Coastal and Estuarine Sediment Dynamics

KEITH R. DYER

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Preface

There is a vast literature on the topic of sediment transport, and, generally, the contributions to it fall into three categories: descriptive marine geological, process-oriented oceanographic, and empirical engineering. I admit this is a rather sweeping generalization but so often the engineering literature starts with dimensional reasoning and then obtains results from experiments to produce empirical relationships with little apparent attempt to relate the results to the natural environment. Conversely, the geological literature establishes some very good physical concepts but fails to quantify them sufficiently to turn them into valid theories. The oceanographic approach is to consider the driving fluid processes in the absence of a satisfactory view of the sedimentary response. Of course there are very notable exceptions to the above statements.

This book is an attempt to bring together some elements of these three approaches: to establish an overall descriptive framework from the geologists; to put in experimental results and theory from the oceanographers, where possible; and to bridge the gaps with empirical results from the engineers where the theory is inadequate. Because of the complex interactions between the fluid, the bed, and the particles in the fluid and on the bed, it is very difficult to achieve a complete flowing logic through the book. It is impossible to avoid a certain amount of repetition, or dropping a topic at a certain point, to take it up again later in a slightly different context. Waves are almost ubiquitous, yet it is simpler to treat tidal currents and waves separately; in most cases of importance, of course, the two act together. Nevertheless without understanding them separately, there is little chance of understanding their interaction. Similarly cohesive and non-cohesive sediments are considered separately, even though there are large areas of the sea bed where the sediments are cohesive until they move, and are non-cohesive until they are deposited.

My objective was to provide a text book with the minimum of complex mathematics and derivations, but one which explains the concepts, which can then be carried forward by the reader to a further level of understanding by reference to the literature. The expert reader will probably note that some of their favourite references are missing. This is partly because I have had to choose in order not to produce an inordinately long and complex book, and partly because I defy any one person to have actually read and understood all the literature. Unfortunately, much of the engineering literature is not readily applicable to the sea and has been omitted as a consequence.

This book is aimed at complementing the many other textbooks in the field rather than replacing them. Since writing the manuscript the excellent book by Sleath (*Sea Bed Mechanics*, Wiley–Interscience) has been published, which I think actually adds to this book, rather than detracting from it, and vice versa.

This book has required considerable effort from many other people besides myself. As the reader will be aware, I have drawn extensively on the published results of work carried out in the last twelve years in the Sedimentation Group of the Institute of Oceanographic Sciences at Taunton—the group that I had the good fortune to lead. That Group has now unfortunately dispersed (not of their own volition) but hopefully it will reform with the same zeal elsewhere. I would like to thank all the members of the Group for their contributions over the years but specifically to several for their comments on drafts of the manuscript: Alan Carr, Alan Davies, Tony Heathershaw, Nick Langhorne, Richard Soulsby and Tim Smith. Also I would like to thank Paul Komar and Ian Robinson for their comments, and Dorothy Croston for all the typing and collation. The mistakes and misunderstandings remaining are mine. Last, but not least, I wish to thank British Rail for space and time for the background reading, and thank the many hotels in whose bedrooms the writing was done.

KEITH DYER

Taunton

June 1985

Symbols

Symbols used throughout the text. Other symbols are defined where they are used.

a	Amplitude of surface wave motion
A	Area
A_b	Amplitude of near bed oscillatory water motion (Equation 3.49)
B	$= w_s/\beta\kappa u_*$
C	Suspended sediment concentration
$\overline{C}$	Turbulent mean concentration
c′	Turbulent deviation of concentration
c	Phase velocity of waves
c_g	Group velocity of waves
C_a	Reference concentration
C_0	Particle concentration in the bed
C_v	Solids volume concentration
$\mathbf{C_D}$	Drag coefficient
d	Pipe diameter
d_0	Wave orbital diameter $= 2\ A_b$
D	Grain diameter: subscript a, b, c, diameter on grain axes; subscript n, nominal diameter
e_b	Bedload efficiency factor
E	Wave energy
E	Erosion rate
f	Friction factor (Equation 3.8)
f_w	Wave friction factor (Equation 3.57)
f	Coriolis parameter
F	Froude number (Equation 3.13)
F_i	Interfacial Froude number
g	Gravitation acceleration
h	Water depth
H	Wave height
H_r	Ripple height
I_l	Immersed weight longshore transport rate of sediment
k	Wave number
k_s	Bed roughness under waves
k	Friction coefficient

