Hydraulics Research
Wallingford

TRANSPORT OF SAND MIXTURES

Formulation and development
of a computer model

Contract Completion Report

G V Miles

Report SR 223
January 1990

Registered Office: Hydraulics Research Limited,
Wallingford, Oxfordshire OX10 8BA.
Telephone: 0491 35381. Telex: 848552

This report describes work funded by the Department of the Environment under Research Contract PECD 7/6/112 for which the nominated officer was Dr R P Thorogood. It is published on behalf of the Department of the Environment, but any opinions expressed in this report are not necessarily those of the funding Department. The work was carried out by Dr G V Miles in the Tidal Engineering Department of Hydraulics Research, Wallingford, under the management of Mr M F C Thorn.

ABSTRACT

The study of sediment transport generally is very difficult but more so in the case of estuaries because the water movements are continually changing with the rise and fall of the tide, certain sediments are not found in some parts, leading to unsaturated loads in the water and a wide range of sediment exists on the bed and in suspension.

Recent research, funded by the Department of the Environment under Research Contract PECD 7/6/56, demonstrated that computer models of sediment transport can simulate the effects of variable tidal movements and partly saturated loads of sediment. The purpose of the present research project was to consider the problems associated with mixtures of sediment and to develop a method for computer simulation of the important physics of sand mixtures. The objective was a predictive model for engineering applications rather than a scientific model of the detailed processes.

The literature review and assessment of available information identified the following basic requirements for a model of sand mixtures.

- provision to model the interaction between size fractions rather than a simple summation of results for independent fractions
- provision to modify the sediment pick-up and deposition rates of individual fractions in proportion to the proportions of each fraction in suspension and on the bed
- provision to model the bed so that the progressive armouring of the bed by coarser grains and/or the equivalent trapping of finer grains can be simulated. A consequence is that the suspended load should gradually evolve into one wholly consistent with the bed material.

A plausible method for simulating the transport of sand mixtures has been postulated which, when tested on demonstration examples, behaved in a wholly sensible manner including the essential features described above. The demonstrations showed that a possible consequence of the different sediment carrying capacity of the flow for the two sand sizes was net erosion in what was fundamentally a depositional situation and net deposition in what was fundamentally an erosive situation. Although this is expected to be a temporary effect in real situations it does emphasise the need for sand mixtures to be considered.

The demonstrations also identified a sensitivity to the initial thickness of bed through which deposits were assumed to mix. The appropriate thickness to use for this mixing layer is not yet known so there is a need for more research on this matter if a correct budget of sediment sizes on the bed is to be obtained.

CONTENTS

1. INTRODUCTION

1.1 General background

A significant feature of estuaries is the wide range of sediment sizes found in them. These sediments are generally sifted and transported by the combined action of tidal currents and waves, but in estuaries tidal currents usually dominate and for the purpose of this work wave effects are neglected.

In the main channels bed stresses are usually too high to allow the finer materials to accumulate although they may settle temporarily at slack water. Only coarse sand and gravel can exist as permanent deposits in such high energy regions. Along the shallow margins of the estuary, and further upstream, the tidal currents are too weak to move the sand and either no sand is transported there or it is covered by silt or clay to produce characteristic mud flats. These mud flats are colonised by various forms of marine life and become the feeding grounds of birds. If conditions are suitable the level of the mud flats rises and eventually a salt marsh develops.

The study of sediment transport generally is very difficult but more so in the case of estuaries because

- the water movements are continually changing with the rise of the tide

- certain sediments are not found in some parts leading to unsaturated loads in the water

- a wide range of sediments exist on the bed and in suspension.

Recent research under contract No PECD 7/6/56 considered the first two of these problems with particular attention on how the relevant physical processes could be represented in computer models. The first phase of that project, covered in Report SR 75(1), concentrated on finding the best numerical model representation of the exchange of sand between the bed and the flow, based on assessments of the available data and theoretical analyses. The report also contains descriptions of the fundamental physical processes affecting sand transport in estuaries and a brief review of existing numerical models of sand transport.

The implications for the suspended load of the unsteadiness in accelerating and decelerating flow and the numerical simulation of these effects were studied in the second phase of the project. These aspects are described in Report SR 148(2). The efficiency of the model was demonstrated by comparison against some flux observations from the Thames Estuary. The work involved use of standard sand transport relations and brief descriptions of three particular methods of solution are included in the report.

