Hydraulics Research
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TRANSPORT OF SAND MIXTURES
A LITERATURE REVIEW

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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

- a wide range of sediment exists on the bed and in suspension.

In recent years sediment transport models have been developed and used for making engineering assessments of the impact of works on the sediment regime. At present the full potential of the models cannot be realised because of the lack of calibration and verification data, and gaps in our understanding of the fundamental sedimentation processes.

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 objective of the present research project is to consider the problems associated with mixtures of sediment.

The first phase of this project included a literature review of the transport of sand mixtures including consideration of field data, threshold of motion, fall velocity and bed, suspended and total load transport. This report summarises the main references on the subject and contains a brief description of the latest theories being considered by other workers in this field. The main factors which will need to be taken into account in the computer model of sediment mixtures have been identified as the incorporation of different saturation concentrations for different mixtures of size fractions, different bed exchange rates resulting from different settling velocities and armouring of the bed by coarser grains, and variable bed composition arising from differential settling and resuspension.

The information obtained from the literature review will be assessed in the next stage of the work and used to formulate a computer model for simulating the transport of mixtures. This will be described in the main contract report due in the Spring of 1990.

CONTENTS

1 INTRODUCTION

The numerical model prediction of sediment transport plays an important role in assessing the impact of engineering works in tidal estuaries. The models can be used to assess deposition/erosion problems during the early design stages and can identify possible future maintenance commitments such as the dredging of shipping channels.

A lot of work has been done in the past on the motion of uniform sands in one dimensional flows. In tidal estuaries the problems become more difficult because the water movements are continually changing with the rise and fall of the tide, a wide range of sediment exists on the bed and in suspension and certain sediments are found in some parts but not in others which may lead to unsaturated loads in the water column.

In order to improve the usefulness of existing sediment transport models in engineering applications a number of developments have been outlined in relation to the modelling sand mixtures:

- incorporation of different saturation concentrations for different size fractions
- different bed exchange rates resulting from variable settling velocities
- variable bed composition arising from differential erosion and deposition
- the possibility of armouring of finer grains by coarser grains
- efficient and accurate methods of calculating saturation concentrations

- initialisation of bed composition in situations of variable supply of erodible material

The aim of this literature review was to identify the key workers in this field of study and to bring together many of the relevant references. This interim report is not an in depth technical review but is intended as a reference guide for the researchers undertaking the next phase of the research contract.

2 GENERAL BACKGROUND

2.1 Mixture theory

The transport of fine materials in turbulent fluid flow plays an important role in a broad range of disciplines and this has been reflected in the research literature. Fluid-solid mixture theory has been developed (McTigue, 1981) which models both the fluid and particulate phases as continua whilst taking account of turbulent fluctuations of the velocities and concentrations. Constitutive equations describing the shear stresses occurring in a mixture have been derived by Ackermann and Shen (1982) [see also Shen and Ackermann (1982)] whilst other researchers have investigated bouyancy forces and concentration distributions in fluid-solid mixtures (Zhaoyin, 1987, and Zhaohui and Tiancheng, 1987).

2.2 Field and flume studies

One of the drawbacks of modelling transport of sand mixtures in estuaries is the dearth of field data. However, in recent years a number of in-situ sedimentation studies have been undertaken by Vale and Sundby (1987), Jarvis and Riley (1987), Bedford et al (1987) which reflect an increasing concern in the lack of relevant field data for the assessment of transport formulae and mathematical models. One of the most extensive sedimentation surveys to be reported in the literature was carried out by Allen (1971) in the Gironde estuary. He monitored tidal current and wave induced transport and investigated their effect on the grain size distributions in the estuary. This data was later used by Owens (1986) as validation data for his sediment transport model.

The pattern of naturally occurring grain size distributions is often approximated by a Gaussian or normal distribution where the log histogram approximates to a parabola. Bagnold and Barndorff-Nielsen (1980), however, found that measured sand grain distributions often approximate to a hyperbolic distribution. Their findings were further substantiated by Deigaard and Fredsoe (1978) who showed, by simulation, that originally log-normally distributed sand will tend to become log-hyperbolically distributed after sorting. Work on size distributions of sand has been continued by Barndorff-Nielsen and Christiansen (1988) whose field studies have shown that the mass-size distributions of sands will vary depending on whether they are from a predominantly depositional environmental or predominantly erosional environment.

