycle

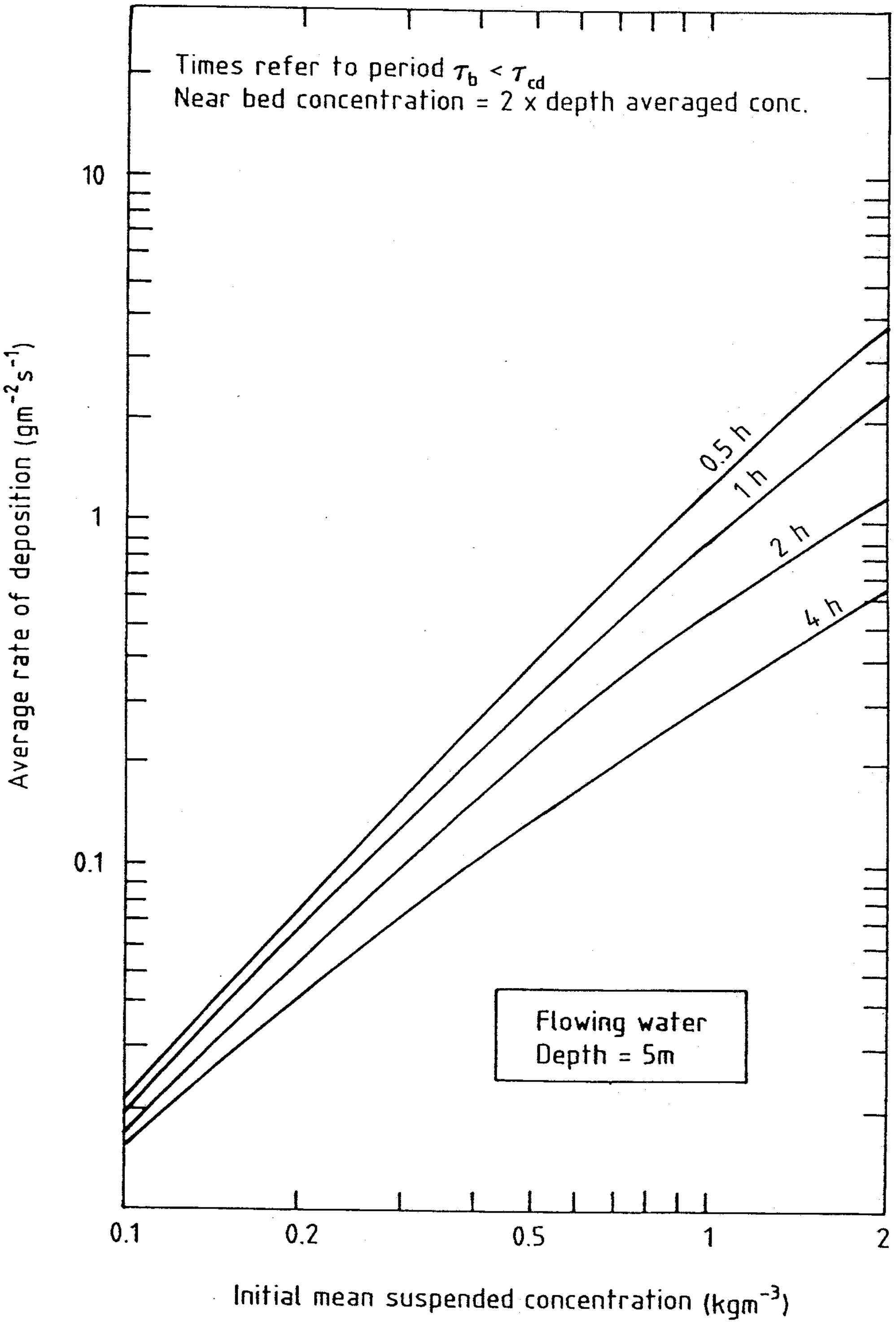


Fig 15 Average rate of deposition in flowing water against mean suspended concentration and time, D = 5m