1.2 Research objectives

The objectives of this research programme were

<u>1st year</u> Undertake a literature search for references on transport of sand mixtures and produce a library of sand transport routines on the computer.

<u>2nd year</u> Assess various theories for sand transport of mixtures, formulate a method for computer simulation of the important physics of sand mixtures, and incorporate it into an existing computer model framework.

<u>3rd year</u> Complete the new model formulation of transport of sand mixtures, and prepare a detailed report, including recommendations of any laboratory and/or field work that may be desirable for model validation.

1.3 Literature review

A literature review of the transport of sand mixtures has been carried out, including consideration of field data, threshold of motion, fall velocity and bed, suspended and total load transport. Generally it was found that there is a dearth of useful data and theories on the subject. Armouring of the bed and the interactive behaviour of a suspended size fraction in the presence of other fractions have been identified as important factors to simulate in the model. A report on the literature review has been written (Ref 3).

1.4 Library of sand transport routines

A short library of sand transport routines was established on the ICL 2972 computer in use at HR upto early 1989. These were written in Fortran 77 to facilitate transfer to other computers and they have now been transferred to the new SUN computer system at HR. The library contains the most commonly used sand transport laws for estuarine conditions - Ackers-White and van Rijn - together with associated routines for the bed stress critical threshold and fall velocity.

1.5 Scope of this report

This report describes the relevant sand transport processes and the formulation of the new model of the transport of sand mixtures.

2. SAND TRANSPORTING PROCESSES

2.1 Basic concepts and definitions

Flowing water exerts hydrodynamic forces on the bed and if this consists of loose particles there is a tendency for movement. As the energy of flow increases particles begin to get dislodged and eventually start to move. This movement does not occur instantaneously for all of the exposed particles because of the statistical nature of turbulence and varying grain sizes of sediment.

The main forces acting on a grain of sediment are a drag force in the direction of flow, its weight and a hydrodynamic lift force due to turbulence. Experimental observations show that turbulent energy cannot support the weight of large particles and these therefore remain in the vicinity of the bed and move by rolling, sliding or jumping. This kind of sediment motion is commonly referred to as the bedload transport. However there is a stage when the turbulent intensity can overcome the weight of smaller particles. Under these circumstances the particles are completely surrounded by water and are then said to be in suspended transport. Suspended load transport is usually accompanied by bedload transport and particles may be part of the suspended load at one time and part of the bedload at another, so there exists an active interchange between suspended and bedload and transition between the two modes of transport is gradual. The combined suspended and bedload is called the bed material load. Note that the total load does not necessarily have to be indentical to the bed material load because it can also include a washload of grain sizes finer than the local bed material. The washload moves readily in suspension and tends to be of a transient nature moving through the area with little influence on the bed.

The most significant sand transport parameters are the density ρ and viscosity ν of the fluid, the density ρ_s and characteristic diameter D of the sediment, the average depth d and bed shear velocity u_* of the flow and the force of gravity g. It is normal to describe sediment transport in terms of the following four dimensionless variables derived from these basic quantities

$D_* = ((\rho_s - \rho)g/\rho\nu^2)^{1/3}D$ is the dimensionless grain size number

$Y = \rho u_*^2/(\rho_s - \rho)gD$ is a measure of the hydrodynamic forces on a grain relative to its weight : often referred to as the Mobility Number

$Z = d/D$ represents the relative depth

$W = \rho_s/\rho$ represents the grain inertia.

Sometimes the grain Reynolds number $X = u_*D/\nu$ is used instead of D_*.

Various empirical relationships have been developed for quantifying the bedload, the suspended load and/or their combined bed material load, notably by Einstein, Engelund-Hansen, Meyer-Peter, Ackers-White, van Rijn and many others described in the engineering literature on the subject. The choice of method depends largely on the particular circumstances of the site and the nature of the sediment being considered. However all methods are based on the physically fundamental concepts that sand transport is a phenomenon with a threshold of motion and there is a maximum capacity that the flow can carry. Flow carrying sediment to its maximum capacity is said to be saturated with sediment.

2.2 Effect of sediment mixtures

The existence of a mixed sediment further complicates the already very complex subject. In particular sediment mixtures lead to considerably less well-defined relationships for quantities such as the fall velocity, the threshold of motion and the amount of sediment in motion for given flow conditions. The mobility of finer grains in a mixture is less than it would be with uniform sediment because of the sheltering influence (armouring) of larger grains. On the other hand larger grains are more exposed than they would be in a uniform bed so they may be easier to set in motion. During suspended load transport there is a tendency for the grain fractions to undergo size-sorting with proportionally more finer sediment in the upper part of the profile than near the bed.