The development of numerical models to simulate graded sediments has demanded that there be complementary physical model studies in order to gain a full understanding of the physical processes encountered in graded sediments (White, 1972; Bridge, 1981; Westrich and Juraschek, 1985; Ribberink, 1987). In particular, Allard (1987) has carried out a series of well controlled flume experiments using sand particles in an effort to isolate certain phenomena and to assess their relative importance. More recently, Wilcock and Southard (1988) undertook a large range of flume studies on a range of graded sediment samples to investigate incipient motion of the individual grain sizes. Rakoczi (1987) has also investigated the effect of sediment mixtures on initiation and development of sediment motion in a series of laboratory investigations.

2.3 Numerical models

The majority of sediment transport research, whether it be flume experiments, field studies or numerical model development, has been carried out for steady uniform flow conditions. Efforts have been made to develop more advanced models to handle unsteady and non-uniform conditions (Brownlie, 1981; Krishnappen, 1981; Tsujimoto, 1987 and Lyn, 1987) but these are generally only applicable to sediment transport in river channels. However, Markofsky et al (1985) have developed a model specifically for use in tidal waters. Using their model, they investigated the sensitivity of model results to numerical as well as physical parameters such as discharge, location of sediment source, stratification and tidal motion. In particular, they investigated methods of limiting the numerical diffusion generated within the model.

In recent years a number of one dimension models have been developed to take account of graded sediments (Borah et al, 1982; Karim and Kennedy, 1985; Karim and Holly, 1986) which show good correlations with flume experiments but which falter when compared with field data. Lu and Shen (1985) chose to investigate the use of an existing sediment transport formula, i.e Einstein's, and found that Einstein's hiding factor could in fact provide reasonable bed load estimates.

Celik and Rodi (1985) proposed a model which involved new approaches for determining eddy-diffusivity, transport capacity and bed-boundary conditions. The model was applied to non-equilibrium transport situations and close agreement between prediction and measurement was found. An alternative two-dimensional vertical model was proposed by van Rijn (1986) in which finite-element methods were used to solve the convection-diffusion equation. The model developed by Lee and Ahn (1986) was derived from convective-diffusion theory but they included a hindered settling effect of the particles and the vertical velocity component due to tidal movement. A series of model tests revealed the sensitivity of sediment transport to these parameters and demonstrated a hysteresis effect of the sediment concentration between flood and ebb tides. Temporal lag between variations in tidal flow and corresponding variations in sediment concentrations were also evident, particularly for grain sizes with low fall velocities.

3 TRANSPORT OF SAND MIXTURES

3.1 Threshold of sediment motion

The importance of the bed shear stress as the governing mechanism causing sediment motion has been recognised for many years and initiation of motion is generally expressed in terms of applied bed shear stress in the form of a Shields' curve (Shields, 1936). Miller et al (1977) have used carefully selected data for the initiation of motion under unidirectional flow conditions to develop a modified Shields-type threshold diagram to extend the limits of the original diagram by three orders of magnitude. However, one of the limitations of the empirical relationships they derived were the grain size distributions used in the experiments. These were fairly closely graded whereas it is known that naturally occurring sediments generally have a much wider size distribution. Other researchers have developed Shields-type threshold curves for graded material. In particular, Singhal et al (1980) conducted a series of experiments using naturally occurring sands. They found that rather than following Shields' curve the experimental data gave alternative relationships for each size of bed material thereby indicating that there was an interaction due to the grading of the sand. They further found that the data could be grouped corresponding to different values of turbulence coefficient which suggested that Shields curve was derived in the short turbulence coefficient range.

