COASTAL PROCESSES

with Engineering Applications

ROBERT G. DEAN
University of Florida

ROBERT A. DALRYMPLE
University of Delaware

CAMBRIDGE
UNIVERSITY PRESS

PUBLISHED BY THE PRESS SYNDICATE OF THE UNIVERSITY OF CAMBRIDGE
The Pitt Building, Trumpington Street, Cambridge, United Kingdom

CAMBRIDGE UNIVERSITY PRESS
The Edinburgh Building, Cambridge CB2 2RU, UK
40 West 20th Street, New York, NY 10011-4211, USA
10 Stamford Road, Oakleigh, VIC 3166, Australia
Ruiz de Alarcón 13, 28014 Madrid, Spain
Dock House, The Waterfront, Cape Town 8001, South Africa

http://www.cambridge.org

First published 2002

Printed in the United Kingdom at the University Press, Cambridge

Typefaces Times Ten 10/13 pt. and Helvetica Neue *System* LaTeX 2ε [TB]

A catalog record for this book is available from the British Library.

Library of Congress Cataloging in Publication Data
Dean, Robert G. (Robert George), 1930–
Coastal processes / Robert G. Dean, Robert A. Dalrymple.
p. cm.
Includes bibliographical references and indexes.
ISBN 0-521-49535-0
1. Coastal engineering. I. Dalrymple, Robert A., 1945– II. Title.
TC205 .D43 2001
627′.58 – dc21 00-067434

ISBN 0 521 49535 0 hardback

Contents

PART THREE. COASTAL RESPONSE

PART FOUR. SHORELINE MODIFICATION AND ANALYSIS

CHAPTER ONE

Overview

In Egypt, the construction of the Aswan High Dam and others on the Nile River has caused extreme erosion problems at the Nile Delta, where whole villages have disappeared as the shoreline has retreated at rates of 30 to 50 m/yr! Before construction of the dams for flood control, irrigation, and water supply, the Nile delivered about 20 million metric tons of sediment annually to the Mediterranean Sea. This sediment supply resulted in two large deltas (Damietta and Rosetta), which extend 50 km into the sea. As each of the dams on the Nile was completed, the reservoir behind the dam began to capture a significant portion of the annual riverine sediment load.*

To combat the ensuing erosion, large coastal structures have been placed along the shoreline near the river mouths to limit further shoreline retreat. Nevertheless, erosion is continuing in water depths below the base of the structures, and storm waves are attacking the coast with increasing intensity.

Surprisingly, the length of shoreline affected by the erosion is relatively short. Further, field measurements conducted by the Alexandria Coastal Research Institute show that, farther from the river mouths, the shoreline continues to advance in response to the prior era of abundant sediment supply and delta building.

1.1 INTRODUCTION

The world's coastlines, dividing land from sea, are geological environments unique in their composition and the physical processes affecting them. Many of these coastlines have beaches composed of loose sediments such as gravel, sand, or mud that are constantly acted upon by waves, currents, and winds, reshaping them continuously. However, despite the different wave climates that exist around the world and the variations in coastline composition, the nature and behavior of beaches are often very similar.

---

* The famed Rosetta stone, which led to the deciphering of hieroglyphics, was found in 1799 in the town of Rosetta. Inscribed on this black basaltic stone, which now resides in the British Museum in London, were three versions of a 196 B.C. decree set forth in hieroglyphics, demotic writing (the everyday script), and Greek. Twenty-three years later, Jean-Francois Champollion was able to translate the hieroglyphics for the first time in 1500 years!

Waves gather their energy and momentum from winds blowing over possibly huge expanses of uninterrupted ocean, yet much of this accumulated energy is dissipated within the fairly narrow surf zone. The breaking of the waves within this zone is responsible for the transformation of organized wave motion into chaotic turbulence, which mobilizes and suspends the sediments composing the beach. Also, the breaking waves create nearshore currents that flow along the shoreline and in the cross-shore direction. These currents can transport large quantities of sediment in both directions in volumes as large as hundreds of thousands of cubic meters of sand per year in some places.