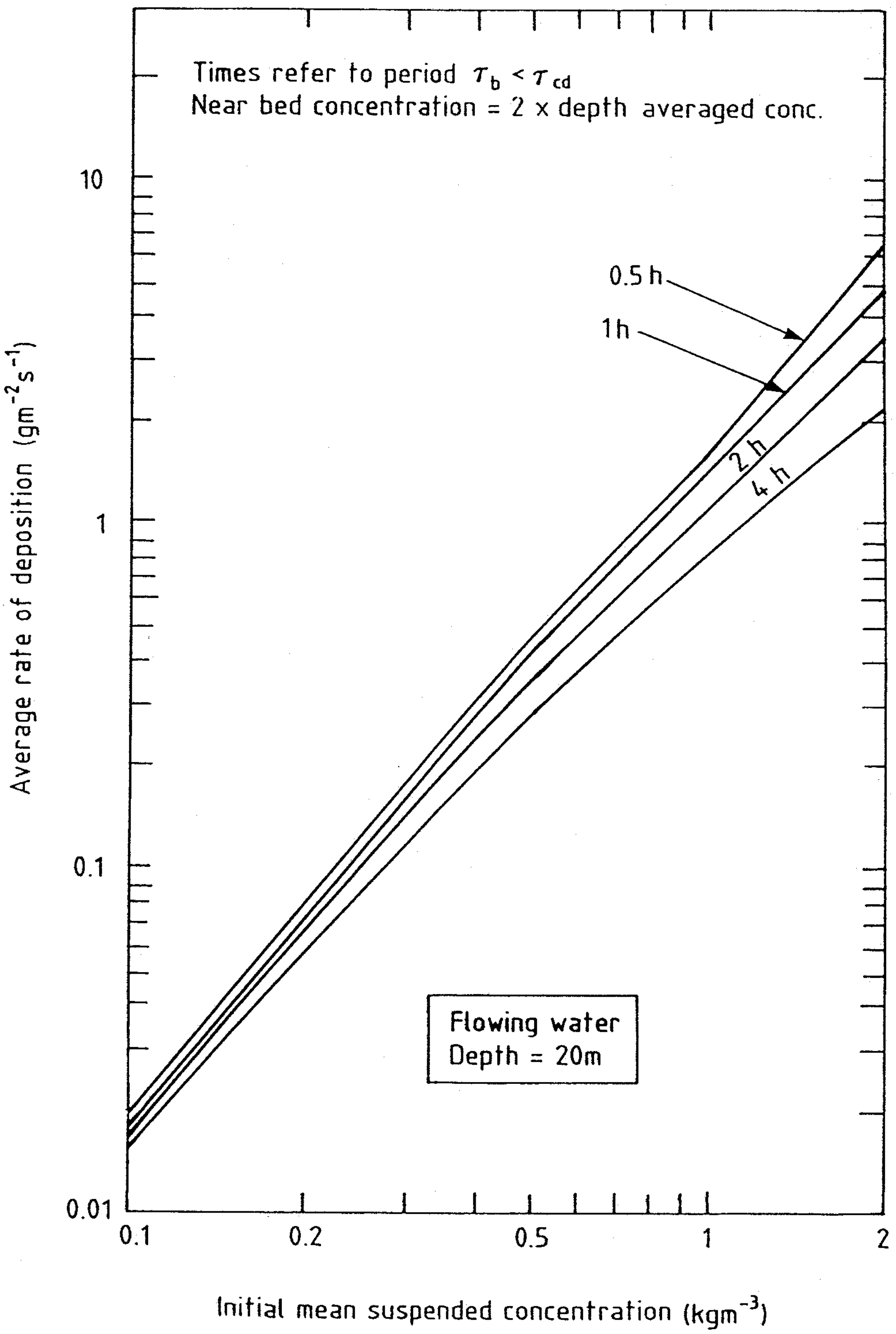
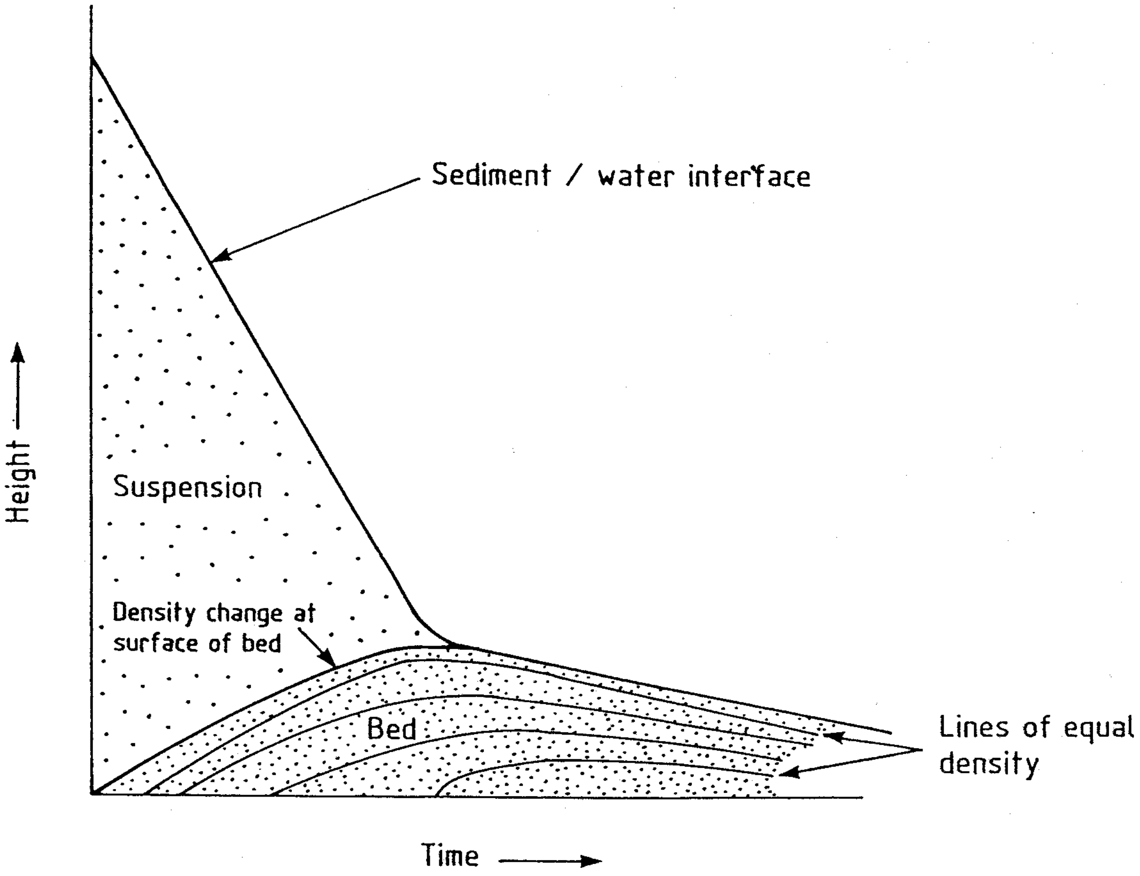


Fig 16 Average rate of deposition in flowing water against mean suspended concentration and time, $D = 20m$