2.3 Essential characteristics of the transport of sediment mixtures

From the literature review and prior experience of shortcomings of single size sand transport models the following characteristics required of a model of sand mixtures were identified.

The main requirement was provision to model mutual interactions between size fractions rather than trying to sum the effects of quasi-independent fractions. At the most basic level this means that the pick-up of sediment is reduced in proportion to the proportions of each sand size on the bed and deposition reduced in proportion to the proportions in suspension, with pick-up or deposition taking place depending on whether the flow is under or over-saturated with sediment for the prevailing flow conditions. For a single, uniform sand there would be no net exchange between the bed and flow if the flow was saturated. However, with mixtures there could be a preferential exchange even when the flow was saturated. For example we would expect a flow which was saturated with fine sediment to lose some of the fine sand to the bed, and replace it by coarser sand if some was available on the bed. Conversely we would expect the average grading of a fully laden flow to get progressively finer if it was flowing over a bed of predominately finer sand.

Allied to the above is the concept of sediment velocity. During sediment transport there is usually an exchange of individual sand grains between the bed and the flow. Thus the velocity of individual sand grains is less than the average velocity of the suspended load. This is not significant in the case of a fully developed bed material load flowing over a bed of the same composition because there would be a more or less one-to-one exchange of particles between the bed and the flow. Under these circumstances the flow would be more or less saturated with sediment and any tendency for deposition or scour could be deduced from local variations in flow. However, in the case of an uneven supply of mobile sediment, preferential exchanges between the mixtures would reduce the effective velocity of individual grains: a coarse grain may be at rest on the bed longer if finer grains are more readily mobilised and fine grains may be sheltered beneath coarse grains if there is enough of these latter present on the bed. These considerations are particularly important for assessing the dispersion of spoil from one site which has been disposed of at another site where the bed sediment sizes are different.

The other requirement is that the total amount of each sediment should be conserved. Satisfying conservation of sediment in suspension presents no problems but it is more difficult to achieve this for the bed. In principle it can be done, but in practice the calculation of the varying proportions of each sand size would require an estimate of the thickness of bed through which the sediment is assumed to be mixed, and the appropriate thickness of mixing layer to use is not yet known.

3. FORMULATION OF THE SEDIMENT MIXTURES MODEL

3.1 Simplification of the problem

Inevitably considerable simplifications were required in order to obtain a manageable model. Nevertheless the formulation adhered to the principle that the essential characteristics of the transport of sand mixtures should be retained.

The most fundamental simplification was to represent the continuous, natural grain size distributions by a set of discrete, representative sand sizes. It was considered that two representative sizes were adequate for investigating the main properties and interactions of sediment mixtures and accordingly the formulation is presented for mixtures of two sand sizes. However, the ideas and the model could be extended readily to three or more sands if required later.

3.2 Threshold of motion and settling velocity

Initialisation of motion is traditionally defined from diagrams of the general form shown in Figure 1. Relations in terms of nondimensional parameters (Fig. 1a) enable normalisation of data from many sources and many conditions, but relations in terms of physical variables (Fig. 1b) are more useful in practice. Strictly there is not a distinct threshold between no motion and mobility, nor between bed and fully suspended transport, but for simplification a precise cut-off was assumed.

3.3 Representation of pick-up and deposition

For a single, representative sand size the rate of exchange of sand between the bed is often simulated by a relation of the form

$$S = \beta(c_s - c)$$

where β is the bed exchange factor introduced in Reference 1, c_s is the expected (saturated) concentration for this type of sand at the prevailing flow conditions and c is the actual concentration present in the model.

This relation represents deposition to the bed if the model is over-saturated with sediment ($c > c_s$) and pick-up from the bed if the model is under-saturated ($c < c_s$). β varies according to the sand size and gives the appropriate rates of deposition or pick-up for the prevailing flow conditions.

For a mixtures it is proposed to represent bed exchanges by relations of the form

$$S_j = b_j \beta_j \, (t_j \, c_{sj} - c_j) \qquad \text{if} \quad c_j < t_j \, c_{sj}$$

and

$$S_j = s_j \beta_j \, (t_j \, c_{sj} - c_j) \qquad \text{if} \quad c_j > t_j \, c_{sj}$$

where

b_j is the proportion of the jth sand fraction on the bed

s_j is the proportion of the jth sand fraction in the suspended load, and

t_j is a transport factor for the jth sand fraction in the mixture.

