Hydraulics Research
Wallingford

SILTATION AND STABILITY OF COHESIVE DREDGED SLOPES MANUAL

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CONTRACT

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ABSTRACT

This report has been compiled to give the practising engineer a manual on the engineering aspects of the siltation and stability of cohesive dredged slopes. It summaries the results of recently completed research into deposition of cohesive sediment, the stability of cohesive dredged slopes and the behaviour of estuarine muds during tidal cycles (see Refs 1, 2, 3 and 4).

The manual gives an introduction to dredged cohesive slopes and information covering deposition of sediment, slope stability and erosion of sediment. Each section presents the engineering information in terms of knowledge and procedures for the user.

CONTENTS

1 INTRODUCTION

The cost of dredging in order to provide access for ships and other vessels can be a large component of a project. There is an initial capital cost involved in creating a dredged area and the subsequent recurring cost of maintenance. In creating a dredged area, material is removed to the required depth leaving side walls sloping up to original bed level. With the passage of time material will accumulate in the dredged section, some having been carried in suspension by the water, and possibly some resulting from gradual failure of the side slopes.

The ability to predict the movement of cohesive sediment within coastal, estuarine or inland waters is crucial to both the technical and financial viability of many existing and proposed engineering works. In particular, the capital and maintenance dredging requirement of a project may form a substantial part of the overall cost of that project. Good predictive measures to forecast the likely rates of settlement of cohesive sediment from suspension are essential to projects which have an element of dredging within them.

The process of deposition of cohesive sediment is controlled by a complex combination of physical and chemical factors which are not fully understood. The size, strength and settling velocity of the settling units of a cohesive sediment are the results of flocculation. These units, or flocs comprise aggregates of flocs which stick together as a result of collisions. The lowest order floc comprises an aggregate of the primary particles but may have a settling velocity perhaps two or three orders of magnitude greater. Parameters which influence flocculation include the size, mineralogy, ph and ionic strength of the particles, the solids concentration of the suspension, the chemical composition of the suspending water and hydrodynamic parameters such as shearing rates within the suspension and the bed shear stress.

The stability of slopes on land (ie, not submerged) has been the subject of a good deal of attention in the past and techniques such as slip circle analysis and the method of slices are well established. These techniques can be applied to submerged or emergent (ie, partly submerged) slopes with little modification, provided they are in still water.

However, dredged slopes are almost invariably found in water which is not still. The effect of currents, waves and tides on the stability of the side-slope may be significant and introduces an extra degree of complexity into the analysis.

The effect of waves on the stability of dredged slopes is a significant factor which has to be taken into account in the initial design and estimation of the cost of maintenance of a dredged channel. The passage of a wave will have two effects, firstly the slope will be subjected to fluctuations in hydrostatic pressure and secondly the slope will be subject to a shear stress generated by the orbital motion of the water. The relative significance of the wave effects is dependent on the depth of water over the slope, the prevailing wave climate and the physical properties of the bed material.

Other factors that can effect the stability of a dredged slope are unidirectional currents, earthquakes, sedimentation and biogeochemical effects, the significance of each will be dependent upon a range of environmental parameters.

This report summarises, in an engineering form, the knowledge and procedures for analysis with respect to the siltation and stability of dredged cohesive slopes which have evolved from the research programme recently undertaken at Hydraulics Research (see Refs 1, 2 and 3). A general manual on the behaviour of estuarine muds has also been recently produced (Ref 4), part which has been incorporated into this report.

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 1 imply 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.

- Variation in settling velocities is considerable for sediment from different locations. The data in Figure 2 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 3.

- 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 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.

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

or

- estimate W_{50} by

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

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 3.

2.2 Rate of deposition in still water

Knowledge

- the rate of siltation or the rate of deposition as it is often termed, 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 6 for low values of suspended sediment concentrations and from Figure 7 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 8 and 9 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.

Recent developments have been made in the modelling of the deposition from flowing water of a distributed sediment. 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, 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

$$\frac{dm}{dt} = - p \; C \; W_{50} \qquad (3)$$

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

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

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 10 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 11, 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 12 and 13 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. STABILITY

3.1 Slopes in still water

There are a number of classical soil mechanics techniques for the calculation of the likely factor of safety of a finite slope. Many of these are based on a circular slip with a solution obtained often by dividing the slip zone into a number of slices and calculating the disturbing and restoring forces on each slice. In application to dredged slopes the shear strength of the mud is most likely to increase with depth (ie effective stress) below the original surface, such that

$$\frac{Cu}{\sigma_v'} = \text{constant} \qquad (6)$$

where

Cu = undrained shear strength (kNm^{-2})
σ_v' = effective stress (kNm^{-2})

It is reasonable in this instance to use a solution given by Booker and Davis (Ref 5) based on an exact plasticity method. The solution is shown in Figure 14 as a graph of the relationship at failure (ie, F = 1) between the slope angle α and the ratio $\frac{Cu}{\gamma' z}$. Also shown on Figure 1 is the infinite slope solution of Morgenstern (Ref 6) as given by the equation.

$$F = \frac{Cu}{\gamma' z} \frac{2}{\sin 2\alpha} \qquad (7)$$

where

F = factor of safety against sliding

Cu = undrained shear strength (kNm^{-2})
γ' = buoyant unit weight of soil (kNm^{-2})
z = depth below surface of sediment (m)
α = slope angle

It is most likely that muds in estuarine or near coastal regions will be underconsolidated. This means that the mud is still consolidating under its self weight and squeezing out water trapped in the pores of the mud. The pressure of the water in these pores will therefore be higher than the ambient hydrostatic pressure. As a result of this excess pore pressure the effective stress within the soil matrix will be less than the total stress and is given by:

$$\sigma_v' = \sigma_v - u \qquad (8)$$

where

σ_v' = effective stress (kNm^{-2})
σ_v = total stress (kNm^{-2})
u = pore pressure (kNm^{-2})

Knowledge

- for any given value of the ratio $\frac{Cu}{\gamma' z}$ the critical slope angle is substantially less for the infinite slope than for the dredged (finite) slope.

- the solution is independent of the actual height of the dredged slope and depends only on the rate of increase of the strength of the mud with effective stress.

- the ratio of undrained shear strength to effective stress $\frac{Cu}{\sigma_v'}$ has been found in practice to be reasonably constant, and therefore, a reduction in effective stress due to an excess pore pressure will accordingly lower the undrained shear strength of the underconsolidated soil.

Procedure

- obtain the value of the ratio of the undrained shear strength to effective stress by measurement or estimation. For normally consolidated clays it is reasonable to assume that the value of Cu/σ_v' is likely to be in the range of 0.15 to 0.40. A typical value would be around 0.25. However, the effects of underconsolidation tend to reduce the rate of increase in effective stress with depth and also to reduce the gain in shear strength with depth. Accordingly, the value of the ratio $Cu/\gamma'z$ will be lower in underconsolidated soils and in normally consolidated soil. In the absence of any site specific data then it would be advisable to choose a number of different $Cu/\gamma'z$ values in the range 0.03-0.15 depending on the anticipated degree of excess pore pressure.

- estimate the critical angle of slope from Figure 14. For example, suppose a mud with an effective weight, γ' of $2.5kNm^{-3}$ had a ratio Cu/σ_v' of 0.15. For the normally consolidated situation $\sigma_v' = \gamma'z$, and hence, $Cu/\gamma'z = 0.15$. From Figure 1 this corresponds to a critical finite slope angle of 22°. However, if the mud was underconsolidated and had an excess pore pressure of say 0.5m head of water ($\gamma w=10kNm^{-3}$) at a depth of 5m then $Cu/\gamma'z = 0.15(5x2.5-0.5x10)/(2.5x5) =0.09$ and the critical slope angle is reduced to around 10°.

3.2 Slopes under wave action

Knowledge

- Henkel (Ref 7) discussed the role of waves in causing submarine landslides. He considered an infinite slope and calculated the static effect of an idealised wave above the sea bed. The solution was presented graphically in dimensionless parameters and is shown in Figure 15.
- the results of experimental work (Ref 3) have indicated that the stability of a cohesive slope subject to wave action is a funtion of the strength of the bed, the slope angle, the applied peak bed shear stress and the time for which the wave action is occuring.

Procedure

- to assess the likely effect of waves on a dredged slope it would be necessary to determine the variation in density with depth through the slope and to obtain a sample of the mud for laboratory testing. This requirement would be over and above the useful geotechnical parameters such as undrained shear strength and pore pressure which would be essential for a static analysis of the stability of the slope.
- in addition to the mud properties it would also be necessary to have a knowledge of the likely significant wave heights and periods in the region where the dredged slope is sited. These coupled with water depths would enable the maximum bed shear stress to be calculated on a probabilistic basis.

4 EROSION

4.1 Threshold of erosion by currents

Knowledge

- a consolidating bed of cohesive sediment has an increasing density with depth.

- 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 16).

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 17 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 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.

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 18 with $E=0.002\ \mathrm{kgN^{-}s^{-1}}$, ie

$$\frac{dm}{dt} = E\,(\tau_b - \tau_{ce}) \qquad (9)$$

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})

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.

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

- the erosion rate of mud from the surface of a mud bed (density $1280kgm^{-3}$) was found to be similar to the proportional excess shear stress relationship for current erosion given in equation 9.

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 $<1200 kgm^{-3}$ and the erosional characteristics of higher density beds.

or

- for an order of magnitude estimate of erosion rate use equation 9 in which τ_b is replaced by the peak bed shear stress due to the waves.

5. REFERENCES

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2. Delo E A. "Deposition of cohesive sediment from flowing water", Hydraulics Research Ltd, Wallingford, England. Report No SR 152, February 1988.

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5. Booker J R and Davis E H. A note on a plasticity solution to the stability of slopes in inhomogenous clays. Geotechnique, Vol 22, No 3, September 1972.