K	Proportionality coefficient in Bagnold's sediment transport formula (Equation 7.8)
$\mathbf{K_s}$	Eddy diffusion coefficient for sediment
$\mathbf{K_m}$	Eddy diffusion coefficient for fluid
$\mathbf{K_{wc}}$	Eddy viscosity under combined waves and currents
l	Mixing length
L	Monin–Obukov length
M	Mobility number (Equation 5.5)
n	Frequency
n	Number concentration of particles
$\mathbf{N_z}$	Coefficient of vertical eddy viscosity
P_l	Longshore wave thrust
q	Transport rate of sediment
q_s	Suspended sediment transport rate
Re	Reynolds number $= ud/\nu$ or uh/ν
Re_*	Grain or boundary Reynolds number $= u_*D/\nu$
Re_w	Wave Reynolds number (Equation 3.54)
Re_s	Settling Reynolds number (Equation 4.3)
R_f	Flux Richardson number (Equation 3.36)
Ri	Gradient Richardson number (Equation 3.37)
T	Wave period
u	Horizontal velocity component
$\bar{u}$	Turbulent mean horizontal velocity
u′	Turbulent horizontal velocity deviation
$\hat{U}$	Depth mean horizontal velocity
u_{100}	Velocity 100 cm above the bed
U_∞	Mean velocity outside the boundary layer
u_m	Near bed maximum orbital velocity (Equation 3.50)
u_*	Friction velocity $= \sqrt{\tau/\rho}$
u_{*c}	Threshold friction velocity
U_r	Ripple migration rate
v	Lateral velocity component
$\bar{v}$	Turbulent mean lateral velocity
v′	Turbulent lateral velocity deviation
$\bar{v}_l$	Longshore current velocity
w	Vertical velocity component
$\bar{w}$	Turbulent mean vertical velocity
w′	Turbulent vertical velocity deviation
w_s	Particle settling or fall velocity
w_0	Settling velocity of single particles in hindered settling formulation
W	Stream power $= \tau u$
x	Horizontal coordinate direction
y	Lateral coordinate direction
z	Vertical coordinate direction
z_0	Bed roughness length

α	Dynamic friction angle (Figure 4.5)
β	$= K_s/K_m$ (Equation 6.3)
β	Bed slope angle, beach slope, resuspension rate (Equation 6.19)
γ	$= (\rho_s - \rho)/\rho$
δ	Boundary layer thickness
δ_L	Viscous sublayer thickness
θ	Dimensionless shear stress (Shield's Entrainment Function) (Equation 4.18)
θ_c	Threshold value of Shield's Entrainment Function
θ	Water surface slope angle (Chapter 3). Angle of wave approach (Chapter 11)
κ	Von Karman's constant (Equation 3.17)
λ	Wavelength of surface wave or bedform
λ_c	Beach cusp wavelength
λ_e	Edge wave wavelength
λ_r	Ripple wavelength
λ_D	Dune wavelength
μ	Coefficient of molecular viscosity
ν	Kinematic viscosity $= \mu/\rho$
ρ	Water density
ρ_s	Density of sediment particles
ρ_m	Bulk density of sediment
σ	Angular frequency $= 2\pi/T$
τ	Shear stress, bed shear stress
τ_0	Bed shear stress
τ_B	Bingham shear stress, or residual stress
τ_b	Bingham shear stress, or residual stress
τ_c	Threshold shear stress
τ_d	Critical shear stress for mud deposition
τ_e	Critical erosion shear stress
φ	Phi unit
ϕ	Angle of repose, or angle of static friction
Φ	Dimensionless transport rate of sediment

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CHAPTER 1

Introduction

Sediment movement occurs as the mobile bed tries to readjust its shape or texture in order to resist better the forces causing movement. In this way sand grains move from a flat bed to cause ripples, ripples move to create sandbanks, and erosion and deposition alters the coastal outline. To be able to describe and predict these changes is essential for successful coastal defence, the prevention of coastal flooding, for navigation, for dredging and the stability of structures such as oil rigs and pipelines placed on the sea bed. Despite many years of research we are still quite a way from being able to do this wholly satisfactorily.

There have been many descriptive studies by geomorphologists and geologists and these have provided the conceptual models for the cause-and-effect relationships. Geomorphologists have mainly restricted their view to the land, but have had a great impact in the understanding of beaches and coast erosion. Geologists have mainly been interested in describing present-day sediments in order to understand the conditions under which similar deposits were laid down in the geological past. Many of these studies have concentrated on the internal structure of the sediments, their textures, fabrics and depositional sequences, in particular concentrating on the accessible intertidal deposits. Reviews of these topics are contained in Allen (1982) and Reineck and Singh (1980). Geologists have also used acoustic surveying techniques. Since the 1930s echo-sounders have provided the means for examining the detailed shape of the sea bed, and since the 1960s side scan sonar has been available for mapping the distribution of bed features. The side scan results show gradations of bedform that can be related to differences in current velocity, and variations of shape have been diagnosed as characteristic features of the tidal current oscillation. These have been summarized by Stride (1982). When coupled with current measurements and sea bed samples, sonar studies have led to regional descriptions of sediment circulation; the sources, sinks and transport paths, based on two simple concepts. One is that sediment becomes finer in the direction of transport and the other is that the asymmetry of the bedforms indicates the direction of transport.