β_j, c_{sj} and c_j are the appropriate bed exchange factor, saturated concentration and model concentration for the jth sediment fraction, and there would be analogous relations for the other sand sizes.

These relations therefore represent pick-up and deposition modified by the appropriate proportions of each sand size on the bed or in suspension. Generally the model concentration will tend towards a modified saturation value taking account of the proportions of mobile sand types available on the bed. If just one sediment size is present then these relations reduce to the relation for a single sand size.

The appropriate form of transport factor is not known and it is likely that laboratory experiments will be required at a later stage to provide some insight of this. In the meantime it is proposed to choose the jth transport factor as

$$t_j = b_j/(\Sigma\, b_i)$$

summed over the mobile fractions only.

Note that the summation is only over the modelled mobile fractions on the bed to cater for the case with just one sand size present on the bed, but not covering the whole bed ($b_j < 1$). Under these circumstances the transport function would be unity, sand would be picked up at a reduced rate, defined by b_j, and the model concentration would eventually equal the expected saturated concentration for the jth sand size.

As well as distributing total load between the modelled sand fractions, the t-functions also provide interaction between them. For example, if there is fine sand in suspension but none on the bed then t_f = 0 and fine sediment is deposited even if the flow is faster than the threshold for the fine sand. The amount of fine sand in suspension tends to zero making capacity for other fractions to be picked up from the bed if such mobile material is available. The composition of the suspended load would therefore gradually change towards becoming compatible with the bed it flows over. This is one of the essential features of the transport of mixtures. Analogous behaviour would occur if flow with relatively more coarse sediment passed over a bed with finer sediment.

3.4 Implementation

The framework of the standard HR SANDFLOW model was amended so that it could deal with two representative sand sizes. It was considered that two basic sand sizes were adequate for investigating the main properties of mixtures, but in any event the programming was done in such a way that the model could be extended readily for three or more sands if required later. Interactions between the size fractions were represented as described in section 3.3.

4. DEMONSTRATION OF THE NEW MODEL

4.1 Test conditions

Two examples were run to demonstrate the operation of the new model.

These tests were run for the same flow conditions used in Reference 2 when studying the simulation of unsteadiness of sediment transport. However here the model was run in steady state mode to make the behaviour of the different size fractions more obvious. The finer of the two sands was chosen to be the same as used in Reference 2, and the other was chosen to be slightly coarser.

The main flow variables were

flow depth	18.6m
mean flow velocity	0.7 m/s

and the following sediment properties were used:

	Very fine sand	Fine sand
fraction (mm)	0.075 to 0.10	0.10 to 0.15
representative diameter (mm)	0.086	0.122
representative fall velocity (mm/s)	4.4	6.0
threshold velocity (m/s)	0.17	0.40

The model allowed a choice of three methods for calculating the saturation concentration, c_s, namely a modification of that of Odd (4), and those of Ackers and White (5), and van Rijn (6). These are all semi-empirical relationships between concentrations and the flow parameters, based on different assumptions and with varying applicability. For the purpose of the demonstrations the first of these methods was applied in the form

$$c_s = A\ (1 - u_\tau^2/u^2)u^3/d$$

where u is the depth-averaged velocity

and u_τ is the threshold velocity.

The transporting efficiency, A, was obtained according to Reference 4 as 0.5 and 0.2 for the very fine and fine sand fractions respectively. The general suitability of these values can be seen from Figure 3 of Reference 2 (eg compare the relative sand fluxes at velocity 1 m/s).

4.2 Depositional situation

In this case the incident flow was taken to be over-loaded with fine sand and the bed to be initially very fine sand. Two initial bed deposits were considered (1 kg/m^2 and 10 kg/m^2) to test the sensitivity to the thickness of the bed mixing layer, and the incident concentration was 10 g/m^3.

Additional tests were made to provide comparable results for the transport of single size sediments under the same conditions, and results from all depositional test are shown in Figure 2.

Deposition of fine sand from the overloaded, incoming flow (Fig. 2b) was essentially the same for all cases considered. Some of the fine sand in suspension was replaced by very fine sand from the bed. The amount of very fine sand picked up (Fig. 2a) varied considerably depending on the initial thickness of the fine sand bed. There was more armouring effect from fine sand deposits when the initial very fine sand bed was thinner. When the very fine sand bed was thicker the amount of very fine sand picked up, approached the amount picked up for the case with only very fine sand present. The total suspended sand load (Fig. 2c) was much more for the thicker very fine sand bed; once again demonstrating the importance of armouring.