At this dynamically active intersection of land and the oceans, humans have been building structures throughout history. Ports and harbors have always served as bases for naval forces and as commercial egresses to upland trade routes or major centers of civilization. More recently, as recreation and tourism at the shoreline have become more important economically, coastal development, taking the form of homes and businesses, has increased to such an extent that over 50 percent of the U.S. population now lives within 50 miles of the coastline. In 1995, it was estimated (IIPLR 1995) that over three trillion U.S. dollars of insured property was located adjacent to the U.S. Atlantic and Gulf shorelines alone. This shoreline development is causing an increasingly important conflict with the natural coastal processes.

There are many historical examples of engineering works that have interfered with sediment transport processes, causing severe beach erosion and associated structural damage or, conversely, large accumulations of sand that have rendered some facilities useless. In addition to the ports, human interactions adversely impacting the shoreline have included navigational channels and jetties, groin fields and seawalls, dam construction on rivers that reduces sand supply to the coast, sand mining of beaches and river beds that supply sand to these beaches, and hydrocarbon and groundwater extraction, inducing local ground subsidence and associated inundation and erosion.

During the past several decades, increasing emphasis has been placed on the coastal zone owing to the rapid development of this region and the hazardous effects and costs of short- and long-term natural processes. Episodic and cyclical events such as hurricanes along the East Coast of the United States and El Niño on the West, monsoons in the Bay of Bengal, and severe storms on the North Sea have caused loss of life and widespread damage, and governments and taxpayers have become concerned about the costs resulting from inappropriate construction practices. As a result, many countries that have expended immense amounts of money to protect shorelines are reexamining their policies. In the United States, most coastal states (including those along the Great Lakes) have initiated or are in the process of initiating controls on the types and locations of coastal structures. These restrictions may require that the structure be able to withstand a rare storm event, such as a 100-year hurricane, and that the structure be set back from the shoreline 30 or so times the annual shoreline recession rate. In addition to the impact of storm events, concern exists over the long-term effects of mean sea level rise and the possibility of an increase in the rate of rise in the coming decades caused by greenhouse gases.

Over the last 50 years, coastal engineering has become a profession in its own right with the objective of understanding coastal processes and developing strategies to cope effectively with shoreline erosion. With a more sophisticated and knowledgeable approach to coastal processes, coastal engineers can design effective coastal protection and mitigation schemes and avoid the mistakes of the past. Also, a greater knowledge of sediment transport mechanics at beaches may permit the development of novel means to mitigate erosion problems. With the population pressure on the shoreline and the threat of sea level rise and coastal storms, the need for coastal engineerings and research into coastal processes is certain to increase (NRC 1999).

The best understanding of coastal processes, including the nearshore flows and the resulting sediment transport, and the ability to transform this understanding into effective engineering measures require the following:

A blend of analytical capability,
An interest in the workings of nature,
The ability to interpret many complex and sometimes apparently conflicting pieces of evidence, and
Experience gained from studying a variety of shorelines and working with many coastal projects.

We say this in part because, at this time, the mathematical and statistical equations governing the behavior of the sand and water at the shoreline are not yet fully known, thus precluding our ability to make models for precise long-term predictions about the coastal zone. In this sense, the field of coastal processes is still as much an art as a science and requires a good intuitive grasp of the processes that occur in the coastal zone. In fact, the best computer and physical modelers are those who are skeptical about their results and continuously compare their models with well-documented case studies and field experiments. Further, much more research is necessary to improve our abilities to make predictions of coastal behavior, particularly in response to man-induced perturbations. However, despite the rudimentary state of our knowledge, the student of the shoreline will find the beauty and dynamic nature of the coast rewarding along with the numerous secrets that Mother Nature still guards so zealously.

In this vein, you will notice that many times we take two approaches to problems: one is the macroscale, which utilizes conservation laws or heuristic arguments that provide reasonable solutions, and the other is the microscale, which involves examining the detailed physics of the process. Presently, the macroscale approach is more useful to the coastal engineer, for the detailed physics of coastal processes are still being unraveled by coastal researchers; however, the day may not be too far off when the macroscale approach is replaced by, or merged, with the microscale one.