However, these studies give no indication of how much sediment is moved, or when, but they provide an obvious framework into which more quantitative studies must fit.

The greatest advances in quantifying the relationships between water flow and the sediment transport rate have been made by engineers in the relatively simple situations found in rivers, irrigational channels and in flumes. The classical description of the sequence of bedforms observed in a flume with increasing velocity was made by Gilbert in 1914, but it was not until 1928 that Shields formalized non-dimensional parameters that described the threshold of grain movement over a range of grain sizes and densities, in terms of the bed shear stress. This development was helped by the advances in fluid mechanics made in the 1920s by Prandtl, and von-Karman and others. The advances enabled formulations of the characteristics of the boundary layer flow near the bed and of the turbulence, and laboratory experiments investigating these aspects eventually gained impetus with the development of hot film anemometers and laser doppler anemometers. Much of this work has been summarized by Hinze (1959) and Schlichtling (1968). More recent work has investigated the intermittent structure of the turbulent shear stresses and traced the movement of individual particles within the flow; thus getting closer to the physics of grain movement.

The pragmatic engineering approach has continued, however, investigating in more detail, for instance, the transition conditions between different bedforms. Additionally engineers such as Rouse, Kennedy and Einstein developed theoretical relationships which were calibrated using laboratory and field data. Several dozen different sediment transport formulae have been developed, each of which is suited to particular data sets or experimental conditions, but they often differ by an order of magnitude, or more, when applied to the same situation. Consequently many problems remain. These approaches have been summarized by Raudkivi (1967), Yalin (1977) and Graf (1971).

One of the most significant contributions to sediment transport studies has been that of Bagnold. Starting in 1940 with his book on desert dunes he has written a series of papers which developed an approach to sediment transport based on sound physical principles. This has resulted in focussing interest in the physics of moving grains, and his approach has been adopted by many oceanographic workers for application to the sea. However this approach has been less readily accepted by the engineers.

Over the last 10 to 20 years there has been increasing interest in combining the engineering, geological and physical approaches and making direct physical measurements of sediment movement in the sea. This has been made possible by improved instrumentation, by better ways of recording large quantities of data, and by computer analysis techniques. Nevertheless, progress has still been hampered by the lack of means of reliably measuring sediment transport. Some of this work has been summarized by Stanley and Swift (1976).

There are a number of differences between flumes and the sea, which means that one has to be careful when applying to the sea theory which has been derived from flume investigations. These differences are summarized in Table

Table 1.1 Comparison between sediment transport in flumes and in the sea

Variable	Flume	Sea
Flow	Uniform in space Steady in time	Non-uniform Tidally varying
Water depth	Centimetres	Metres, to hundreds of metres
Bed shear stress	Calculated from water surface slope	Calculated from velocity profiles, or from turbulent shear stresses
Bed shape	Initially flat	Bed normally rippled
Sediment	Single grain size	Multimodal and multi-component
Waves	Monochromatic, regular	Irregular spectrum

1.1. The most fundamental difference is the presence of random waves in the sea. Though many studies of wave induced sediment motion have been carried out in flumes, there are distinct limits on the water depths and wave periods that are possible because of the size of the flumes, and because the waves are usually regular and of a single period. Also any studies of combined waves and currents are restricted to co- and contraflow situations. Whereas in flume experiments it is possible to calculate the drag on the bed by measuring the surface water slope, in the sea this cannot be done, and the stress measurements are intimately entwined in problems of bedform induced form drag and the effects of moving sediment on the near-bed velocity profiles. Because the tidal flow is oscillatory, the bed surface bears the effects of the previous half-cycle modified by the sometimes rapid deceleration. The bedforms will not grow until these effects have been reversed, and consequently lag effects between shear stress and bedform development are greater in the sea than in rivers.

In many areas the sediment distribution has been acted upon for hundreds or thousands of years by the tidal and wave processes. Present day movement is therefore often minimal, and sediment is only likely to move at spring tides and even then the rates of transport are likely to be small, as the threshold of movement will only just be exceeded. In other areas sediment movement may only occur when there is storm wave activity to enhance the tidal streams. Because the forces have been acting for so long it is also possible that the original source of the sediment moving on the shelf may have been exhausted and the amounts of material in transport may be the merest shadow of that in the past. The present day currents may therefore be competent to move more than the measured load of sediment if the sediment were available.