6. Morgenstern N R. Submarine slumping and the initiation of turbidity currents. Marine Geotechnique, pp189-220, ed. A F Richards, Univ. of Illinois Press, 1967.

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FIGURES.

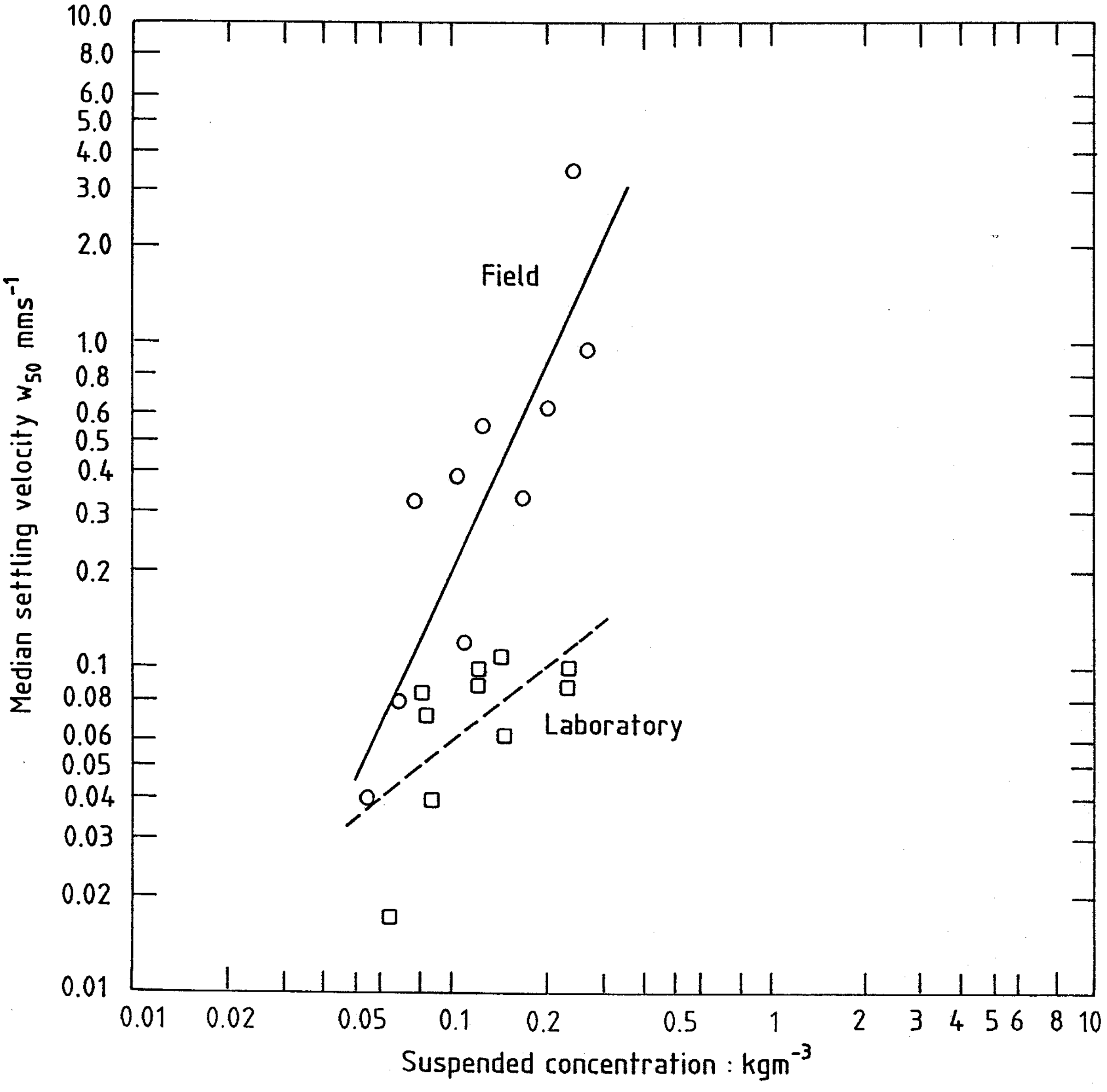


Fig 1 Median settling velocity against suspended concentration : field and laboratory

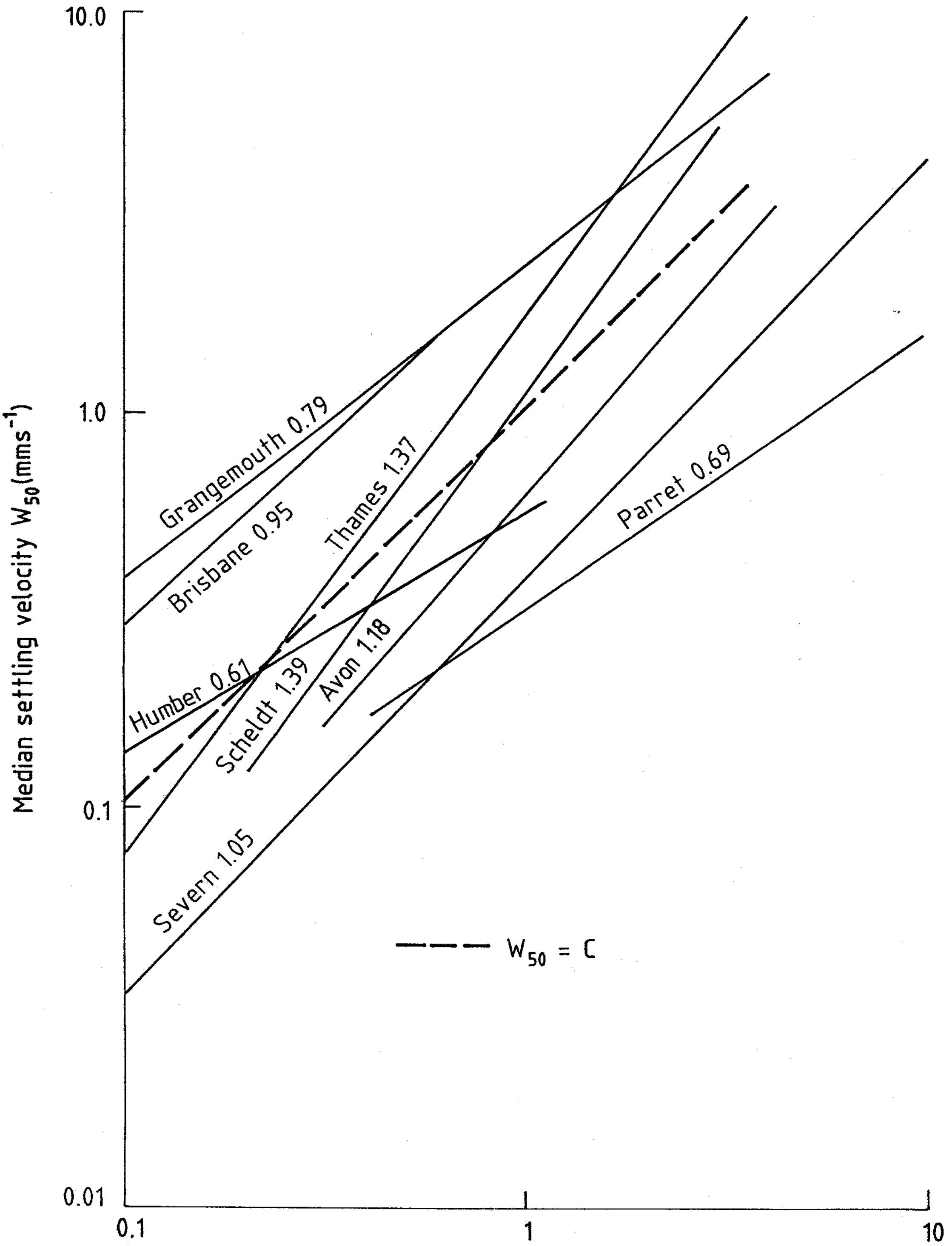


Fig 2 Median settling velocity against suspended concentration : comparison of eight estuaries