We have organized this book into four parts so that it will be coherent and useful to readers with different backgrounds and interests. Part One provides a general description of coastal processes with emphasis on long-term forces and responses. This section can be read with little or no background in mathematics and points out the ever-present forces tending to cause equilibrium both in profile and in planform. When natural or human-induced changes occur, a new set of forces is induced to reestablish equilibrium consistent with these changes. Familiarization with this material will assist in developing an overall comprehension of, and intuitive feel for, large-scale, long-term dynamics. Also reviewed are the coastal landforms found in the coastal zone and their causative forces. Many times the geometry of these forms contains information that can assist in characterizing the dominant waves, currents, and other important forces. Part Two develops the theories representing the forces in the nearshore region with a focus on longshore and cross-shore hydrodynamic processes. This part is relatively mathematical and may be of more value to the reader with a strong research background. For the less mathematically inclined reader, the equations may be largely ignored. Although Part Three, dealing with the response of the shoreline to the forcing, is strongly recommended for those concerned with the construction of coastal engineering works or remedial erosion measures, this material is not absolutely necessary as a prerequisite to Part Four, which is directed toward engineering applications. The emphasis in Part Four is twofold: (1) presentation of techniques to predict the impact that a project may have, and (2) discussion of various methods employed to mitigate beach erosion.

In writing this book, the challenge has been to assist students of the coasts to sharpen their abilities to interpret coastal phenomena, to predict the consequences of a given coastal project, and to incorporate this knowledge into the design process but at the same time to provide the level of scientific detail to satisfy a researcher in the field. We hope we have met the challenge. The measure of our success, of course, will be the degree to which the book can be applied to improving existing coastal projects and beneficially guiding decisions and design of future coastal construction.

1.2 SOME TERMINOLOGY OF THE COASTS

1.2.1 DESCRIPTIVE TERMS

It is a remarkable fact that beaches around the world are quite similar in composition and shape. The beach profile, which is a cross section of the beach taken perpendicular to the shoreline, is generally composed of four sections: the offshore, the nearshore, the beach, and the coast, as shown in Figure 1.1. The sand making up this profile

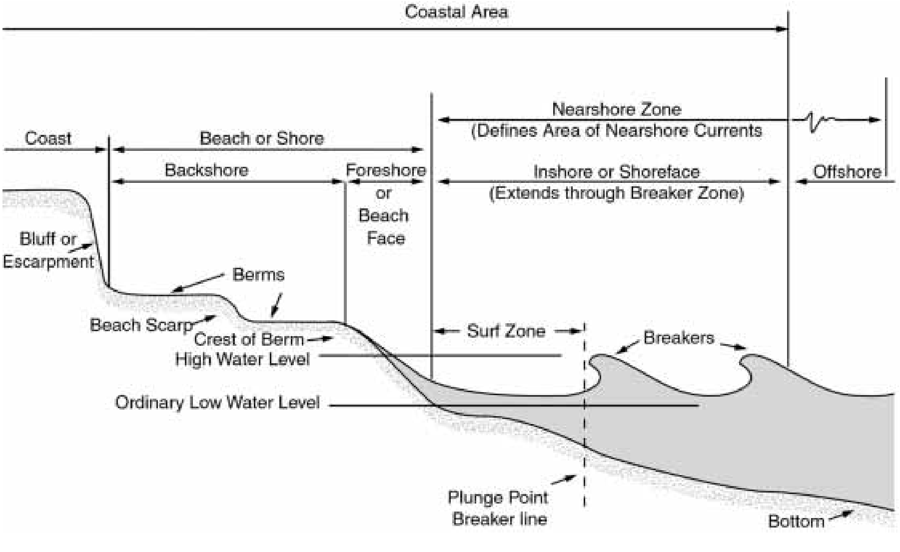

Figure 1.1 Beach profile terminology (adapted from the *Shore Protection Manual* 1984).