The bed changes of the very fine (Fig. 2d) and fine (Fig. 2e) sand fractions behaved as expected with more erosion of very fine sand when more very fine sand was available on the bed (because of less armouring) and more deposition of fine sand when more very fine sand was available on the bed (because of better trapping by the bigger bulk of very fine sand). When just fine sand was simulated the model, as expected, predicted net deposition everywhere (Fig. 2f) from the overloaded flow. However, when very fine sand was included there was in fact a small amount of net erosion at the downstream end. The reason for this is that the flow could carry a larger amount of very fine sand for the same flow conditions.

4.3 Erosive situation

In this case the incident flow was taken to be only partly loaded with the very fine sand, with a fine sand bed. Two initial bed deposits (1 kg/m^2 and 10 kg/m^2) were considered and the incoming concentration was 5 g/m^3. As before additional tests were made to provide comparable results for single size sediments under the same conditions and the results from all erosive tests are shown in Figure 3.

For a very fine sand bed the partly loaded flow in the model picked up very fine sand as expected (Fig. 3a). However, when a fine sand bed was included the amount of very fine sand in suspension decreased. This is sensible because there should be a continuous exchange of sand between the flow and the bed. When only very fine sand was available on the bed more very fine sand was picked up than deposited in order to correct the deficit in suspended load. When fine sand was present on the bed, some of this was picked up (Fig. 3b) in preference, because there was more of it. Eventually the load should become the appropriate saturated load for the bed material. The trend towards this can be seen from the decreasing very fine sand concentrations in Figure 3a and the increasing fine sand concentrations in Figure 3b. If a longer length had been simulated then the result would have evolved further towards a wholly fine sand load. The total load (Fig. 3c) for the mixtures was less than for the wholly very fine sand simulation because part of the load consisted of less mobile fine sand.

The erosion/deposition of the very fine fraction (Fig. 3d) was consistent with the trends described above when considering the suspended load. There was always a tendency for fine sand to be eroded (Fig. 3e). The net results for the two sand sizes are shown in Figure 3f. Without any very fine sand at all the model, as expected, predicts a net erosion of bed material. However, when very fine sand is included the model actually predicts net deposition. The reason is that the fine sand bed traps some of the very fine sand: the flow cannot take up an equivalent amount of fine sand because it is less mobile so the total amount on the bed increases.

5. CONCLUSIONS AND RECOMMENDATIONS

1. From a literature review and assessment of available information the following fundamental requirements for a model of transport of sand mixtures were identified.

   - provision to model the mutual interaction between size fractions rather than a simple summation of results for independent fractions

   - provision to modify the sediment pick-up and deposition rates of individual fractions in proportion to the proportions of each fraction in suspension and on the bed

   - provision to model the bed so that the progressive armouring of the bed by coarser grains and/or the equivalent trapping of finer grains can be simulated. A consequence of the latter is that the suspended load should gradually evolve into one wholly consistent with the bed material.

2. A plausible method for dealing with the transport of sand mixtures has been postulated. When tested on demonstration examples the new model

behaved in a wholly sensible manner including the desirable features discussed above. The armouring effect when more of the coarser sand was present on the bed led to lower suspended concentrations of the finer sediment. Conversely, the trapping of finer sediment by a coarser sand bed produced a trend towards a suspended load made up wholly of the dominant bed material.

3. The demonstrations showed that it was possible to get net erosion in what was fundamentally a depositional situation and net deposition in what was fundamentally an erosive situation. This was a consequence of the different capacities of the flow for the two sand sizes. Although this is expected to be a temporary effect in a real situation, while the composition of the bed adjusts to the flow and suspended load conditions, it does emphasise the need for the model of sand mixtures.

4. The demonstrations identified a sensitivity to the initial thickness of bed through which deposits were allowed to mix. See, in particular the effect on total suspended load in Figure 2c and total bed changes in Figure 2f.

5. The most appropriate thickness of mixing layer to use is not yet known, therefore there is a need for more research to investigate how the thickness of the disturbed surface layer of sediment varies with the main flow and sediment parameters. This information is essential if a correct budget of the sediment sizes is to be obtained. It is recommended that this should be done in a laboratory flume because natural conditions are too variable to obtain controlled results. The experiments should include a range of tests to determine the sensitivity of the pick-up, transport and deposition of sediment mixtures to different flow rates, different incident sediment loads and different mixtures of bed sediments, to provide real quantitative checks on the model.