Hammond et al (1984) undertook a number of in-situ studies in tidal areas where the bed material was classified as a gravel (2 - 50mm). Comparisons between observed data, Shields' curve and their own flume experiments were conducted. As expected with graded bed material, they found that the larger grains experienced a disproportionately large fraction of the bed shear stress due to their increased exposure and this resulted in their threshold of motion being lower than that predicted for a uniform bed. These experiments helped to reinforce the importance of grain protrusion in coarsely packed, non-cohesive grains.

It is generally assumed that the tractive force at initialisation of motion will be the same as that at which the motion ceases. Reid and Frostick (1984) have shown that this is not necessarily the case when considering coarse-grained mixtures. Their field studies on coarse-grained alluvial streams indicated a hysteresis effect in which the threshold of motion was initiated at one value of the shear stress but that motion was ceased at a much lower shear stress than that predicted by the Shields curve. Whilst this may not be directly applicable to sand transport, it does indicate a need to consider possible hysteresis type effects in bed load transport.

The threshold of motion cannot be considered as a purely deterministic phenomenon because of the fluctuations of bottom flow and the randomness of both particle size and their position in the bed. The random variable approach was adopted by many of the earlier researchers, such as Einstein (1942), and more recently improved stochastic models have been developed (Mingmin and Qiwei, 1982) which incorporate a combined method of mechanistics and probability.

3.2 Fall velocity

Sediment transport calculations and mathematical modelling of erosion and deposition generally require an estimate of the sediment settling, or fall, velocity. Because the calculations are sensitive to fall velocity best estimates are essential. In the 1970's Zanke (1977) derived an expression for sand particles (0.1 - 1.0mm), and for coarser particles van Rijn (1984) gives an alternative expression. Of particular use in sand transport calculations, Hallermeier (1981) utilised published measurements of fall velocities of commonly occurring sand particles to develop an empirical relationship for use with fine, medium and coarse sands.

Refinements of fall velocity calculations to take account of shape factors (Prashun and Knofczynski, 1985) and concentration dependent fall velocities (Lavelle and Thacker, 1978) have been proposed in recent years. However, a limiting factor in fall velocity data lies in the fact that the majority of tests are carried out under controlled laboratory conditions. Efforts are now being made to carry out in-situ fall velocity measurements (van Rijn and Nienhuis, 1985) and the effect of uniform flow on particle settlement has also been considered (Li and Shen, 1975).

3.3 Bed load transport

Sediment mixtures introduce an additional degree of complexity into bed load transport calculations. In the past, a number of bed load transport formulae have been developed which are based on an effective, or representative, grain size. For use with sediment mixtures the fundamental approach has been (instead of adopting a single representative sediment size) to split the sediment up in to a number of size ranges and to take a representative sediment diameter for each range. Size distribution and particle interaction, however, are known to play an important role in transport processes and attention is now being focussed in this area. The physical processes to be considered are, on the one hand, a sheltering of finer grains by larger grains thereby reducing their transport rate; on the other hand, larger grains are more exposed than they would otherwise be in a uniform bed and their transport is greater due to the larger fluid forces they experience.

Proffit and Sutherland (1983) modified existing bed load formulae for use with non-uniform sediments by defining an exposure correction factor which allows for the increased mobility of coarse particles and reduced mobility of finer particles, as compared with their mobility in a uniform sediment bed. Acceptable correlation with laboratory controlled data was found by Profitt and Sutherland but, as is often the case, comparison with field data was less successful. The variation between bed material distribution to transported material distribution was thought to be the prime reason for the discrepancies. Systematic tests to isolate the effect of bed material gradation and sorting on bed load transport are relatively scarce but their importance was investigated by Klaassen (1987). He found that vertical sorting of bed material had an appreciable effect on bed form dimensions and hence resistance to flow and transport rates. Klaassen et al (1987) have furthered their work in the dune regime area and found, contrary to the flat bed case, that the transport rates of coarser grains is reduced. The reduction in transport rate was due to a temporary storage of coarse grains in the troughs of adjacent dunes.