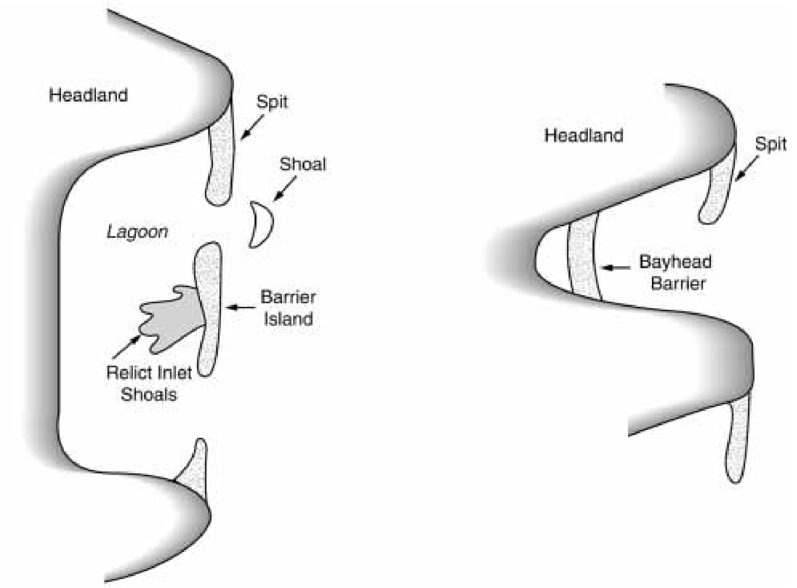

Figure 1.2 Shoreline planform terminology.

is shaped by waves coming from the offshore and breaking in the nearshore zone, where sandbars may exist. The *foreshore*, or *swash* zone, is the region of the profile that is alternately wet or dry as the waves rush up this steep portion of the profile. The dry beach may have one or more *berms*, which are horizontal sections of the profile, and *scarps*, which are near-vertical cuts caused by wave action during higher water levels perhaps associated with a storm. The landward portion of the beach may have sand dunes created by winds blowing sand off the beach into these features (aided by the sand-trapping capability of beach grass and other vegetation) or a bluff or a cliff (particularly on elevated eroding shorelines).

In planform (looking down on the coast as in an aerial photograph), the shoreline may have several interesting features. In Figure 1.2, the coast is fronted by a *barrier island* with tidal inlets transecting it at various locations. This situation occurs in numerous locations around the world, and a large concentration of barrier islands is found in North America. The inlets provide a means of water flow between the ocean and the lagoon system behind the islands. Often, old depositional features associated with relict (closed) inlets can be found, as shown in the middle of the barrier island. A *baymouth barrier* is a sandy feature that closes off a bay, whereas a *spit* is a depositional feature that grows from a headland or other prominent feature.

Tidal inlets play a major role in the sand budget of many shorelines, for these inlets affect the longshore transport of sand along the coast by capturing a significant portion of it and hence removing it from the active beach system. The size and shape of inlets are the result of a balance between the sand that is carried into them by the waves and the scouring ability of tidal flows that course through them daily. Some of their common features are shown in Figure 1.3. The two most important features of a tidal inlet are the ebb and flood tidal shoals, which may be very voluminous features that began when the inlet was created; tidal shoals can increase to tremendous sizes,