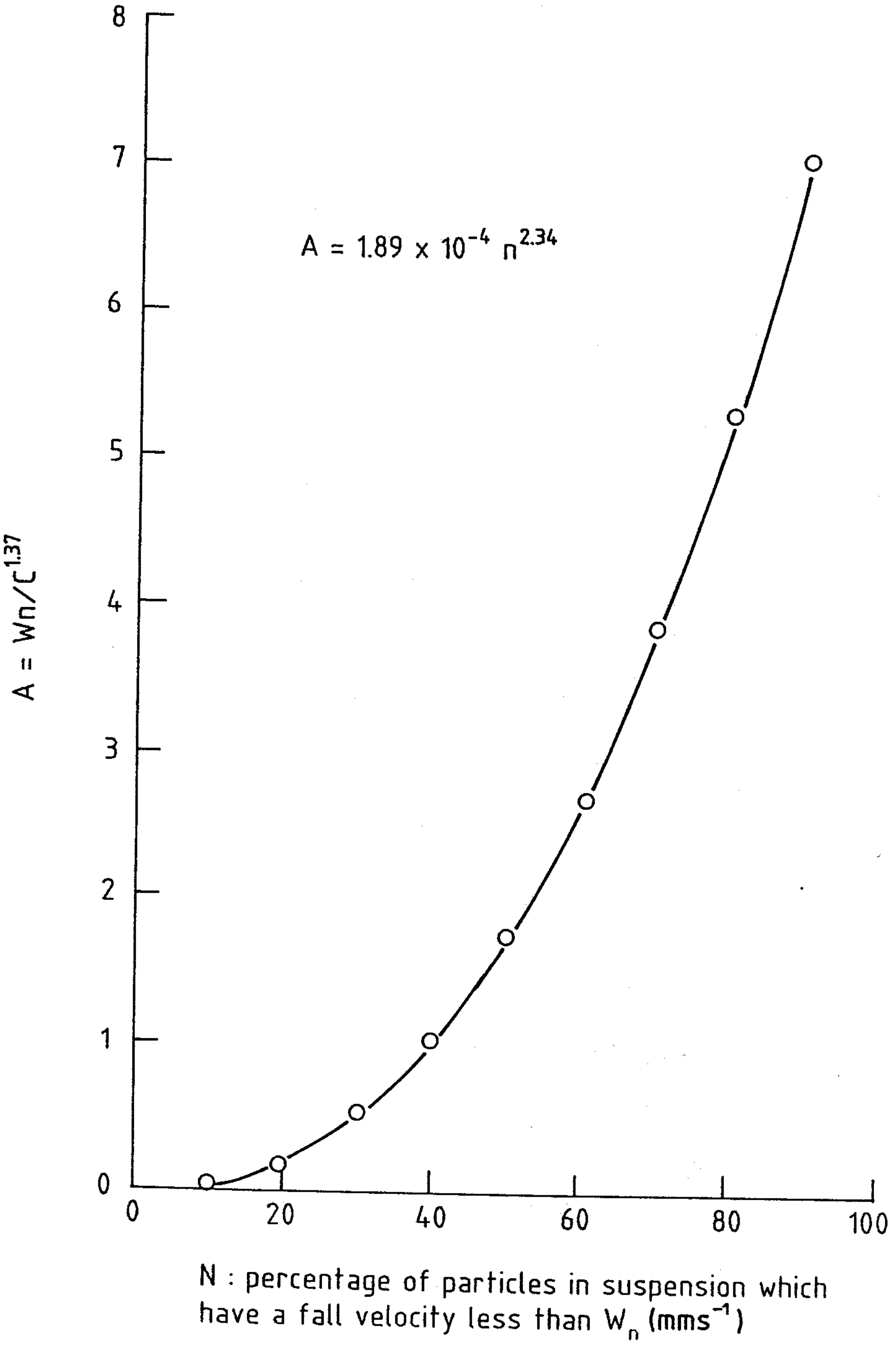


Fig 3 General equation for Thames settling velocity data

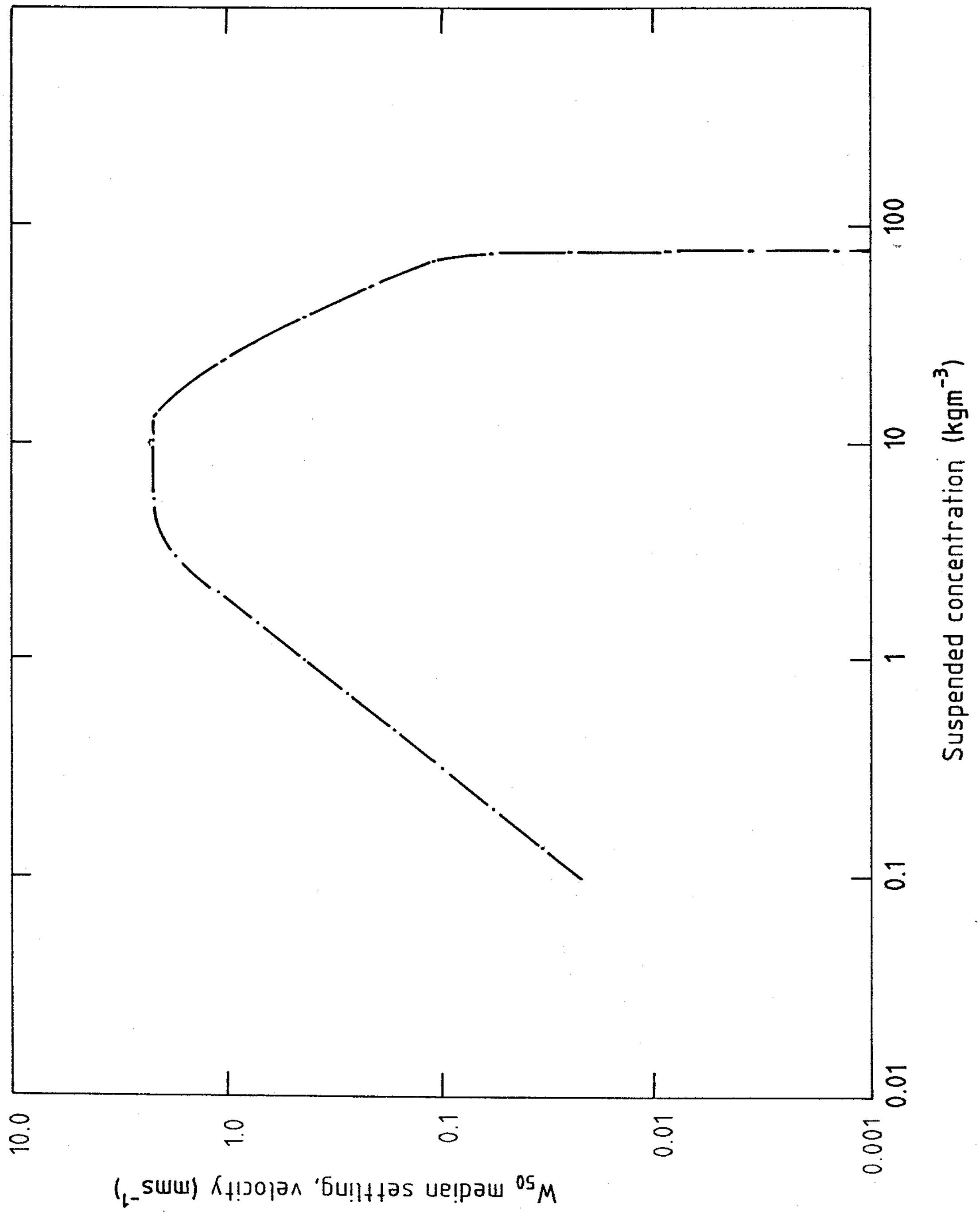


Fig 4 Median settling velocity against suspended concentration for Severn Estuary