Misri et al (1984) undertook an extensive experimental program to investigate the bed load transport of non-uniform sediments and made comparisons with predictions using Einstein's method (Einstein, 1942). The predicted transport varied considerably from these experimental results and Misri et al evolved an alternative method of calculating transport rates in non-uniform mixtures. They developed a coefficient similar to Einstein's sheltering coefficient which took account of the sheltering of finer grains but also increased the exposure of coarser grains. Their work was found to give satisfactory results for laboratory data but the method did not give good results when compared with field data. Samaga et al (1986) recognised some of the inadequacies of Proffit and Sutherland's and Misri et al's experimental studies and undertook a further set of flume studies for non-uniform sediments. The studies confirmed Misri et al's findings concerning the inadequacies of Einstein's method and due to the much wider range of variables studied led to an improved exposure correction factor. This had the advantage of being based on a combination of flume and field data.

An important feature of sediment transport in tidal estuaries are spatial and temporal lag effects. These can be defined as the alluvial system's inability to immediately overcome constrained sediment boundary conditions and to immediately respond to an imposed change in discharge.

A one dimensional unsteady flow and sediment routing model with the ability to incorporate these effects is described in Phillips and Sutherland (1985). The performance of the model was tested against laboratory flume experiments and a good correlation between simulated and measured sediment hydrographs and yields were reported. This was a continuation of Sutherland's previous research in this field which included investigation of non-equilibrium bed load transport in steady flows (Bell and Sutherland, 1983) and his work with Proffit (Proffit and Sutherland, 1983) on non-uniform sediments.

In recent years Armanini and di Silvio (1987) developed a model to simulate erosion/deposition in tidal channels with non-uniform bed material. They recognised the shortcomings of using local and instantaneous equilibrium conditions. The phase shift between hydrodynamic and sedimentologic quantities was incorporated in their model by the inclusion of spatial and temporal lag effects. In their study of the evolution of a trench dredged across a tidal channel, they found the results were less sensitive to the composition of the sediment mixture than in similar studies using steady flow (Armanini and di Silvio, 1985).

3.4 Suspended load transport

The suspended transport of uniform sediments has been studied extensively during the last five decades. Suspended load transport describes the motion of particles which are fully surrounded by the fluid. Owing to the weight of the particles there is a tendency to settle but this is counter balanced by the irregular, turbulent velocity components of the fluid. The hydraulic conditions of the fluid determine whether a particular grain fraction is in suspension or not. There exists an interchange between the bed load and suspended load in addition to that between the bed load and the bed.

During suspended load transport there is a tendency for the grain fractions to undergo size-sorting (Sengupta 1975). The grain size distribution at different heights above the bed becomes skewed when compared with that of the bed load material. The resulting suspended load distribution has been found to be a function of the initial bed load distribution and the flow velocity (Sengupta, 1979).

Samaga and Ranga Raju (1985) carried out a series of flume experiments and field tests to gain a better understanding of the physical processes affecting suspended transport of mixtures. The processes involved are : the sheltering or exposure effect which influences the concentration of size fractions close to the bed; the interference of one size fraction with the others in the process of entrainment and suspended load, thereby affecting the exponent in the sediment distribution equation. The findings of Samaga and Ranga Raju concluded that some of the well established suspended sediment transport methods gave poor results for the individual size fractions in a mixture. An alternative method was developed, based on a correction factor for each size fraction, which gave better results although only one set of field data was used in the comparison. Further validation is required to fully verify the method.

Samaga et al's interest in this field of research has included investigations into the concentration distributions of sediment mixtures (Samaga et al, 1986). The agreement between existing predictors and field data was found to be unsatisfactory. The field data suggested that the sediment distribution exponent for any size fraction in a mixture was not constant over the whole depth of flow. A two layer model was proposed which gave improved results against limited field data.

3.5 Total load transport

The total bed material load is the sum of the bed load and suspended load but excludes the wash load. The present day methods for the calculation of total load are of two kinds. Firstly, a summation of the bed load and suspended load and, secondly, methods which directly relate total load with the flow parameters. In the case of non-uniform sediments the transport rate of one size fraction is strongly affected by the presence of the other fractions and calculations based on a representative size fraction will not be correct.

Ackers and White's sediment transport method was modified by Day (1980) for use with graded sediment by including an initial motion parameter for each size fraction.