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

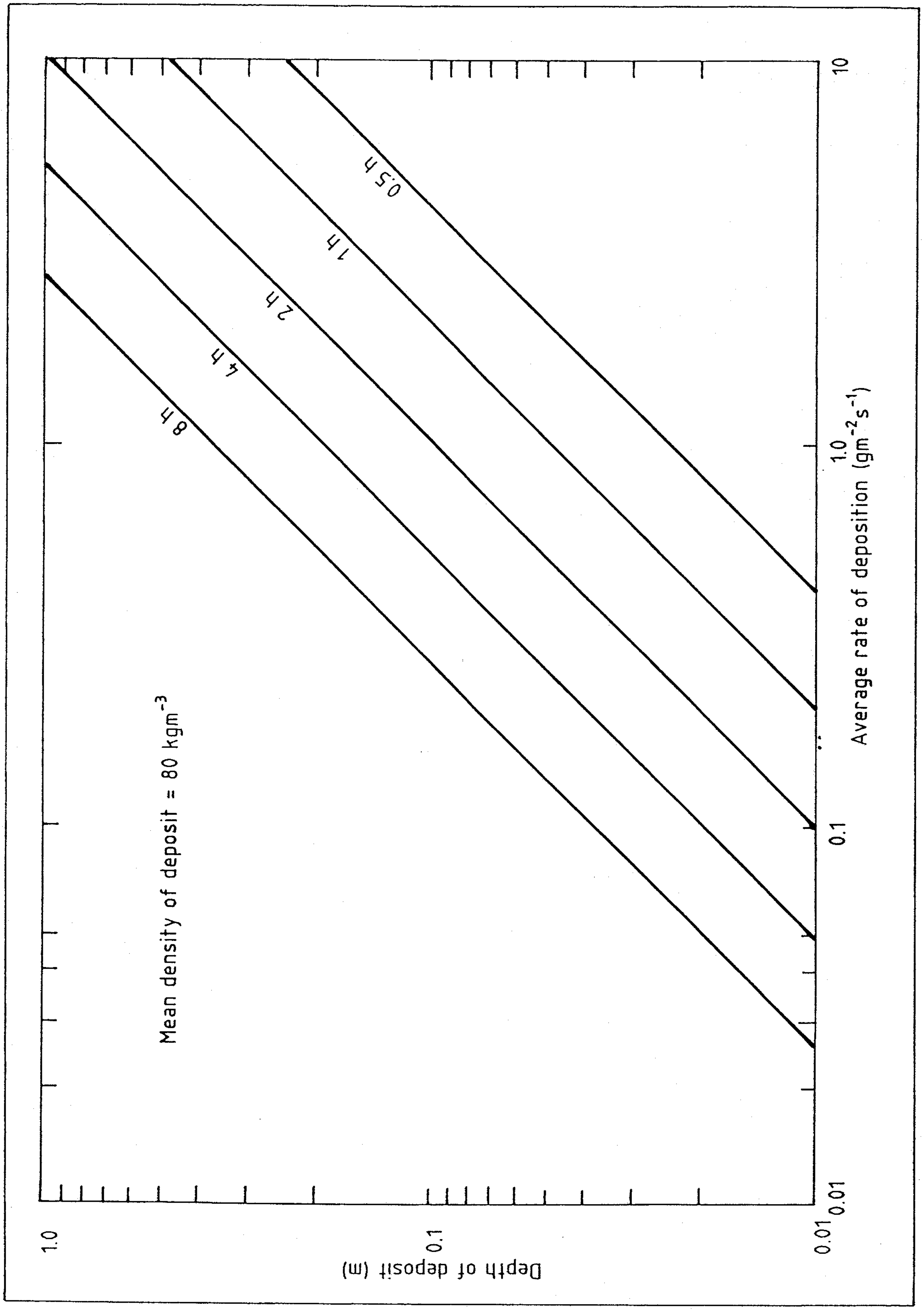


Fig 18 Depth of deposit against average rate of deposition and time

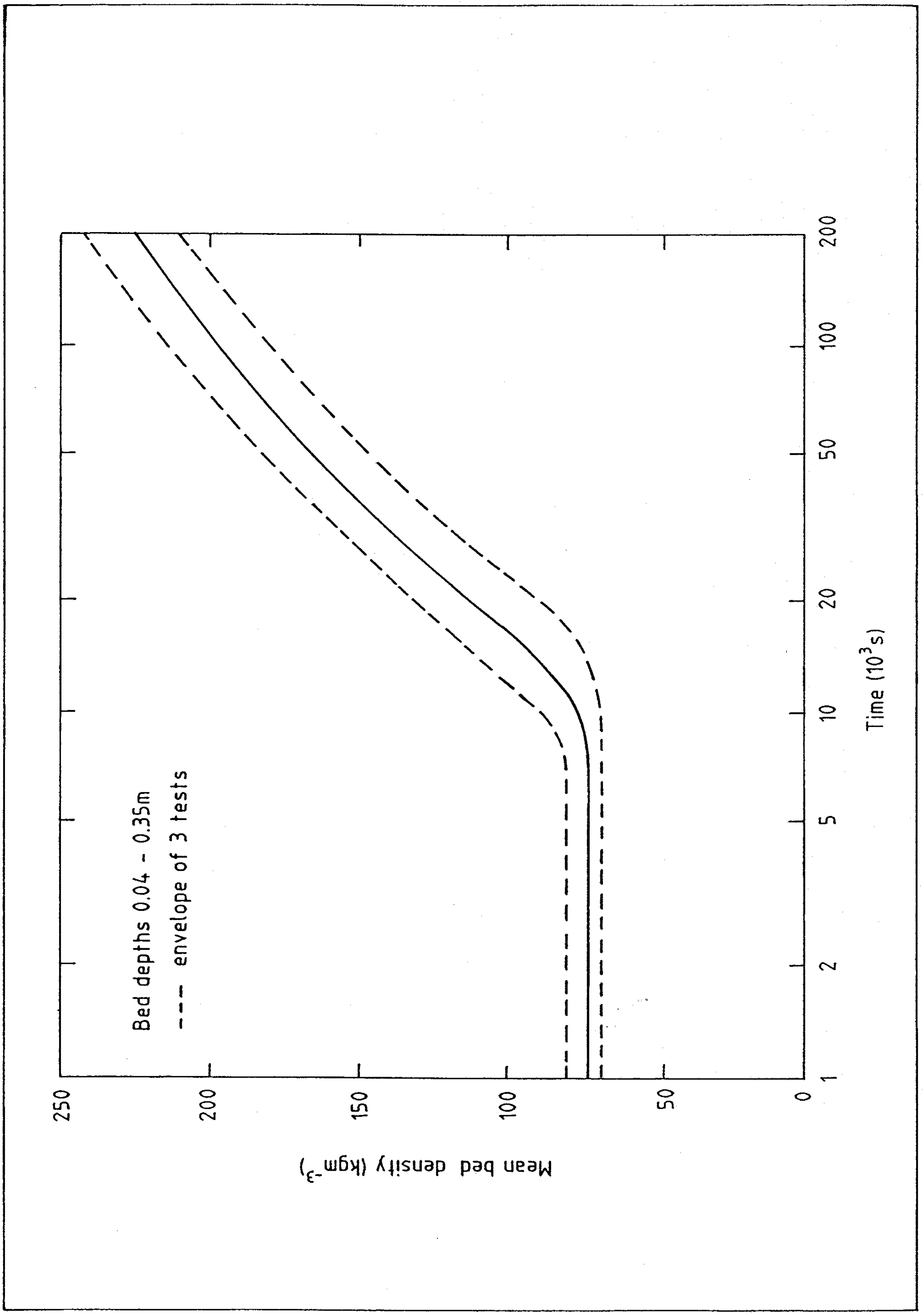


Fig 19 Rate of increase of mean density with time of a consolidating bed

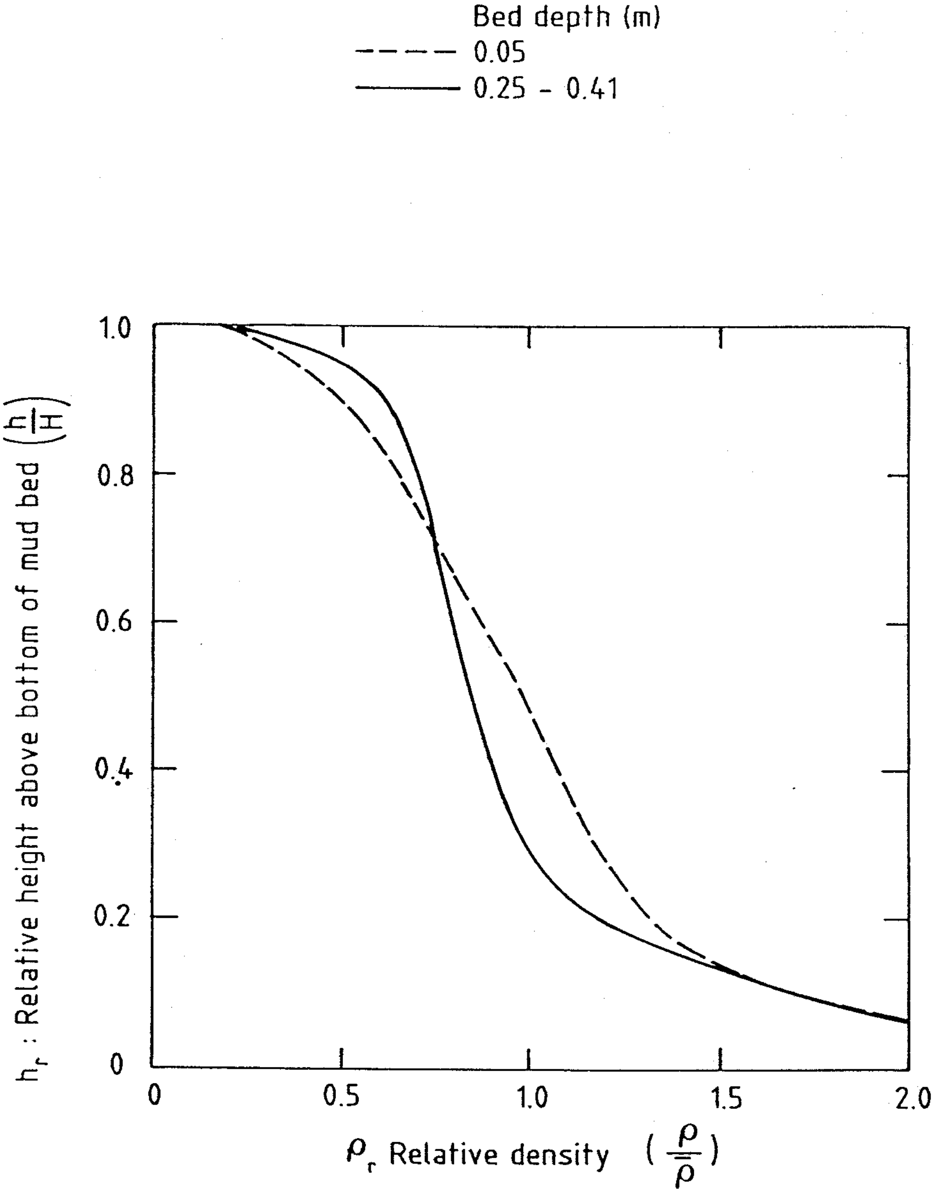
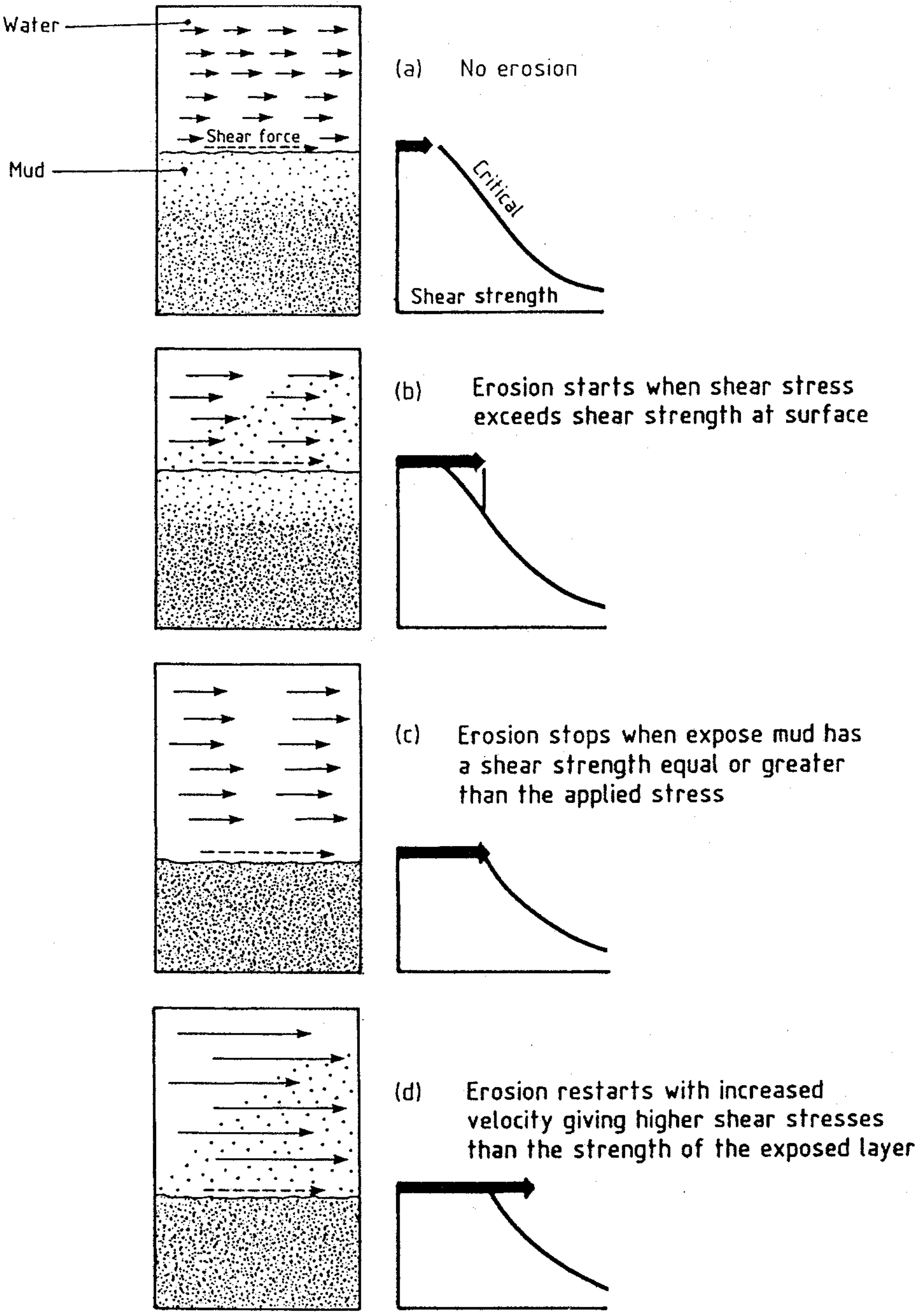


Fig 20 Dimensionless density-depth profiles of mud beds



(a) No erosion

(b) Erosion starts when shear stress exceeds shear strength at surface

(c) Erosion stops when expose mud has a shear strength equal or greater than the applied stress

(d) Erosion restarts with increased velocity giving higher shear stresses than the strength of the exposed layer