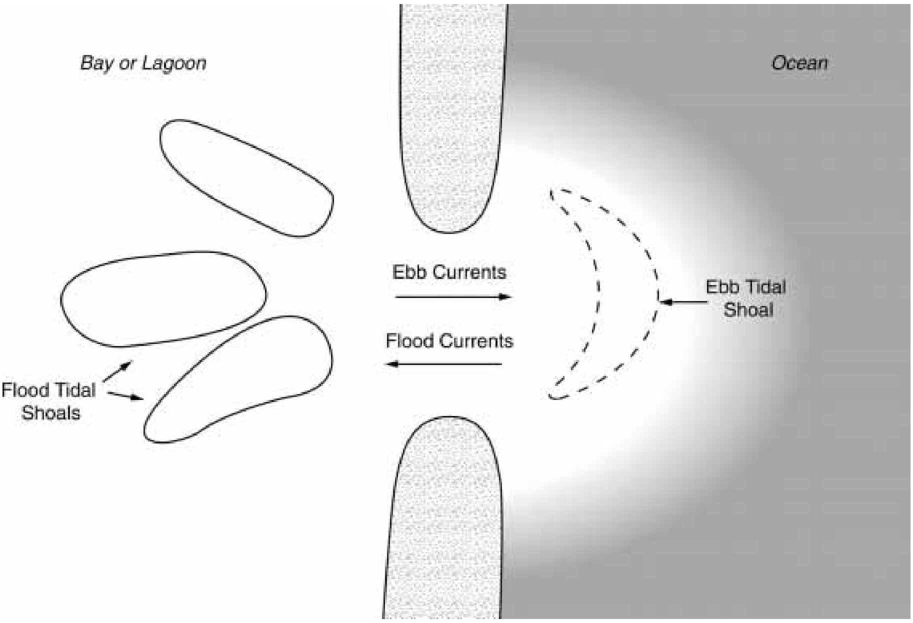

Figure 1.3 Tidal inlet terminology.

often containing amounts of sand equivalent to many years' worth of the annual gross transport of sand along the shoreline. These shoals are created by the ebb and flood inlet currents, which jet out sand transported into the inlet by waves. (Chapter 13 will discuss tidal inlets in detail.)

Estuaries differ from inlet-bay systems in that a river provides a considerable amount of fresh water to the bay system, leading to the formation of strong salinity differences often characterized by density fronts. The water chemistry of estuaries is more complicated than that of a more homogeneous inlet-bay system, and phenomena such as the flocculation of fine sediment occur. Estuaries are a subject unto themselves, and other texts can provide the reader with more information.

1.2.2 TRANSPORT PROCESSES

The beach profile and planform shapes discussed in the preceding section are a result of the action of waves and currents at the shoreline. The waves not only suspend the sediments but give rise to nearshore currents that carry the suspended sediment alongshore or cross-shore. As will be discussed in Chapter 5, a *longshore current* is driven by waves breaking obliquely to the shoreline and flows in a direction corresponding to the wave direction. Often, this current turns seaward and becomes a *rip* current, taking sediment (and hapless swimmers) offshore.

The sediment carried by the waves and currents is referred to as the *littoral drift*, and the amount of sediment moved along the coast is the *littoral transport*, or longshore sediment transport, which is usually measured in units such as cubic meters per year or cubic yards per year (see the appendix to this chapter for conversion among different units). As the wave environment changes during the year, the transport can change directions; however, at most coastlines there is a dominant direction of sediment transport. *Downdrift* refers to a direction coincident with this dominant transport direction, whereas *updrift* is the opposite direction.

The *cross-shore transport*, which is caused by wave- or wind-induced mean cross-shore flows, is largely responsible for the existence of sandbars and other beach profile changes. These changes can be slow, on the order of years in duration, or they can occur rapidly during storms with time scales on the order of hours.

1.3 EXAMPLES OF COASTAL ENGINEERING PROJECTS

An unfortunate legacy of construction at the shoreline is the large number of projects built without the requisite historical data for the site or appropriate knowledge about coastal processes. These deficiencies, in part, are due to the relatively recent development of our understanding of coastal behavior and the difficulty of obtaining wave and sediment transport data. Additionally, concern over the effect of a coastal project on adjacent beaches has only become important in the last several decades as more and more people use beaches for dwellings, recreation, and industry.

Here we will describe several examples to illustrate the broad range of problems in the field and, we hope, to whet your appetite for the opportunities and challenges ahead. Many of the problems presented will be addressed in detail in later chapters of this book. Some problems illustrate pitfalls that can be encountered, whereas others pose general or specific coastal engineering concerns.

A common thread in most of the problems is that there are often never enough data available to assess the problem accurately. Either the data (say for waves or for littoral transport) do not exist, or the length of the data record is too short to draw reliable conclusions. To counter this recurring problem, a major tenet of coastal engineering should be *to design flexibility wherever possible into every project to correct for unknown parameters and poorly estimated factors and to allow for fine-tuning of the project afterwards*. This necessary flexibility requires that the coastal engineer plan carefully and creatively to enable project performance to be improved, if necessary, depending on the subsequent interaction of the project with the environment.