Samaga et al (1985) proposed a method for the computation of total load transport of each size fraction in the bed material. The method used the transport relationships of uniform bed material as a basis but then introduced a sheltering coefficient to account for the graded bed material. The resulting semi-empirical total load transport formula was based on flume data but verification of the method with field data was not reported. A full assessment of the method has therefore yet to be made.

4 DISCUSSION

This interim report has highlighted the key workers researching into the transport of sand mixtures and has identified the presently available relevant literature. This report does not contain an in depth technical assessment of the literature but merely indicates what ideas and information are available for the use in next phase of the research project.

The published research highlights the need to model interactions between size fractions rather than attempting to seem the effect of quasi-independent fractions. Although suitable studies are not numerous, models should be validated against field data wherever possible as comparisons with laboratory measurements often give falsely optimistic results

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6 REFERENCES

Ackermann N L and Shen H (1982). Stresses in rapidly sheared fluid - solid mixtures. ASCE J of Engineering Mech Div, vol 198, No EM1, pp95-113.

Allard J (1987). Sediment transport in rivers - research activities of the National Hydraulics Laboratory (France). Euromech 215, Genova, Italy, pp133-136.

Allen G P (1971). Relationship between grain size distribution and current patterns in the Gironde estuary (France). J of Sedimentary Petrology, vol 41 No 1, pp74-88.

Armanini A and di Silvio (1985). Transport of suspended sediments along channels with a trench. XXI Congress of IAHR, vol 3, Melbourne, Australia.

Armanini A and di Silvio G (1987). Erosion - deposition processes in tidal channels with non-uniform bottom material. Congress of IAHR, Lausanne, Switzerland.

Bagnold R A and Barndorff-Nielsen O (1980). The pattern of natural size distributions. Sedimentology, vol 27, pp119-207.

Barndorff-Nielsen O E and Christiansen C (1988). Erosion, deposition and size distributions of sand. Proc. of R. Soc. vol 417, pp335-352.

Bedford K W, Wai O, Libicki C M and von Evra R (1987). Sediment entrainment and deposition measurements in Long Island sound. ASCE J of Hydraulics Engineering, vol 113, No 10, pp1325-1342.

Bell R G and Sutherland A J (1983). Non equilibrium bedload transport by steady flows. ASCE J of Hydraulic Engineering, vol 109, No 3, pp351-367.

Borah D K, Alonso C V and Prasad S N (1982). Routing graded sediments in streams : applications. ASCE J of Hydraulic Engineering, vol 108, no HY12, pp1504-1517.

Bridge J S (1981). Hydraulic interpretation of grain - size distributions using a physical model for bedload transport. J of Sedimentary Petrology, vol 51 No 4, pp1109-1124.

Brownlie W R (1981). Unsteady sediment transport modelling. Proc of Speciality Conf. Water forum '81, San Fransisco, USA, pp1193-1200.

Celik I and Rodi W (1985). Mathematical modelling of suspended sediment transport in open channels. 21st IAHR Congress, Melbourne, Australia, pp533-538.

Day T J (1980). A study of the transport of graded sediments. Hydraulics Research Station Report No IT 190, pp10.

Deigaard R and Fredsoe J (1978). Longitudinal grain sorting by current in alluvial streams. Nordic Hydral., vol 9, pp7-16

Einstein H A (1942). Formulas for the transportation of bed-load. Trans. ASCE, vol 107.

Hallermeier R J (1981). Terminal settling velocity of commonly occurring sand grains. Sedimentology vol 28 pp859-865.

Hammond F D C, Heathershaw A D and Langhorne D N (1984). A comparison between Shields threshold criterion and the movement of loosely packed gravel in a tidal channel. Sedimentology vol 31, pp51-62.

Jarvis J and Riley C (1987). Sediment transport in the mouth of the Eden estuary. Estuarine, coastal and shelf science, vol 24, pp463-481.

Karim M F and Holly F M (1986). Armouring and sorting simulation in alluvial rivers. ASCE J of Hydraulic Engineering, vol 112, No 8, pp705-715.