Fig 21 The cohesive sediment erosion process

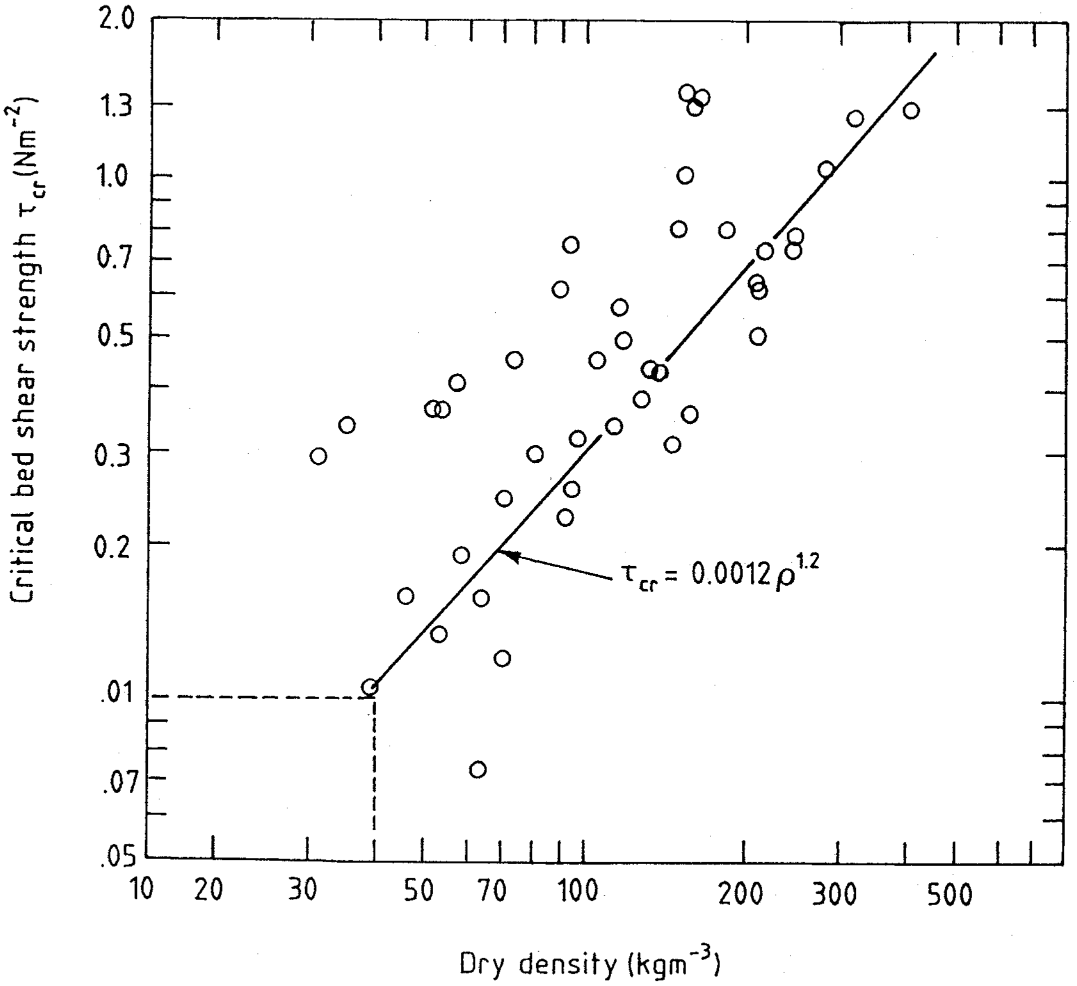


Fig 22 Erosion threshold stress against bed density

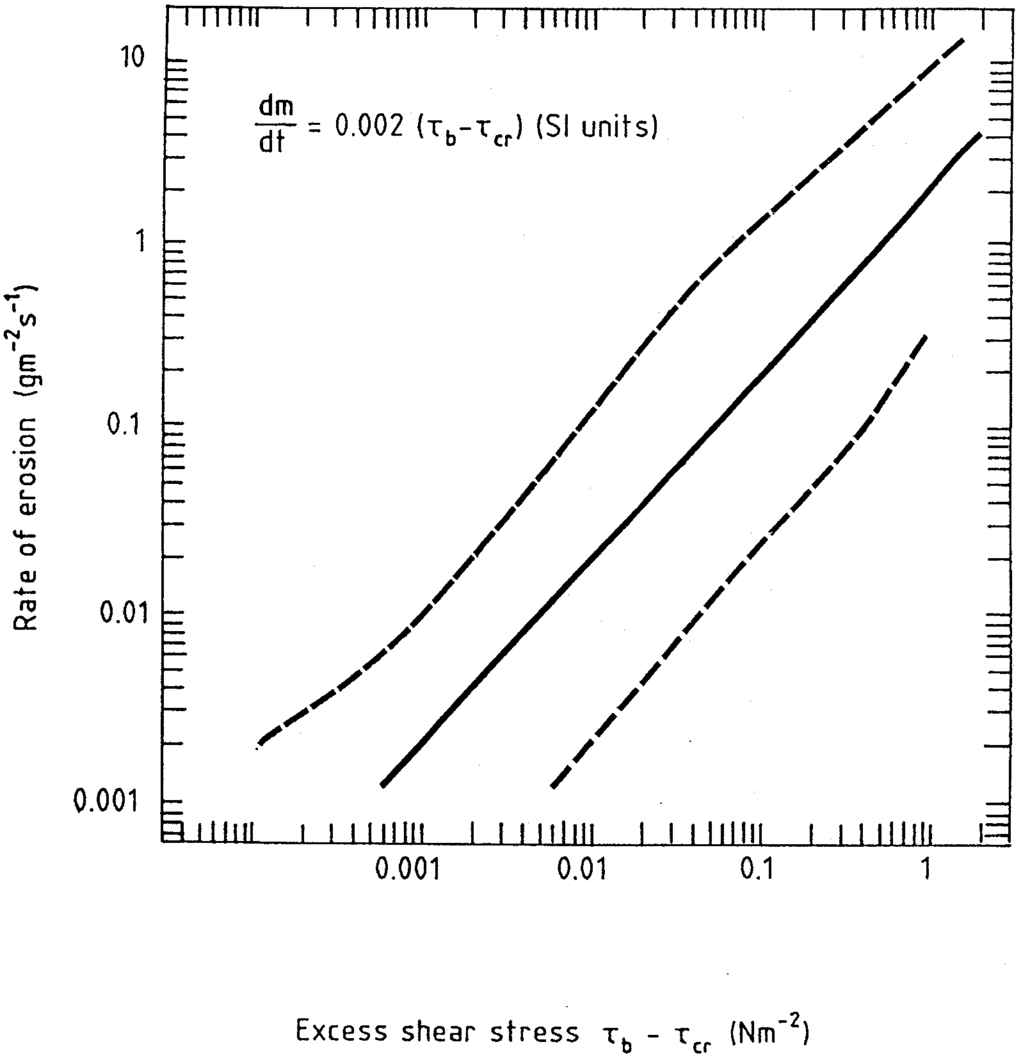


Fig 23 Rate of erosion against excess bed shear stress