6. REFERENCES

1. Miles G V. Numerical model simulation of entrainment of sand bed material. Hydraulics Research Ltd, Wallingford, OX10 8BA, UK. Report SR 75, February 1986.

2. Wild B R. A numerical sand transport model with time dependent bed exchange. Hydraulics Research Ltd, Wallingford, OX10 8BA, UK. Report SR 148 February 1988.

3. Walmsley N. Transport of sand mixtures. A literature review. Hydraulics Research Ltd, Wallingford, OX10 8BA, UK. Report SR 200, April 1989.

4. Odd N V M. The Wash water storage scheme. Numerical model studies of the Great Ouse estuary: A transport function for fine sand in the estuary. Hydraulics Research Station, Wallingford, OX10 8BA, UK. Report DE 9 August 1973.

5. Ackers P, White W R (1973). Sediment transport: New approach and analysis. Proc ASCE, 99, HY 11 pp 2041-2060.

6. van Rijn L C (1984). Sediment transport, part II: Suspended load transport. Journal of Hydraulic Engineering, 110, 11, pp 1613-1641.

FIGURES

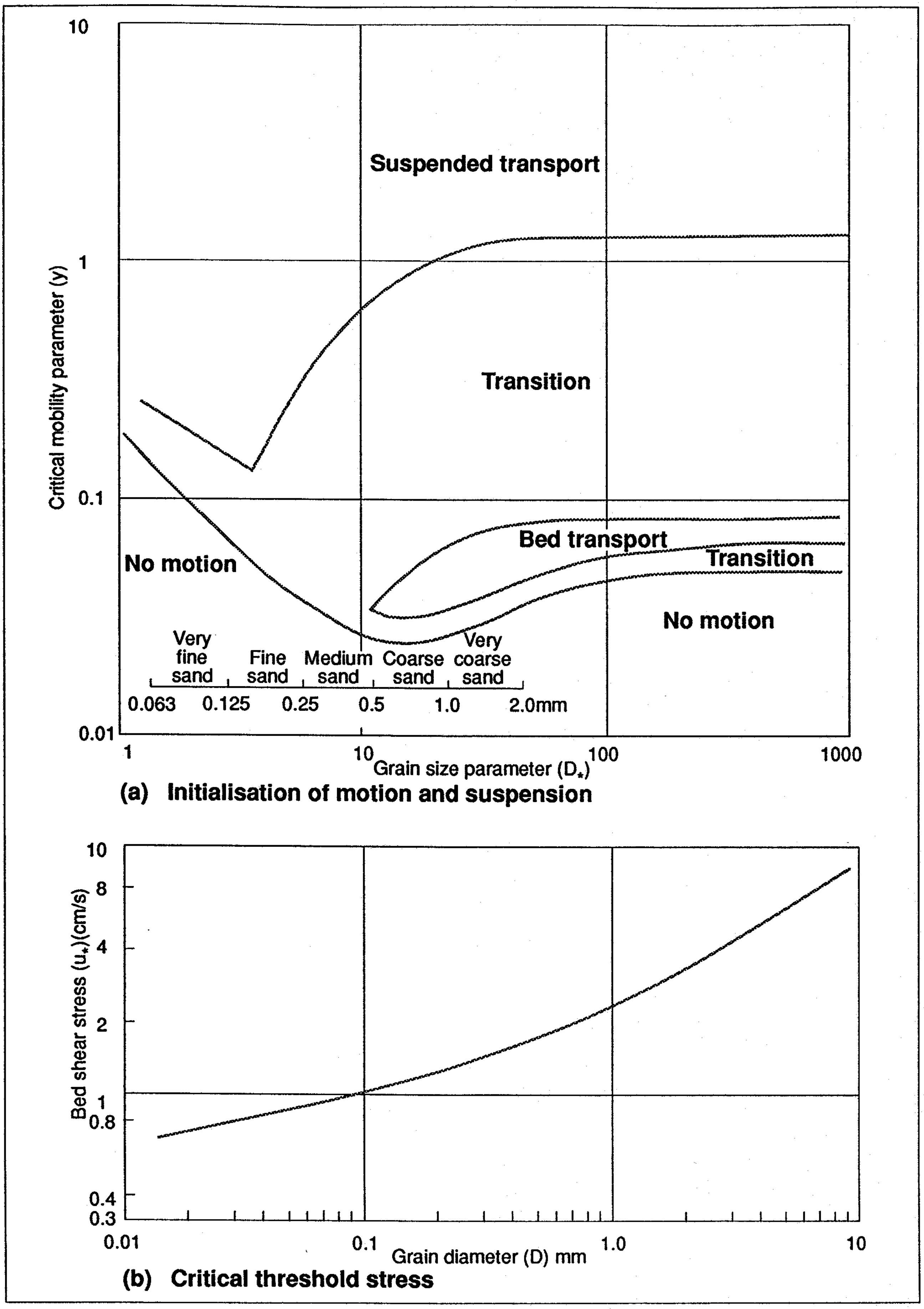

Fig 1 Initiation of motion

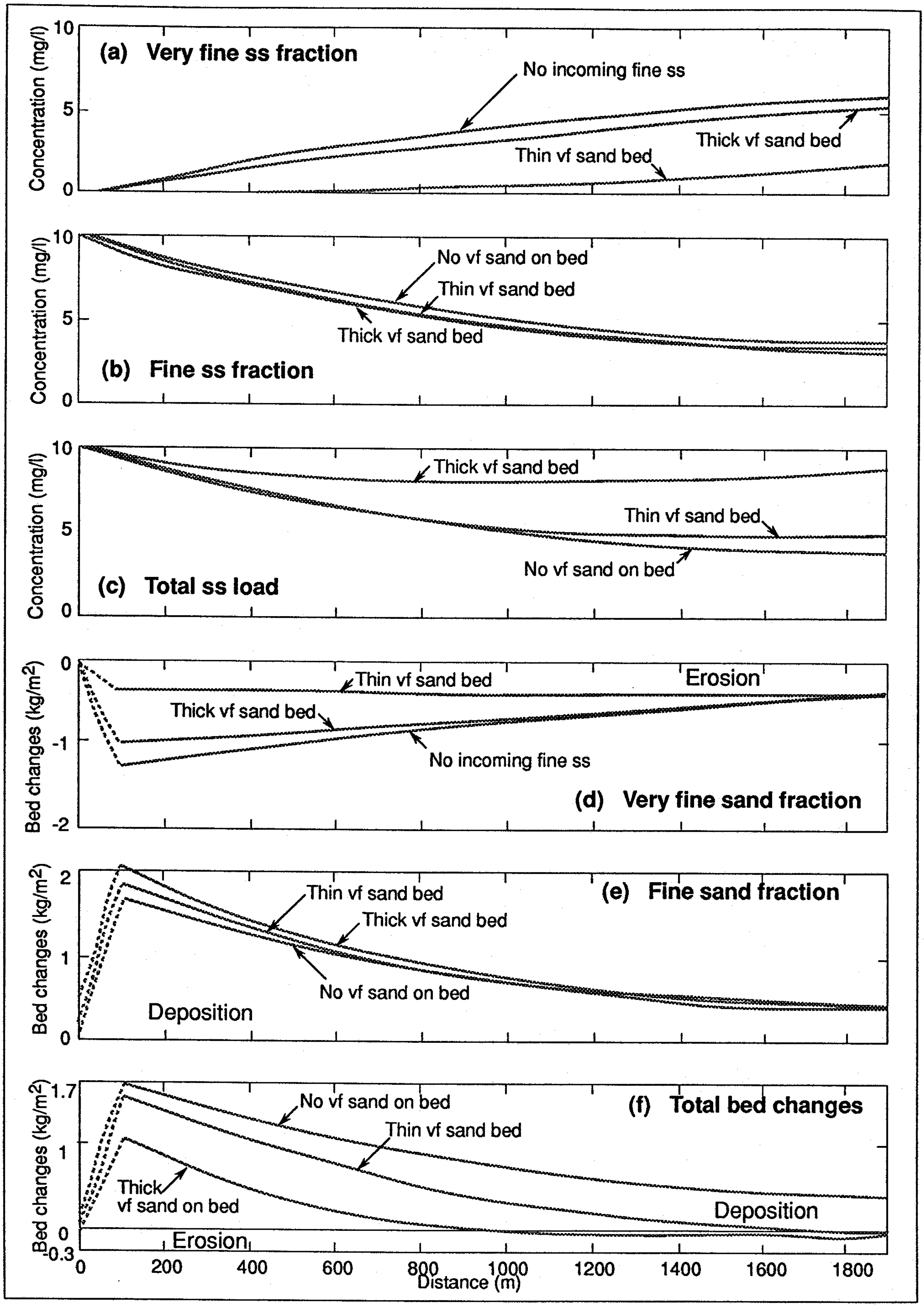

Fig 2 Demonstration of depositional conditions. Fine sediment suspension flowing over very fine sand bed