Karim M F and Kennedy J F (1985). Kinematic analysis of bed degradation in alluvial streams with non-uniform sediment. 21st IAHR Congress, Melbourne, Australia, pp554-560.

Klaassen G J (1987). Experiments on the effect of gradation on sediment transport phenomena. Euromech 215, Genova, Italy pp235-241.

Klaassen G J Ribberink J S and de Ruiter J C C (1987). On the transport of mixtures in the dune phase. Euromech 215, Genova, Italy, pp212-216.

Krishnappen B G (1981). Field verification of an unsteady non-uniform sediment laden flow model. 19th IAHR Congress, New Delhi, India, pp217-229.

Lavelle J W and Thacker W C (1978). Effects of hindered settling on sediment concentration profiles. IAHR Jnl of Hydraulic Research, vol 16, No 4 pp347-355.

Lee J K and Ahn S H (1986). Model of diffusion movement of suspended load due to tidal flow. 5th IAHR Congress, Asian and Pacific Regional Division, Seoul, Republic of Korea, pp129-142.

Li and R M and Shen H W (1975). Solid particle settlement in open-channel flow. ASCE J of Hydraulic Engineering, vol 101, No HY7, pp917-931.

Lu J Y and Shen H W (1985). Evaluation of H A Einstein's hiding factor for transport of non-uniform sediment sizes. 21st IAHR Congress, Melbourne, Australia, pp561-564.

Lyn D A (1987). Unsteady sediment transport modelling. ASCE J of Hydraulic Engineering, vol 113, No 1, pp1-5.

McTigue D F (1981). Mixture theory for suspended sediment transport. ASCE J of Hydraulic Engineering, vol 107, No 6, pp659-673.

Markofsky M, Lang G and Schubert R (1985). Suspended sediment transport in tidal waters: turbidity maximum, numerical simulation, physical aspects. 21st IAHR Congress, Melbourne, Australia, pp130-137.

Miller M C, McCave I N and Komar P D (1977). Threshold of sediment motion under unidirectional currents. Sedimentology, vol 24, pp507-527.

Mingmin H and Qiwei H (1982). Stochastic model of incipient sediment motion. ASCE J of Hydraulics, vol 108, No HY2, pp211-224.

Misri R L, Garde R J and Ranga Raju K G (1984). Bedload transport of coarse non uniform sediment. ASCE J of Hydraulic Engineering, vol 110 No 3, pp312-328.

Owens P H (1986). Mathematical modelling of sediment transport in estuaries. PhD thesis, Univ. of Birmingham, UK 220pp.

Phillips B C and Sutherland A J (1985). Numerical modelling of spatial and temporal lag effects in bed load sediment transport. 21st IAHR Congress, Melbourne, Australia, pp571-576.

Prashun A L and Knofczynski M (1985). Improved computation of fall velocity. 21st IAHR Congress, Melbourne, Australia, pp 349-354.

Proffitt G T and Sutherland A J (1983). Transport of non-uniform sediments. IAHR J of Hydraulic Research vol 21 No 1, pp33-43.

Rakoczi L (1987). Effect of granulometry on sediment motion : a new approach. IAHR Congress, Lausanne, Switzerland, pp154-159.

Reid I and Frostick L E (1984). Particle interaction and its effect on the threshold of initial and final bedload motion in coarse alluvial channels. Sedimentology of gravels and conglomerates, Canadian Society of Petroleum Geologists, Memoir 10, pp61-68.

Ribberink J S (1987). Bed-load transport of non-uniform sediment: physical phenomena and morphological modelling. Euromech 215, Genova, Italy pp208-211.

van Rijn (1984). Sediment transport, Part III: Bedforms and alluvial roughness. ASCE J of Hydraulic Engineering, vol 110, No 11, pp1613-1641.

van Rijn (1986). Mathematical modelling of suspended sediment in non uniform flows. ASCE J of Hydraulic Engineering, vol 112, No 6, pp433-455.

van Rijn L C and Nienhuis L E A (1985). In-situ determination of fall velocity of suspended sediment. 21st IAHR Congress, Melbourne, Australia, 1985 pp145-148.