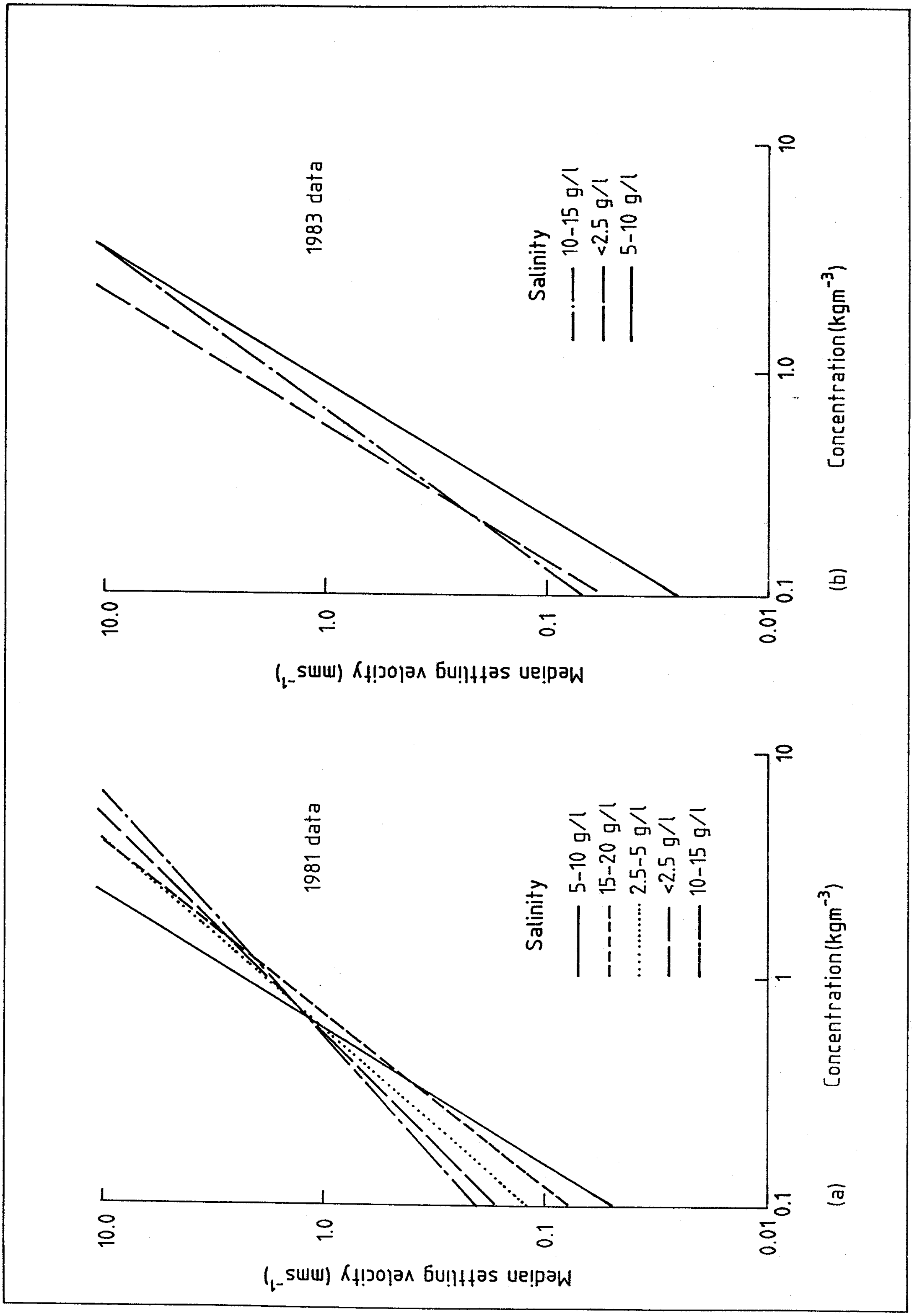


Fig 5 Effect of salinity on median settling velocity

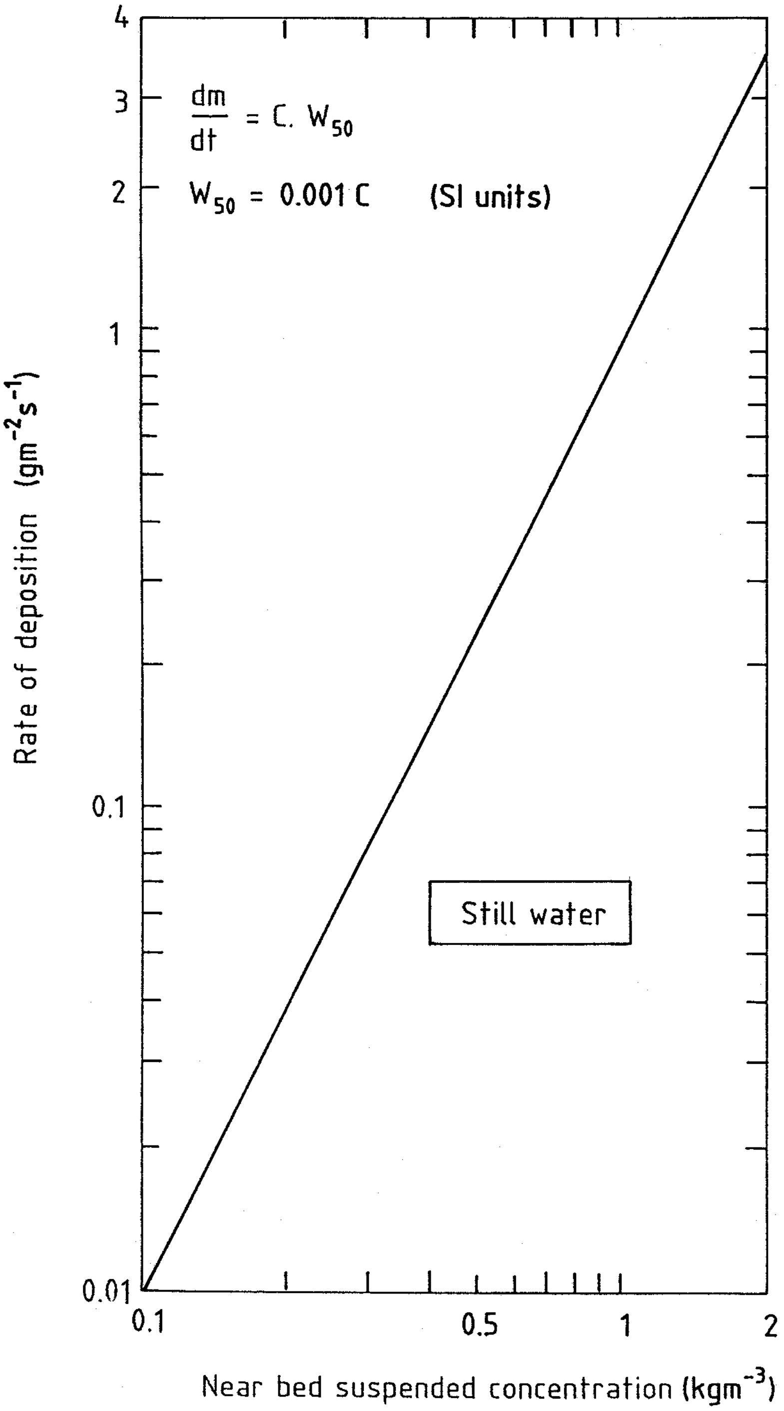


Fig 6 Rate of deposition against near bed suspended concentration

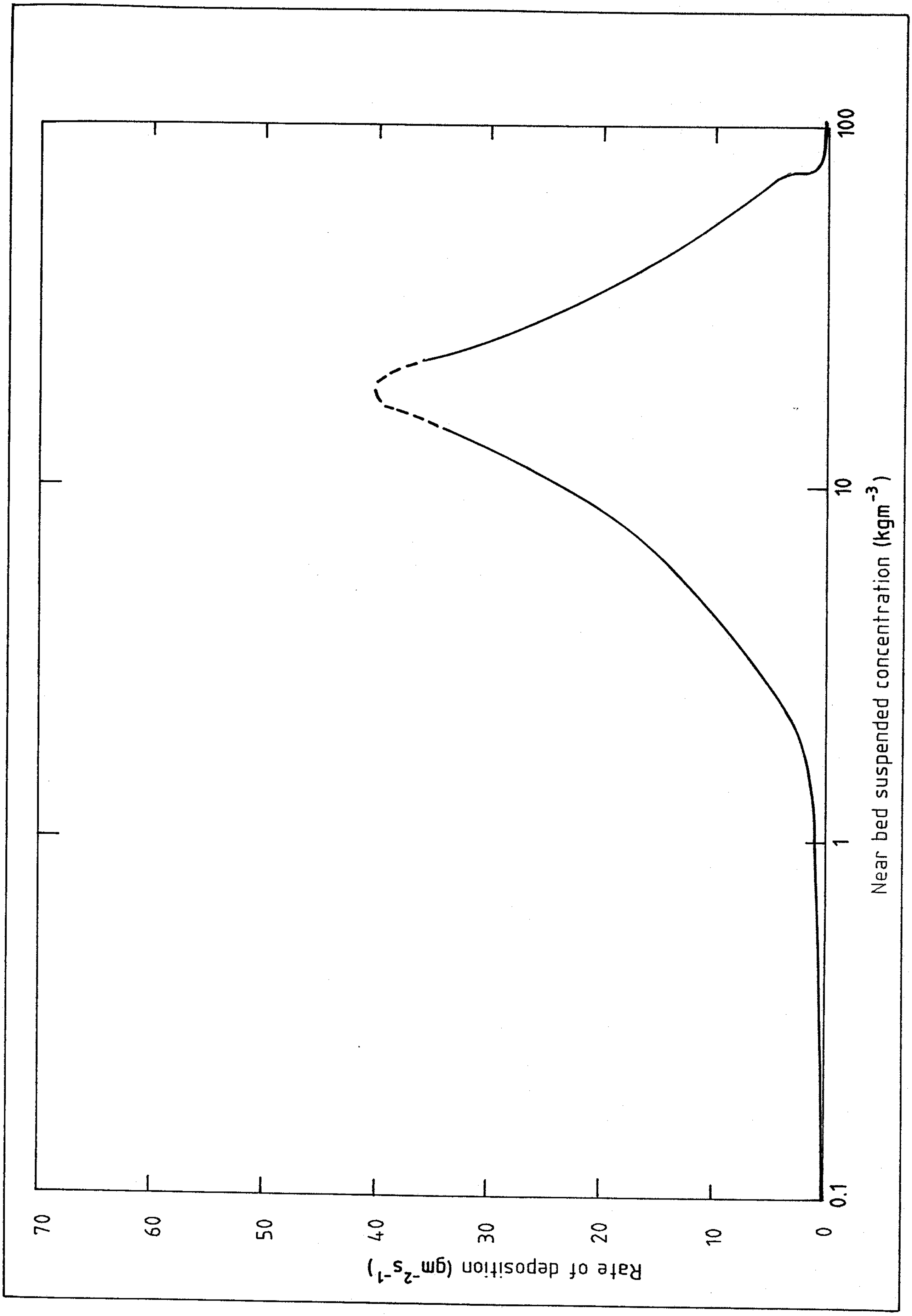


Fig 7 Rate of deposition against near bed suspended concentration : high concentration

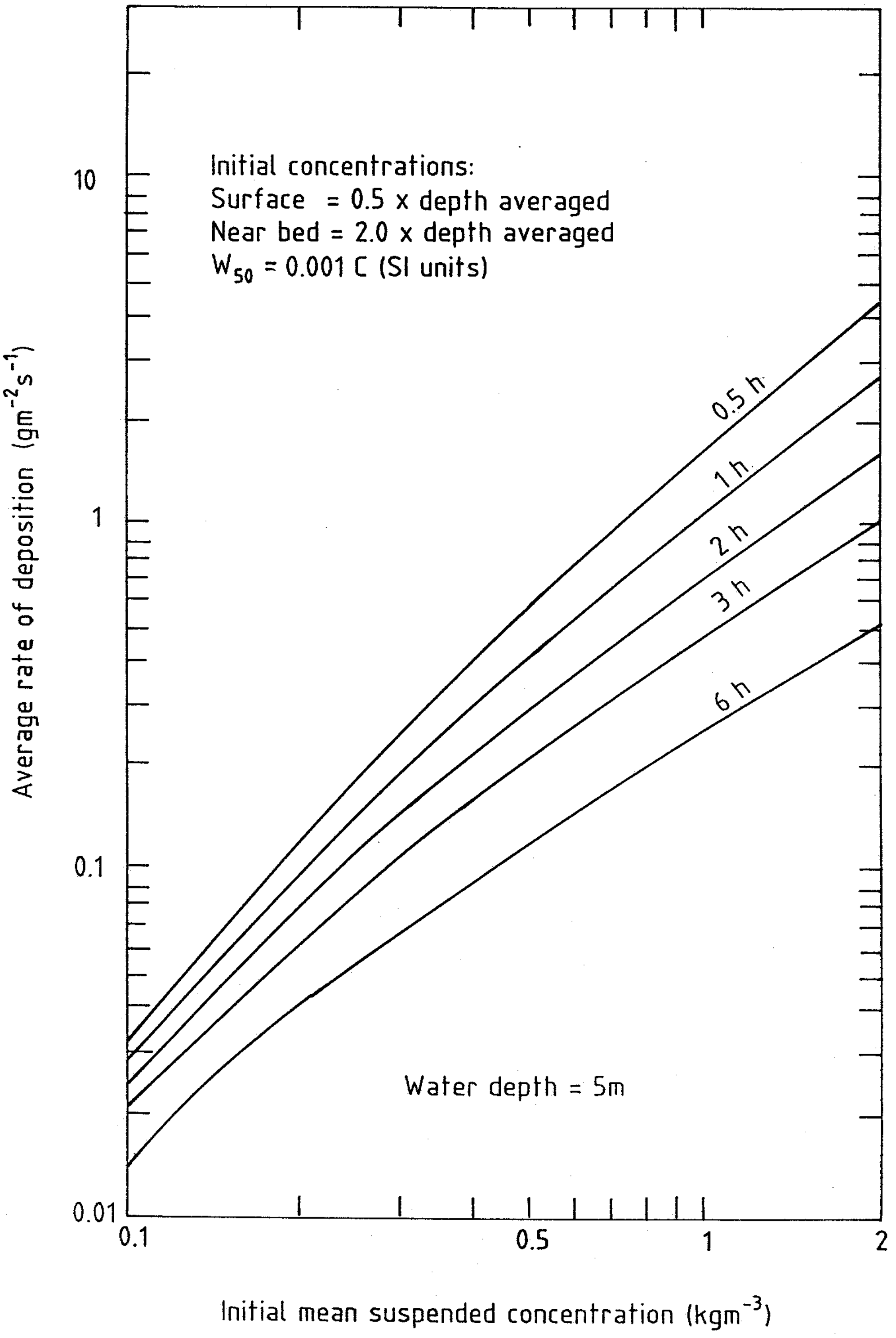


Fig 8 Average rate of deposition against initial mean suspended concentration and time, D = 5m