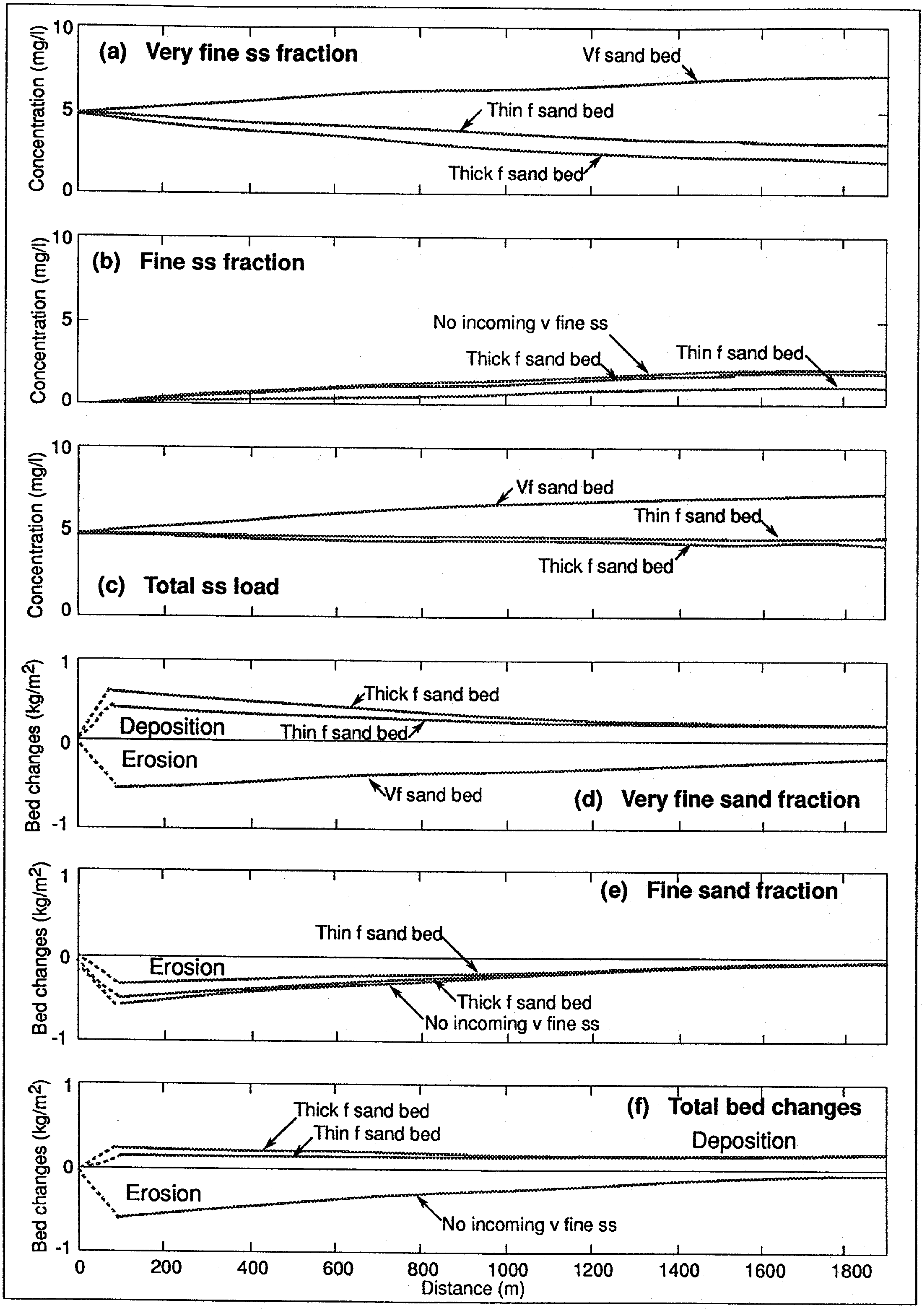

Fig 3 Demonstration of erosive conditions. Very fine sediment suspension flowing over fine sand bed