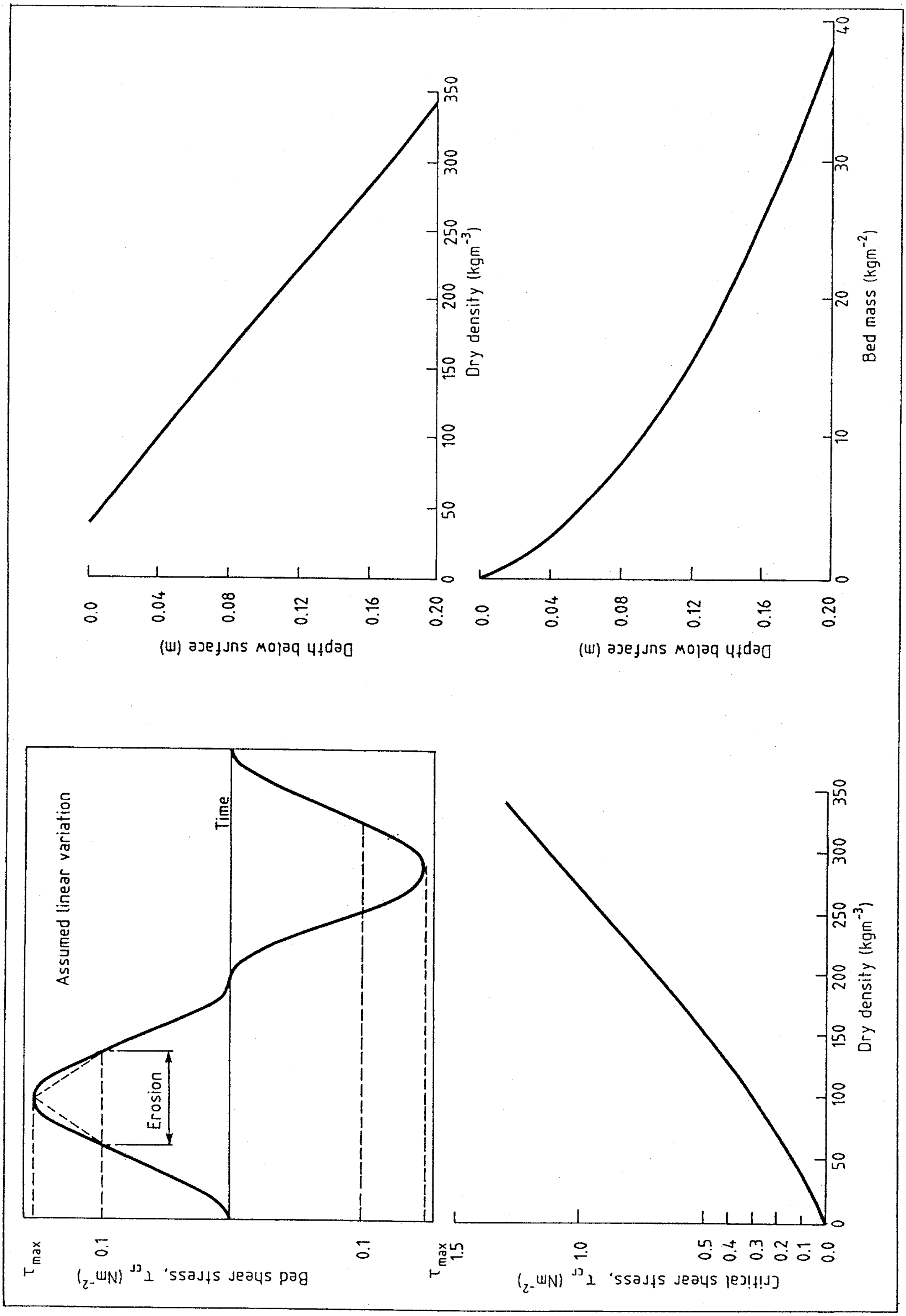


Fig 24 Periods of erosion in a tidal cycle and assumed bed characteristics

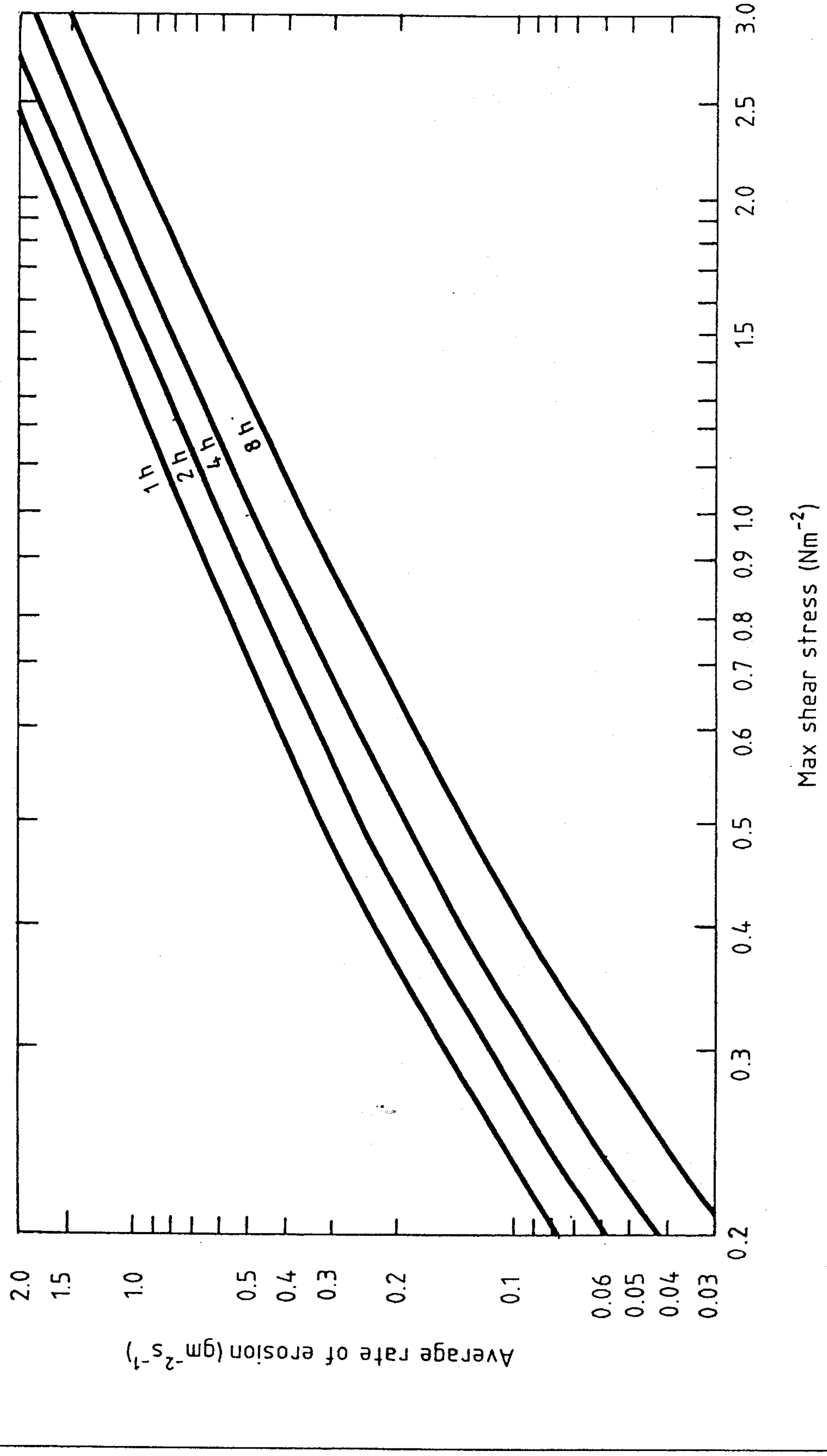


Fig 25 Average rate of erosion against maximum shear stress and time