These days there are a number of workers who have developed instrumental rigs that can be placed on the sea bed to remotely record sediment movement during storms, but the results from them are meaningful only when placed in the overall regional context. This requires conventional marine geological investigations to determine the sediment circulation patterns, as well as widespread measurements of the current field, both tidal and non-tidal. Once the physics of sediment movement is adequately known, then the flow field can be mathematically modelled and the sediment transport calculated, using the direct measurements as validation. Though this is done at the moment, there are usually inadequate measurements to prove the modelling and this, coupled with deficiencies in the sediment transport theory, make the errors unacceptably large. However, the modern instrumentation developments lead one to expect that these problems will be overcome.

When it comes to using the results of these studies in the geological context, there are additional difficulties. In the ancient sediments one does not see the sediment transport, but only a fraction of the sediment originally deposited. In situations where it is possible to estimate the original rates of deposition of sand, it is obvious that sedimentary beds a few tens of metres thick would have been deposited in a few months or years. This contrasts with the millions of years that elapse for the formation of units a few thousand metres in thickness. As a result we see perhaps only one percent of the potentially deposited sediment. Obviously large quantities of sediment have been intermittently re-eroded, or there are horizons during which nothing was deposited for long periods. This dilemma has been highlighted by van Andel (1981). Eventually we need to know what controls the final preservation of the deposits that we see being formed today. This knowledge will aid the search for oil and other sedimentary deposits of economic importance.

Table 1.2 Variables important in sediment transport

Sediment size, shape, density and mineralogy of grains
Sediment settling velocity
Sediment availability
Flow depth
Water density, viscosity
Bed shear stress
Bedform wavelength, height, steepness
Maximum tidal velocity
Residual tidal velocity
Wave period, amplitude

It is apparent from the above that there are many variables that have to be considered in sediment transport studies in the sea. These are listed in Table 1.2. The influence of these various factors will be considered in the following chapters. Since the sediment movement is driven by the near-bed flow, and the moving sediment itself affects this flow, we have to devote considerable space to an examination of the fluid forces and boundary layer flow.

CHANGING SEA LEVEL

The sediments on the shelves and coasts, and in the estuaries of the world, are derived from the land via river discharge, from coast erosion and from redistribution of sediments dumped on the shelf during glacial periods or during low sea level stands. The present low relief of the continental shelves and coastal plains is thought to be the result of continual transgression and regression of the sea, and the consequential migration of the shoreline. During periods of sea level retreat shorelines are abandoned and the waves are able to attack the newly-exposed rock of the sea bed. The rejuvenated landscape will cause the rivers to incise their courses, and they will discharge large amounts of sediment increasingly further out onto the shelf. Because of the changing length and depth of the embayments the magnitudes of both the tidal and residual currents would change. However, they could either increase or decrease depending on local conditions.

During transgressions, beaches would be gradually pushed shorewards. Longshore transport would cause bays to become infilled and the submerged valleys of the rivers would become buried under sediment. The river discharge of sediment would diminish, however. If the rate of sea level rise is fast then banks, beaches and other sedimentary features would become relict beneath the sea.

Estuaries are likely to be more numerous during transgressions than during regressions. They are ephemeral features being fairly rapidly altered and destroyed, having an average life of probably only thousands of years. The ephemeral nature of estuaries has been discussed by Schubel and Hirschberg (1978).

The sediment response to the changing sea level is unlikely to be immediate and, as a consequence, the sediment distribution and characteristics are likely to be modified for some time after the sea level becomes static. In some areas, however, the sediment will fairly quickly achieve a reasonable equilibrium with the mean currents and wave forces, even though, because of the natural variability, considerable amounts of transport can occur. In many circumstances it is difficult to tell whether there are any long term trends because the large variations mask them, and it may take only a small variation of sea level to destroy a local equilibrium.

Sea level can alter because of a number of causes. Changing ocean currents and variation in the temperature of the ocean water can cause minor fluctuations, but there are two main effects: eustatic and isostatic variation.

Eustatic variations arise because of alterations in the volume of the world's oceans due either to changes in the elevation of the ocean floor or to the variation in the actual volume of water present in the oceans. The ocean floor may vary in its elevation due to plate tectonic activity, since the width and elevation of the mid-ocean ridges changes with slight variations in the rate at which sea floor spreading occurs. A rise of the ridge would cause the water to rise onto the coastal plains. These movements are of long time scale ($\sim$ 10 my) and can account for the major geological transgressions and regressions. Alternatively the volume of water present in the oceans can be changed by the amount trapped as ice in the glaciers on the continents. If the present glaciers were to melt, a sea level rise of about 60 m would result. Over the last half a million years or so, during the Pleistocene glaciation, many glacial periods and interglacials have