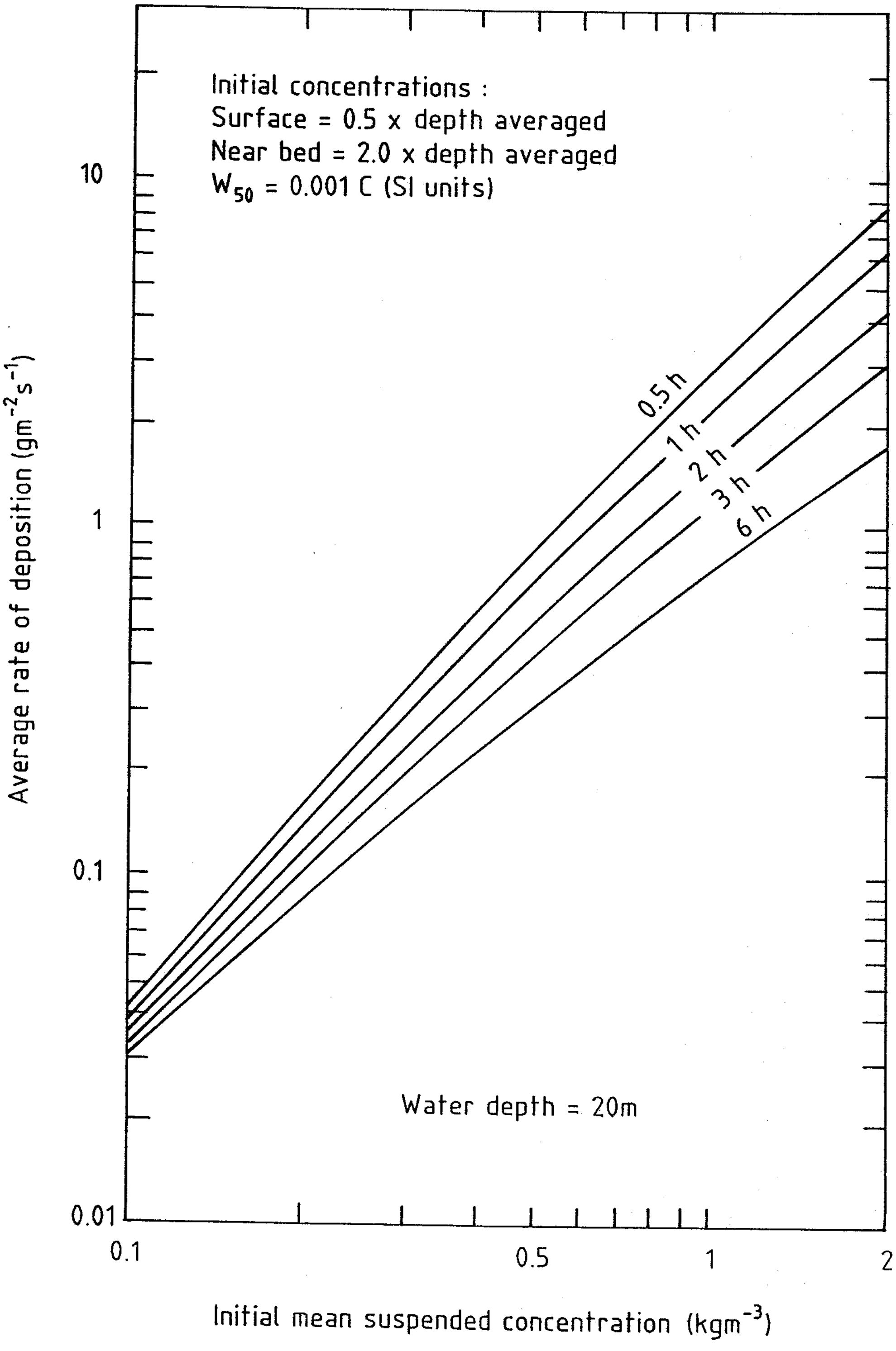


Fig 9 Average rate of deposition against initial mean suspended concentration and time, D = 20m

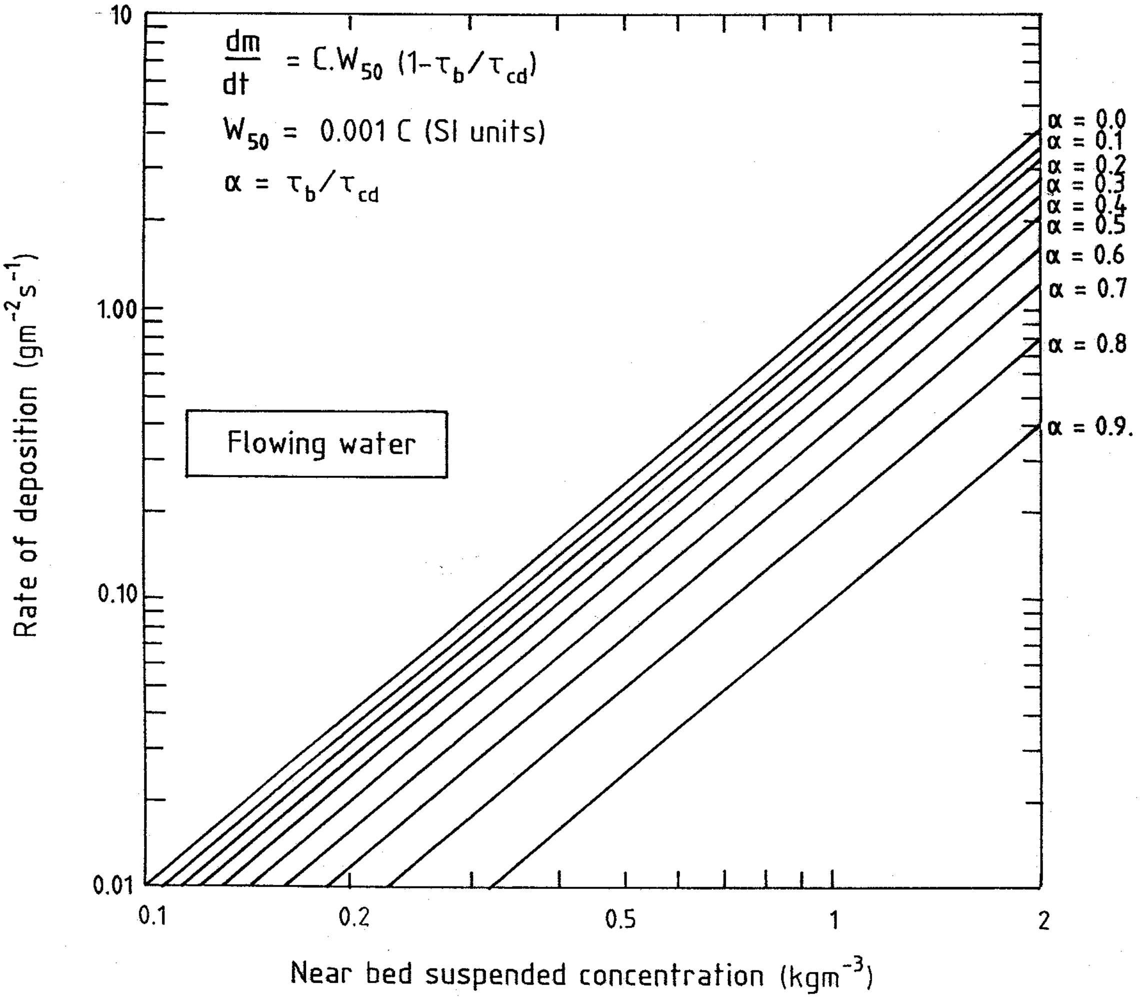


Fig 10 Rate of deposition in flowing water against near bed suspended concentration