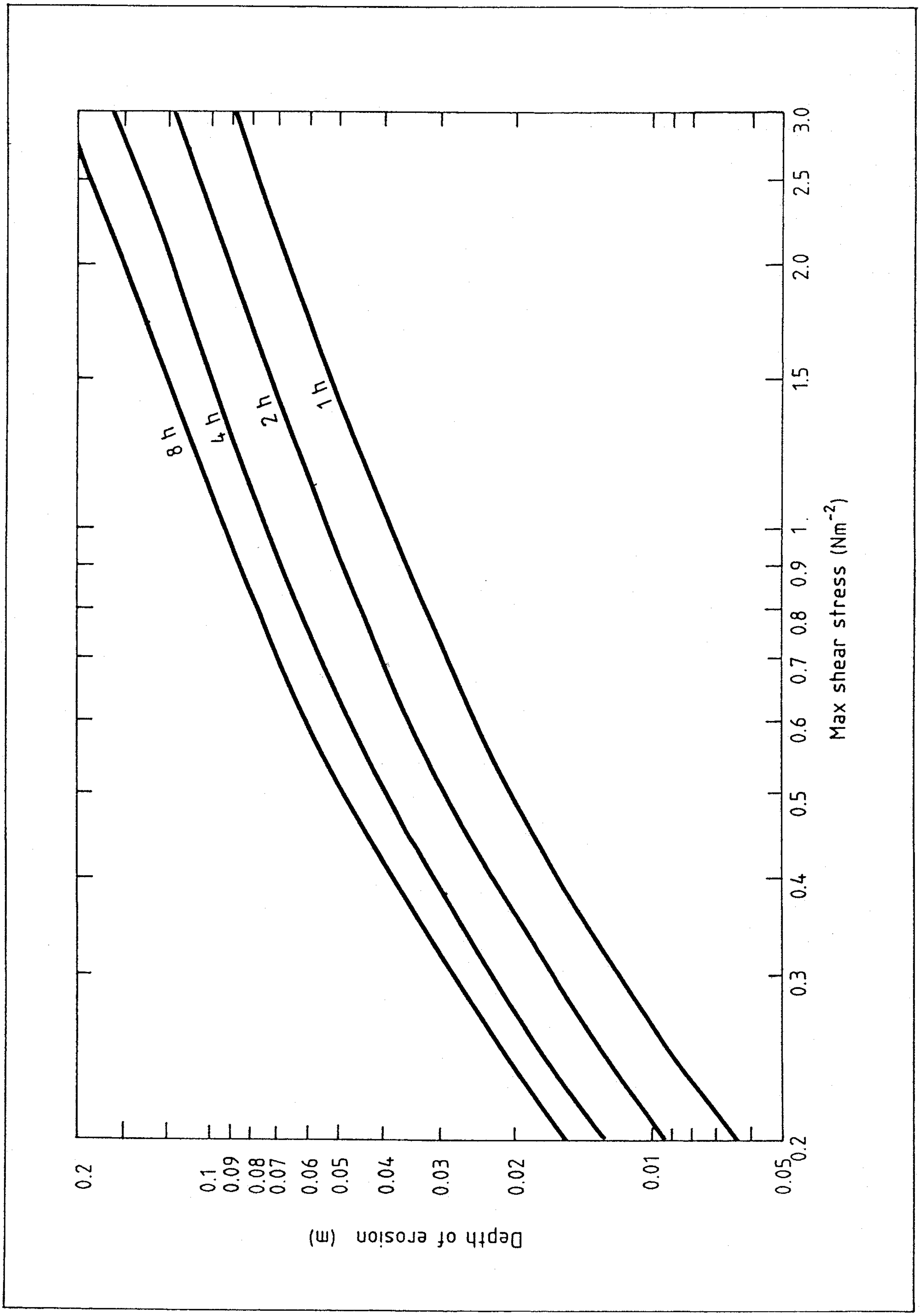


Fig 26 Depth of erosion against maximum shear stress and time

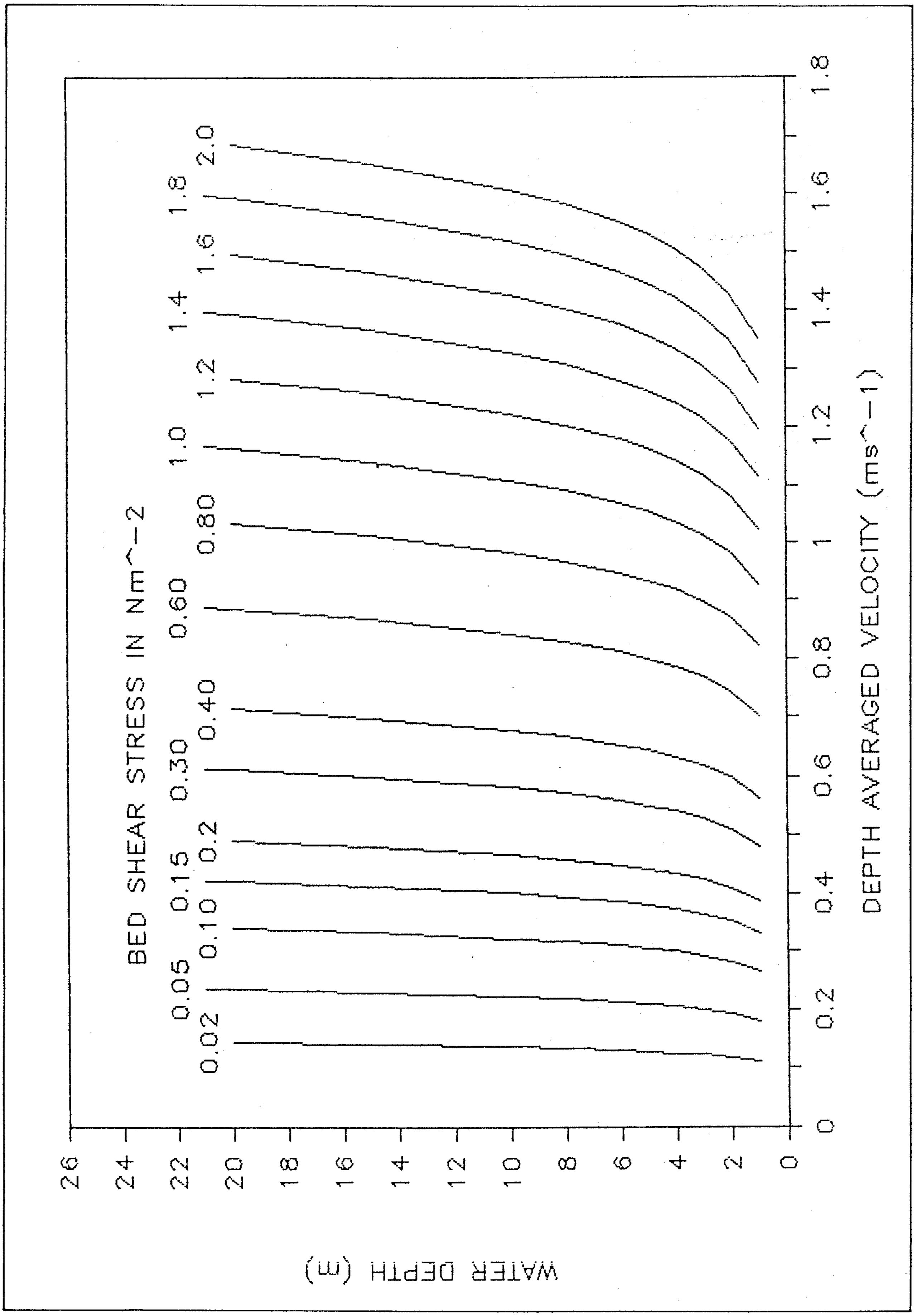


Fig 27 Current induced bed shear stress - smooth turbulent law