Samaga B R, Garde R J and Ranga Raju K G (1985). Total load transport of sediment mixtures. Irrigation and Power Journal, vol 42, No 4, pp345-353.

Samaga B R, Ranga Raju K G and Garde R J (1986). Suspended load transport of sediment mixtures. ASCE J of Hydraulics Engineering, vol 112, No 11, pp1019-1035.

Samaga B R and Ranga Raju K G (1985). Concentration distribution of sediment mixtures in open-channel flow. IAHR J of Hydraulics Research, vol 23, No 5, pp467-483.

Samaga B R, Ranga Raju K G and Garde R J (1986). Bed load transport of sediment mixtures. ASCE J of Hydraulics Engineering, vol 112, No 11, pp1003-1018.

Sengupta S (1975). Size-sorting during suspension transport - lognormality and other characteristics. Sedimentology, vol 22, pp257-273.

Sengupta S (1979). Grain size distribution of suspended load in relation to bed materials and flow velocity. Sedimentology, vol 26, pp63-82.

Shen H and Ackermann N L (1982). Constitutive relationships for fluid-solid mixtures. ASCE J of Engineering Mech Div, vol 108, No EM5, pp 748-763.

Shields A (1936). Awendung der Ahnlichkeitsmechanik and Turbulenzforschung auf die Geschiebebe - bewegung, Mitteil. Preuss. Versuchsanst. Wasser, Erd. Schiffshau, Berlin, No 26.

Singhal M K, Mohan J and Agarwal A K (1980). Critical tractive force for cohesionless graded material. Irrigation and Power Journal, vol 37, No 2, pp 219-224.

Tsujimoto T (1987). Non-uniform bed load transport and equilibrium bed profile. Congress of IAHR, Lausanne, Switzerland, pp177-182.

Vale C and Sundby B (1987). Suspended sediment fluctuations in the Tagus estuary on semi-diurnal and fortnightly time scales. Estuarine, coastal and shelf science, vol 25, pp 495-508.

Westrich B and Juraschek M (1985). Flow transport capacity for suspended sediment. 21st IAHR Congress, Melbourne, Australia. pp 591-594.

White W R (1972). Sediment transport in channels: A general function. Hydraulics Research Station, Report No INT 104, pp21.

Wilcock P R and Southard J B (1988). Experimental study of incipient motion in mixed-size sediment. Water Resources Research, vol 24, No 7, pp1137-1151.

Zanke U (1977). Berechnung der Sinkgeschwindigkeiten von Sedimenten, Mitt. des Franzius - Instituts fur Wasserhau Heft 46, Seite 243, Technical University, Hanover.

Zhaohui W and Tiancheng S (1987). The effect of fine particles on vertical concentration distribution and transport rate of coarse particles. IAHR Congress, Lausanne, Switzerland, pp80-85.

Zhaoyin W (1987). Bouyancy force in solid-liquid mixtures. IAHR Congress, Lausanne, Switzerland, pp86-91.

APPENDIX I

Main workers in the field

(a) Internal

G V Miles	(Tidal)
N V M Odd	(Tidal)
R L Soulsby	(Maritime)
R Bettess	(Rivers)
P Lawrence	(ODU)
E Atkinson	(ODU)

(b) Others

J Allard	Laboratory Nationale d'Hydraulique. 6 quai Watier, 78400 Chatou, France.
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W R Brownlie	W M Keck Laboratory of Hydraulics, California Inst of Technology, Pasadena, California.
R Deigaard	(Denmark)
R J Garde	Dept of Civil Engineering Univ of Roorbee, Roorbee U.P, India.
F M Holly	Dept of Civil and Environmental Engineering, Univ of Iowa, Iowa City, Iowa, USA.