1.3.1 BEACH NOURISHMENT

Beach nourishment, or beach fill, is the placement of large quantities of sand on an eroding beach to advance the shoreline seaward of its present location. Beach nourishment is one of the more common methods for erosion mitigation because this approach usually does not involve the construction of permanent structures. This erosion control technique is a way of setting the beach system back in time to when the shoreline was more advanced seaward. Central among the engineering questions to be addressed are: What is the additional beach width that results for a given volume of added sand? What is the lifetime of the project? What are the amounts of turbidity and biological disruption to be caused during placement of the fill material? What are the advantages of using coarser but possibly more expensive sand?

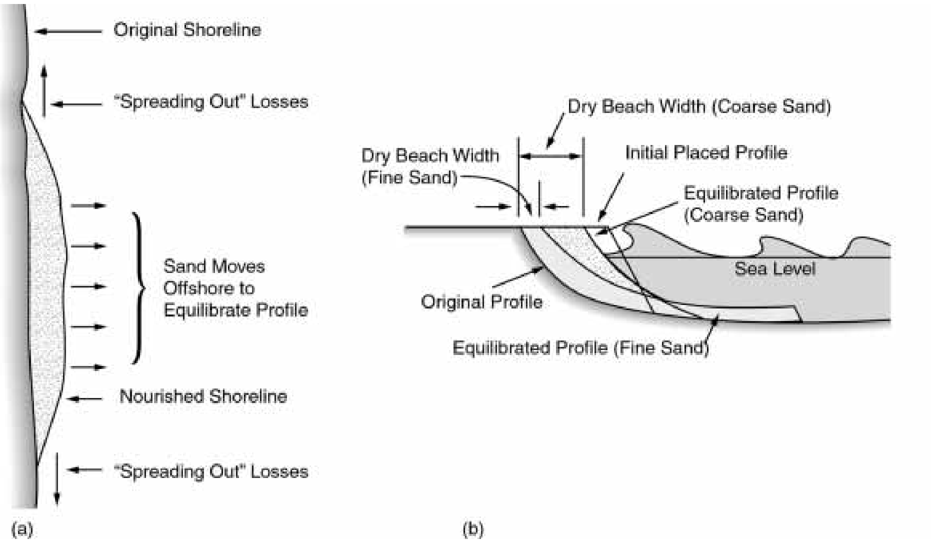

Figure 1.4 Beach nourishment showing plan view and profile (from Dean and Abramian 1993). (a) Plan view showing "spreading out" losses and sand moving offshore to equilibrate profile. (b) Elevation view showing original profile, initial placed profile, and adjusted profiles that would result from nourishment project with coarse and fine sands.

When a beach nourishment project is constructed, there are two known processes that diminish the expected additional beach width, each operating on a different time scale (see Figure 1.4). Equilibration of the on–offshore beach profile from the arbitrary shape created by placing sand on the beach to the natural equilibrium shape created by the environment occurs on a shorter time scale of months or years and includes a transfer of sand from the dry beach and the shallow constructed portions of the profile to the offshore to form an equilibrium profile. The second process is a result of the planform perturbation created by the fill that results in the sand spreading out in the alongshore directions. For reasonably long projects, this time scale is on the order of several years to decades.

The gradual transport of the beach nourishment sand away from the placement area results in a diminution of the beach width in the region of interest. Eventually the beach will erode back to its original position, for the beach fill has not removed the cause(s) of erosion but only provided new sand to be eroded. (Beach fill is the *only* erosion mitigation scheme that involves adding new sand to the coastline.) As the beach recedes to its original position, another beach fill (renourishment) may be required. In fact, for long-term protection of a beach using beach nourishment, a plan for periodic renourishment must be developed.

Generally, the material for beach nourishment projects is obtained by dredging from an offshore *borrow area*, although land sources are also used. The material obtained is frequently finer and more poorly sorted than that naturally present on the beach, which may reduce the effectiveness of the project. It will be shown in our studies of equilibrium beach profiles later in the book that, if sand finer than the native is used, a much greater volume of fill may be required to yield a desired beach width. Also, the longevity of the project will be shown to depend critically