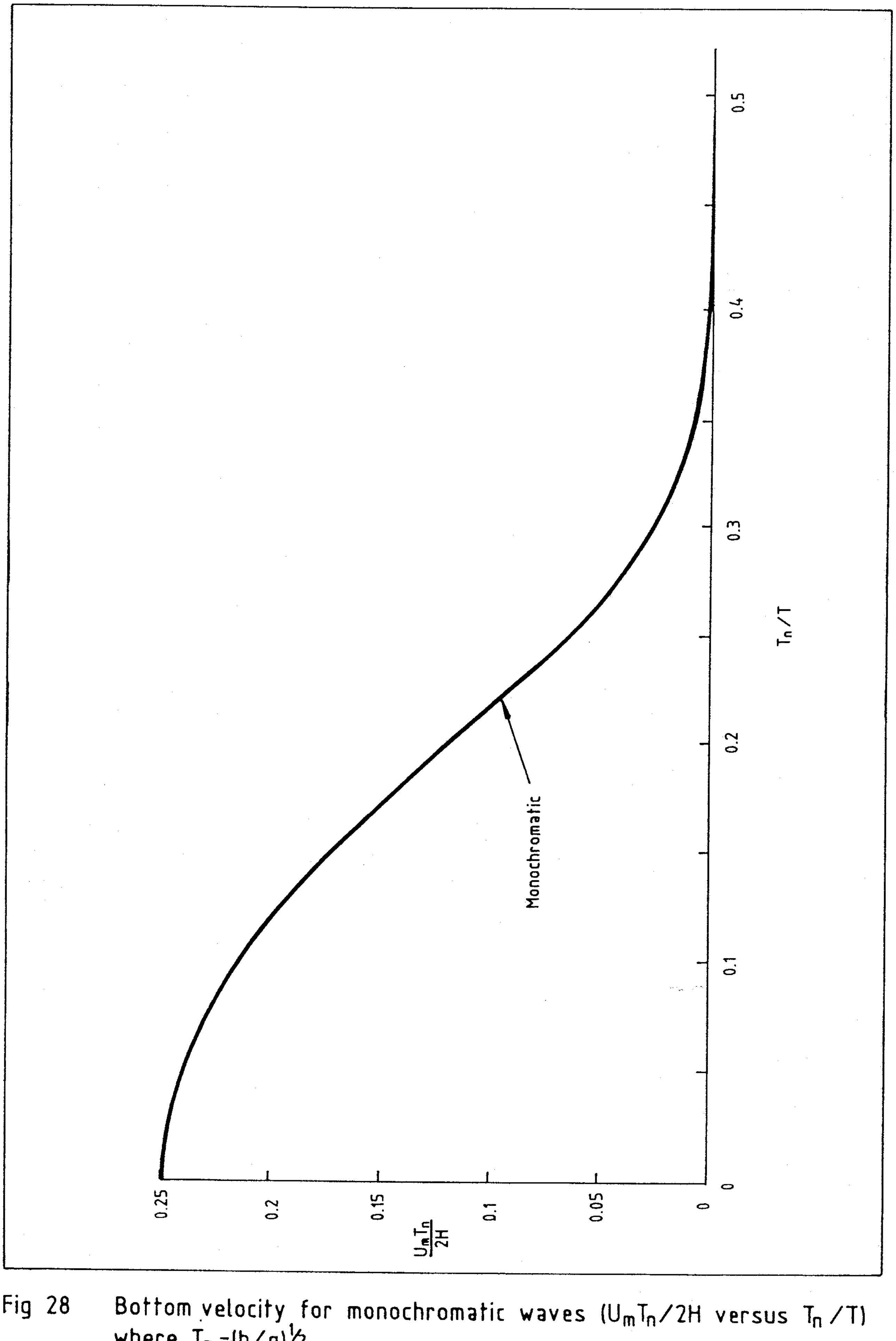
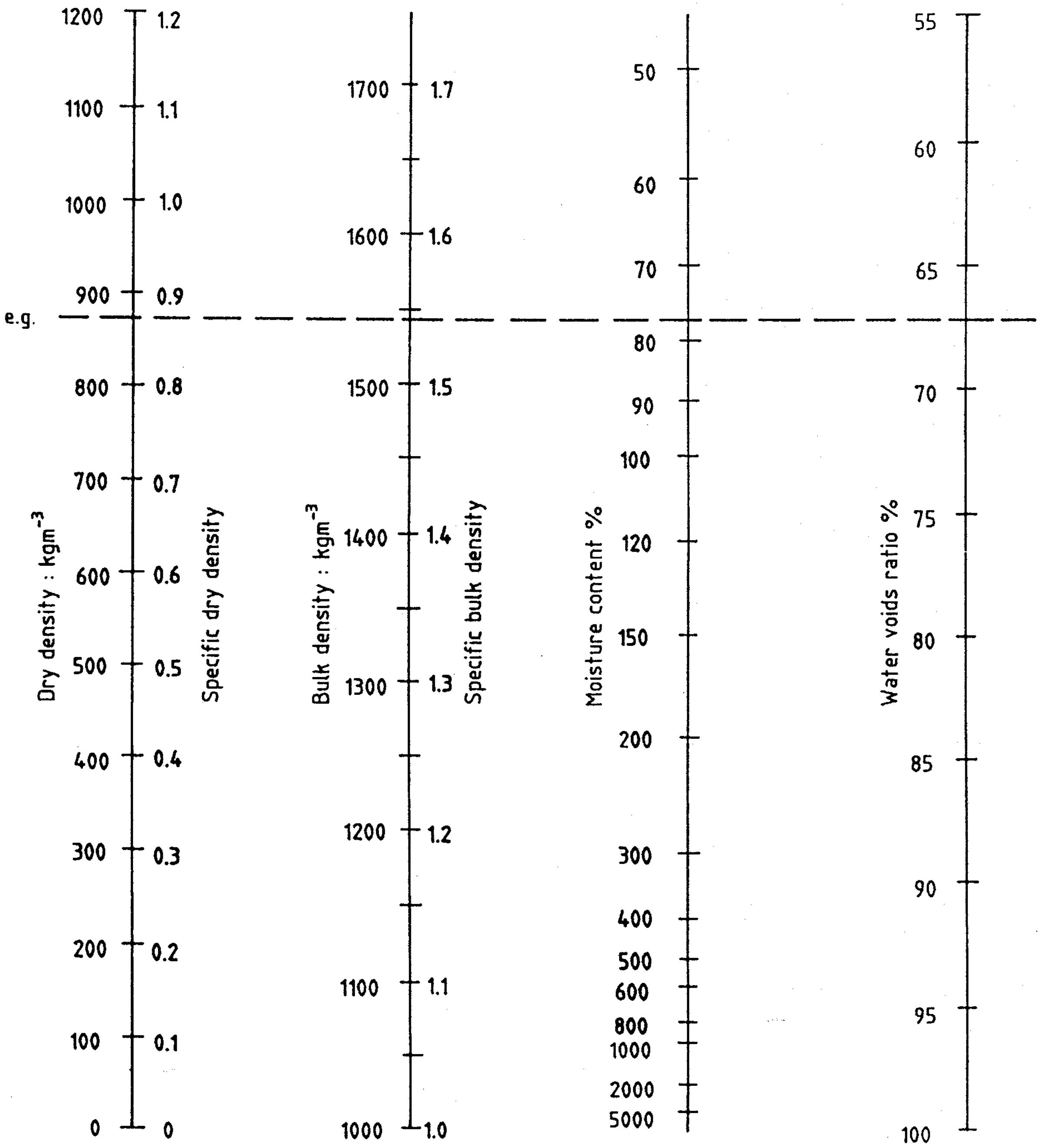


Fig 28 Bottom velocity for monochromatic waves ($U_mT_n/2H$ versus T_n/T) where $T_n = (h/g)^{1/2}$



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