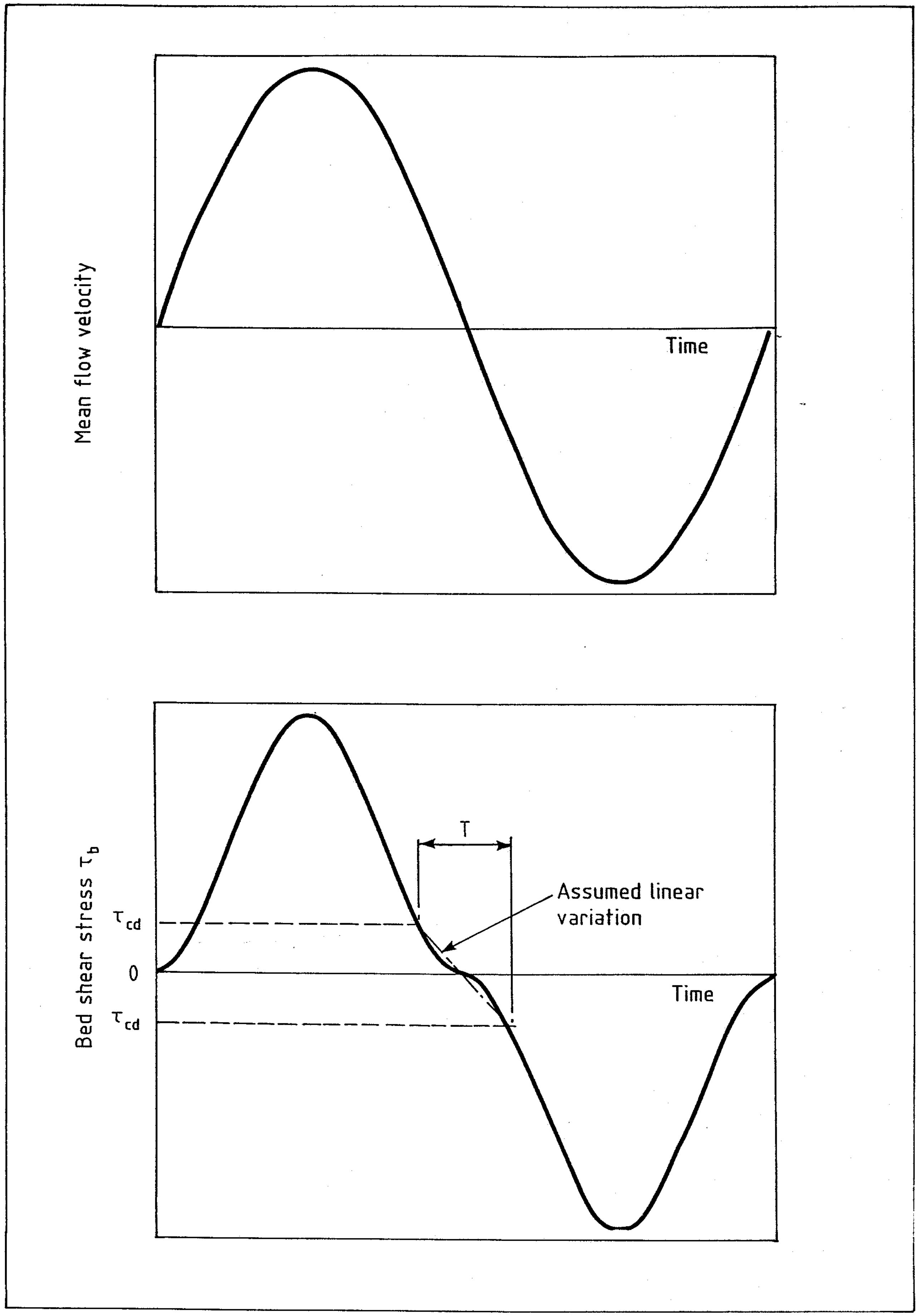


Fig 11 Periods of deposition in a tidal cycle

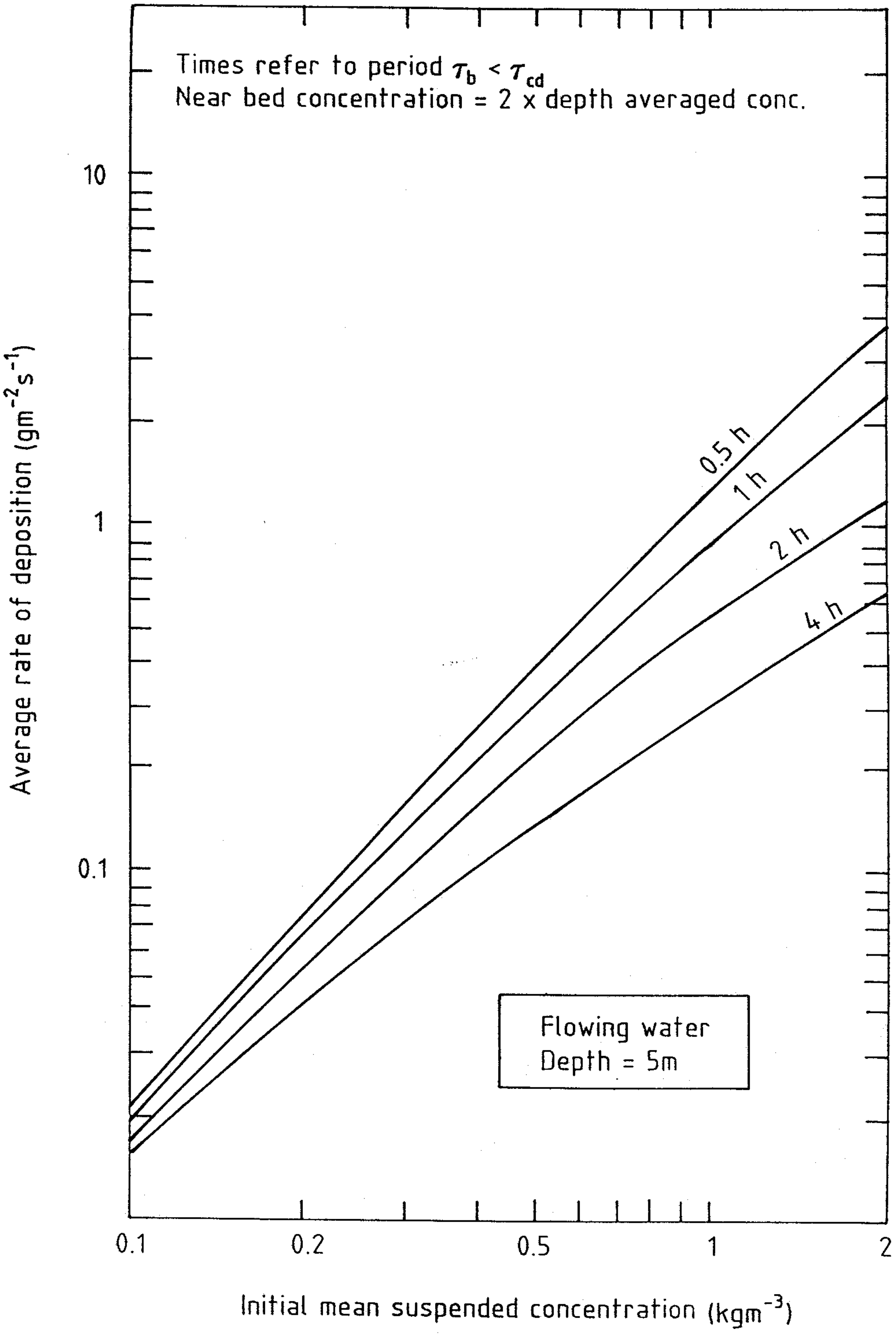


Fig 12 Average rate of deposition in flowing water against mean suspended concentration and time, D = 5m

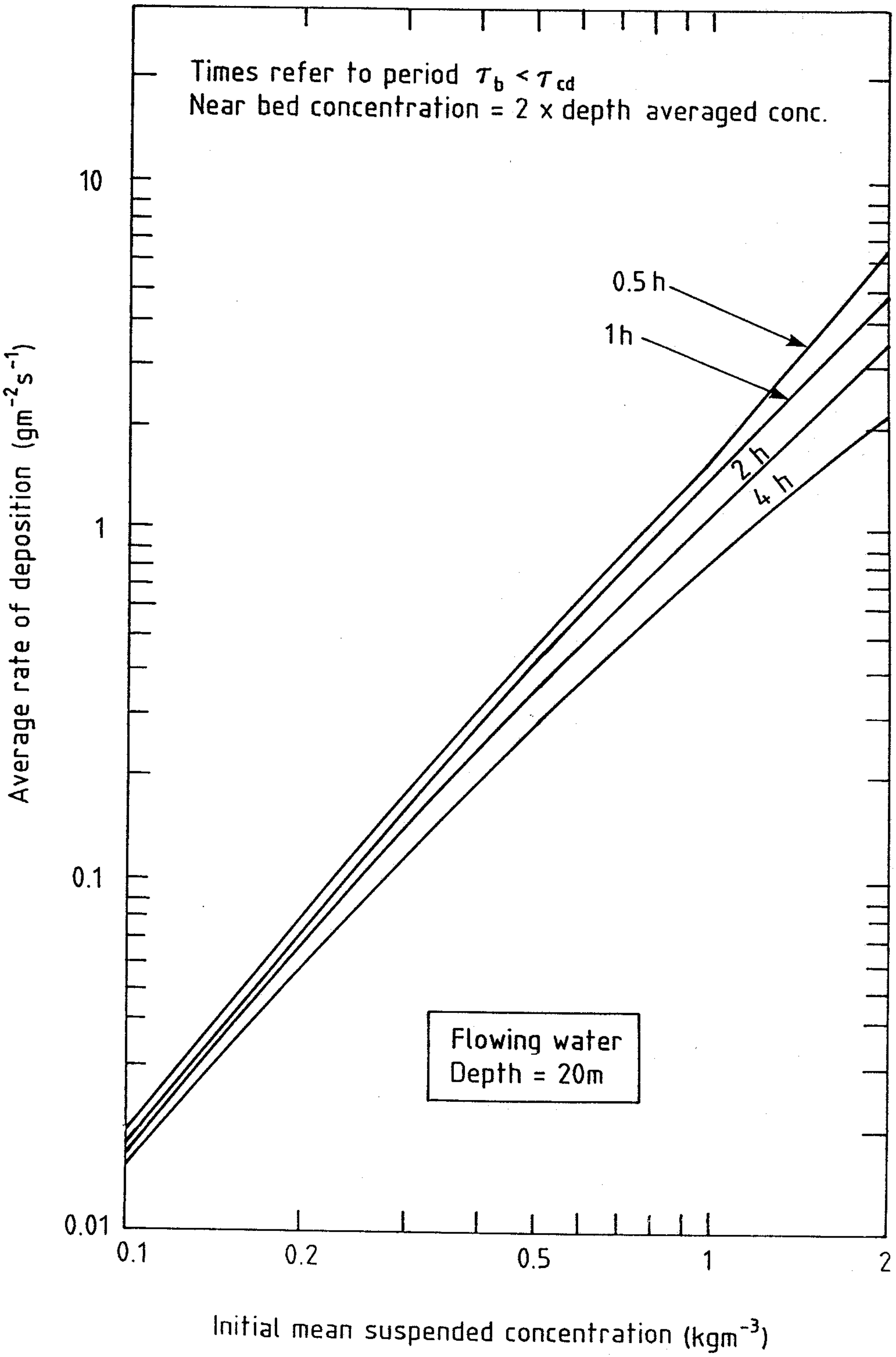


Fig 13 Average rate of deposition in flowing water against mean suspended concentration and time, D = 20m