G J Klaassen	Fluid Mechanics Group, Dept of Civil Engineering, Delft Univ of Technology, Delft, The Netherlands.
P A Mantz	Lamar Univ, Tescas formerly of Imperial College of Science and Technology.
R L Misri	Dept of Civil Engineering, Regional Engineering College Srinagar, J and K, India.
G T Proffitt	Ministry of Works and Development, Turangi, New Zealand.
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APPENDIX II

Additional References

Bhowmik N G (1981). Transport of sediment in natural rivers. Proc. of speciality Conf. Water forum '81, San Fransisco, pp 1201-1208.

Brownlie W R (1983). Flow depth in sand-bed channels. ASCE J of Hydraulic Engineer, vol 109, No 7, pp959-990.

Brownlie W R (1985). Compilation of alluvial channel data. ASCE J of Hydraulic Engineering, vol 111, No 7, pp1115-1119.

Holly F M and Karim M F (1986). Simulation of Missouri river bed degradation. ASCE J of Hydraulics Engineering, vol 112, No 6, pp497-517.

Holly F M (1986). Numerical simulation in alluvial hydraulics. 5th Congress of IAHR, Asian and Pacific Regional Division, Seoul, Korea, pp79-99.

Holtorff G (1983). Steady bed material transport in alluvial channels. ASCE J of Hydraulic Engineering, vol 109, No 3, pp368-384.

Hydraulics Research Ltd. Report No SR 75 (1986). Numerical model simulation of entrainment of sand bed material 22pp.

Hydraulics Research Ltd. Report No SR 148 (1988). A numerical sand transport model with time dependent bed exchange.

Hydraulics Research Station (1973). Report No DE9. The Wash water storage scheme, numerical model studies of the Great Ouse estuary - a transport function for fine sand in the estuary. 35pp.

Ikeda S and Asaeda T (1983). Sediment suspension with rippled bed. ASCE J of Hydraulic Engineering, vol 109, No 3, pp409-423.

Klaassen G J (1987). Armoured river beds during floods. Euromech 215, Genova, Italy, pp225-230.

Mantz P A (1983). Semi-empirical correlations for fine and coarse cohesionless sediment transport. Proc. Instn Civil Engineers, Part 2, vol 75 No 3, pp1-3.

McBean A and Al-Nassri S (1988). Uncertainty in suspended sediment transport curves. ASCE J of Hydraulic Engineering, vol 114, No 1, pp63-74.

Miles G V (1981). Sediment transport models for estuaries. Hydraulics Research Ltd, Wallingford, UK. 27pp.

Parker G (1987). Governing equations for longitudinal grain size variation due to differential sorting and abrasion in rivers. Euromech 215, Genova, Italy, pp217-220.

Ribberink J S (1987). Mathematical modelling of one-dimensional morphological changes in rivers with non-uniform sediment. Communications on hydraulic and geotechnical engineering. Delft Univ. of Techonology, 200pp.

Ribberink J S and von der Sande J T M (1985). Aggradation in rivers due to over loading - analytical approaches. IAHR J of Hydraulic Research, vol 23, No 3 pp273-283.

van Rijn (1981). The measurement of sediment concentrations in tidal conditions. 19th Congress of IAHR, New Delhi, India, pp525-534.

Shen H W and Hung C S (1983). Remodified Einstein procedure for sediment load. ASCE J of Hydraulic Engineering, vol 109, No 4, pp565-578.

Shen H W and LU J Y (1983). Development and prediction of bed armouring. ASCE J of Hydraulics Engineer, vol 109, No 4, pp611-629.

di Silvio G (1987). Adaptation processes through the surface of sedimentary systems. Euromech 215, Genova Italy.

Singh V P and Scarlatos P D (1985). Sediment transport on vertically two-dimensional man-made canals. 21st IAHR Congress, Melbourne, Australia, pp577-582.

Tanapore Z S (1981). Engineering applications of sediment theories to the fluvial and coastal environment. 19th IAHR Congress, New Delhi, India, pp86-133.

Todoravic P (1982). A stochasic model of longitudinal dispersion of bed sediment based on the granulation function. Advances in Water Resources, vol 5, pp42-46.

Walton T L and Douglass S L (1985). Stochastic sand transport using ARIMA modelling. 21st IAHR Congress, Melbourne, Australia, pp166-172.