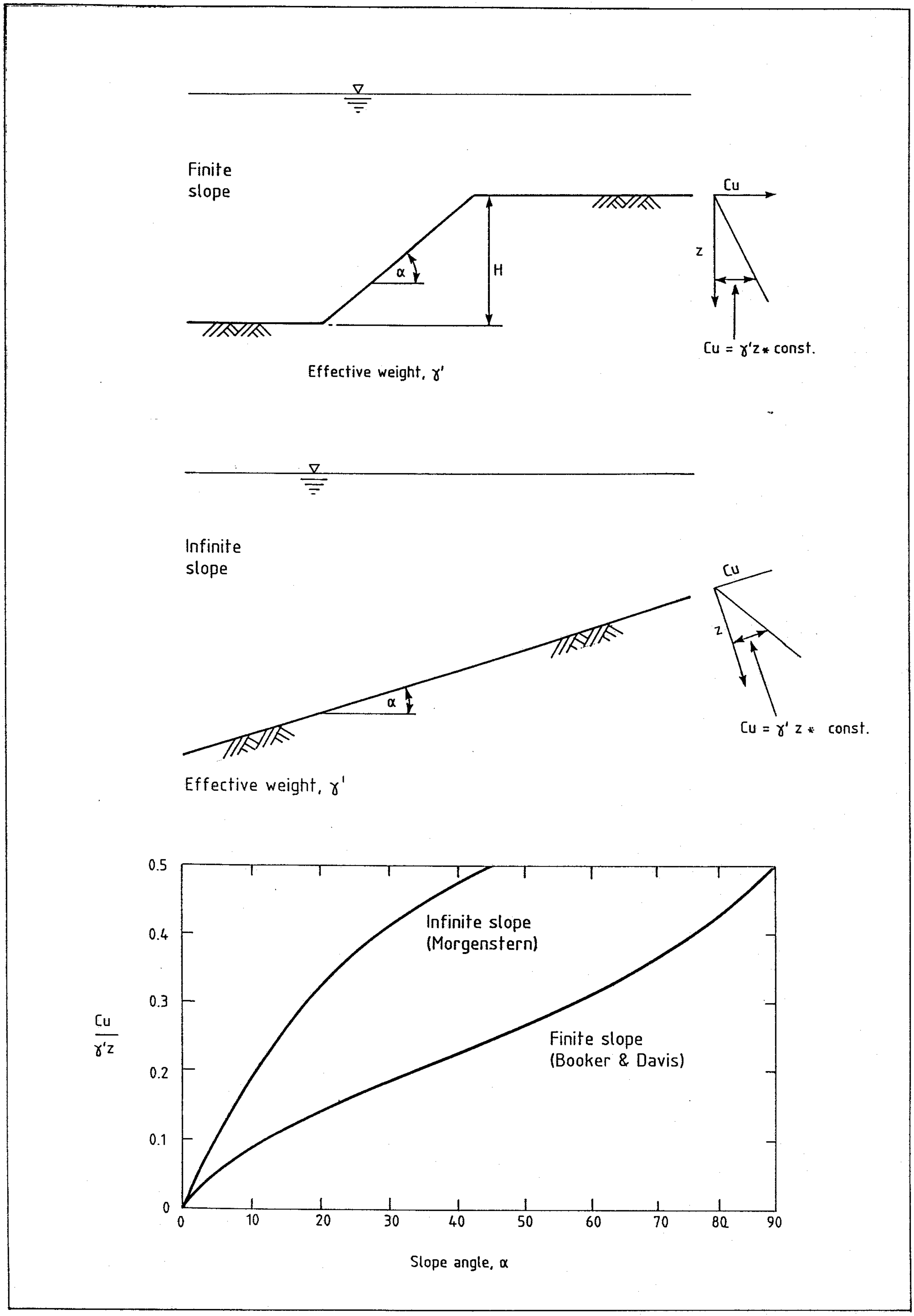


Fig 14 Slope angle and rate of increase in cohesion for finite and infinite slopes

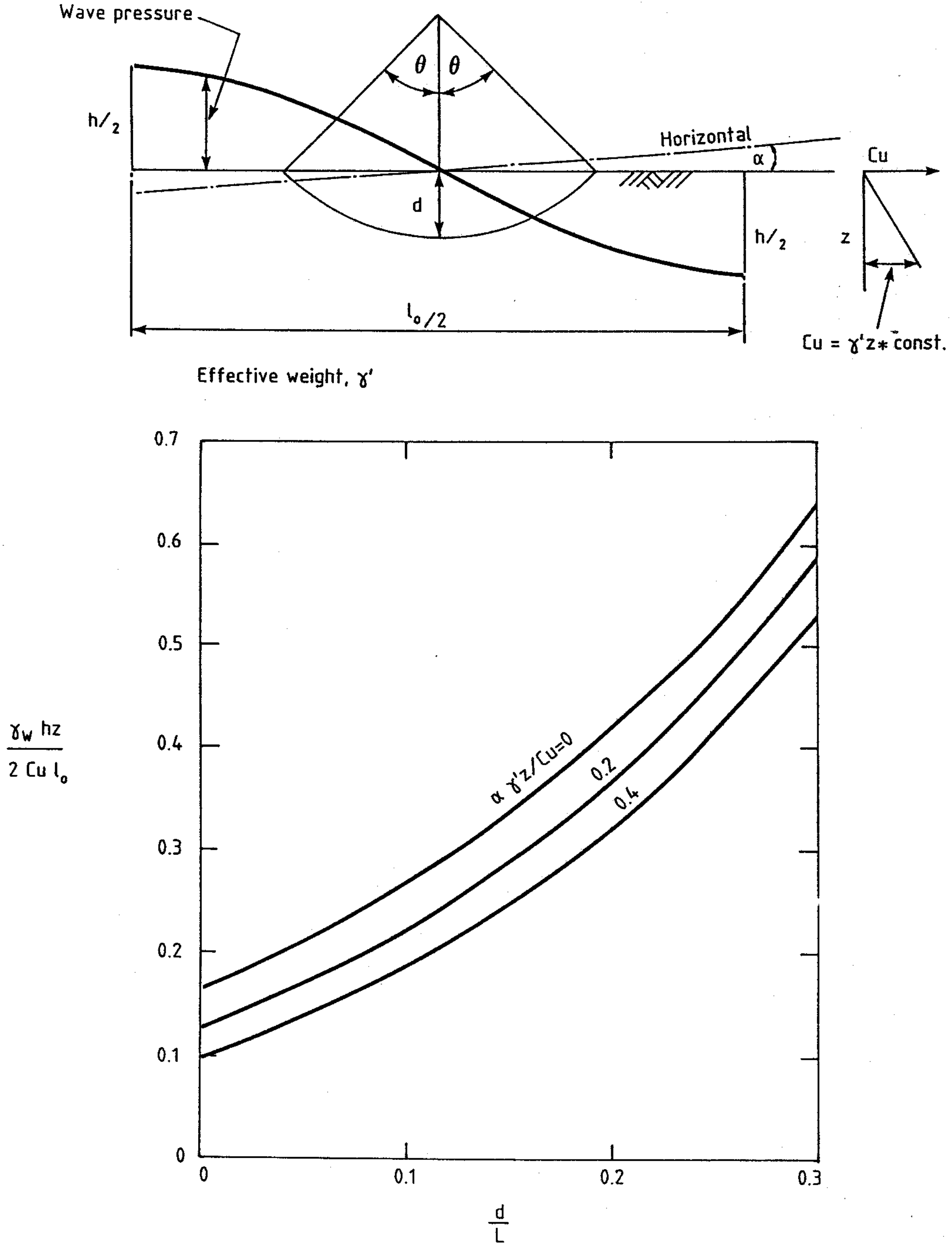
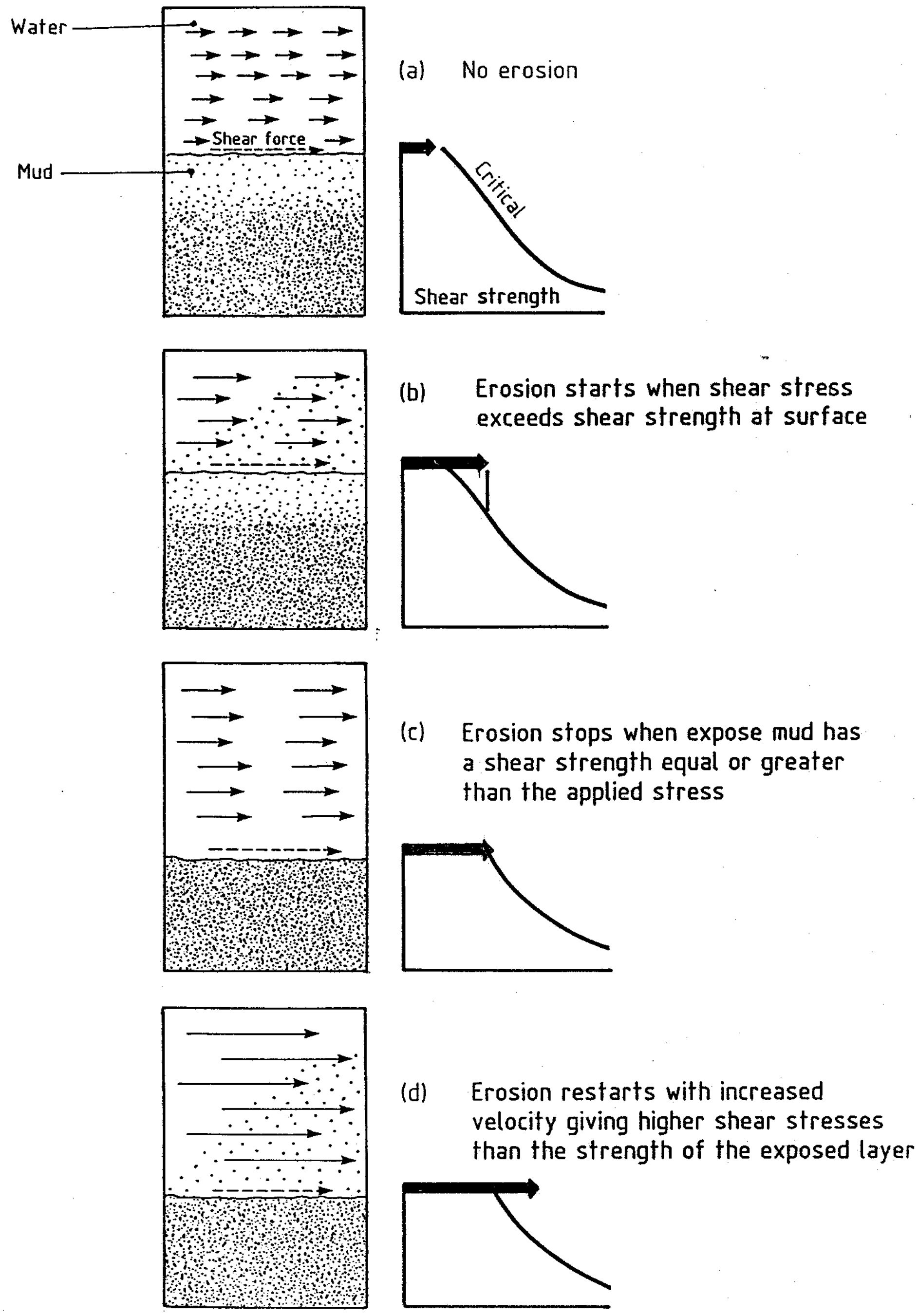


Fig 15 Solution for waves over an infinite slope (Henkel)



(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 16 The cohesive sediment erosion process

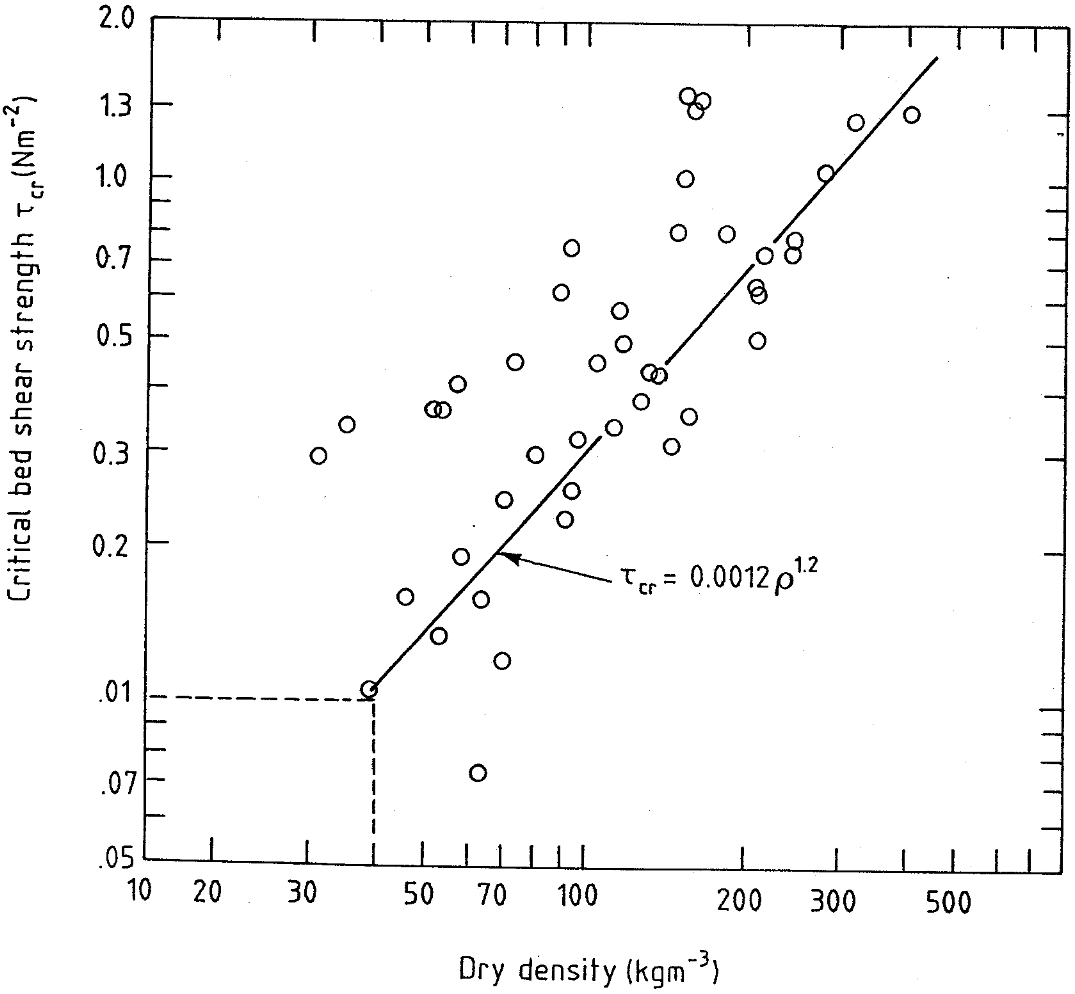


Fig 17 Erosion threshold stress against bed density

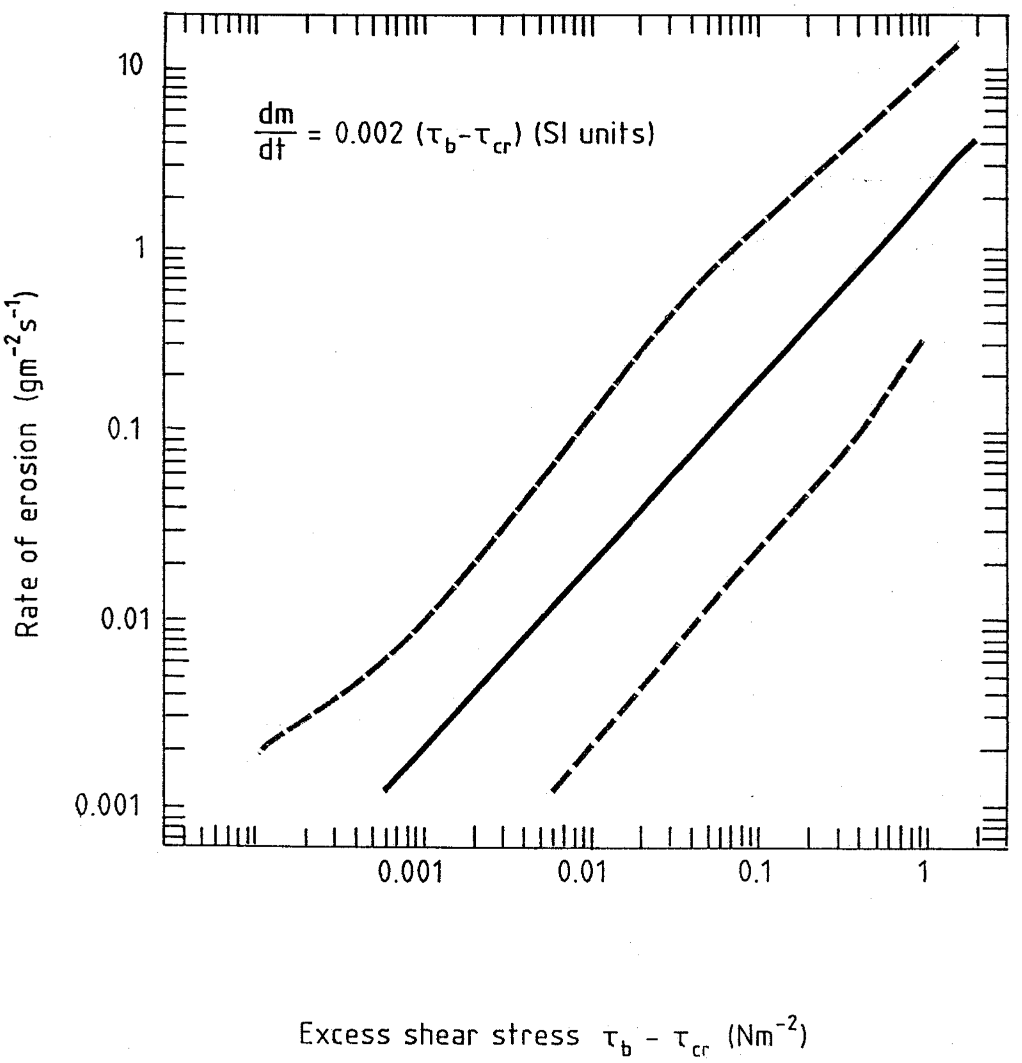


Fig 18 Rate of erosion against excess bed shear stress