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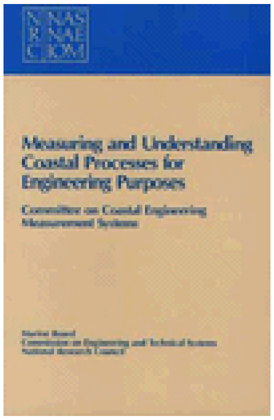

Measuring and Understanding Coastal Processes for Engineering Purposes

Measuring and Understanding Coastal Processes

Committee on Coastal Engineering Measurement Systems, Marine Board, National Research Council

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THE NATIONAL ACADEMIES
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Measuring and Understanding Coastal Processes for Engineering Purposes

Committee on Coastal Engineering Measurement Systems
Marine Board
Commission on Engineering and Technical Systems
National Research Council

NATIONAL ACADEMY PRESS
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This report has been reviewed by a group other than the authors, according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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Preface

Understanding the effects of the sea's forces in the rapidly changing, high-energy environment of the surf zone is a difficult task for both the scientist and the engineer. But this knowledge is fundamental to planning and managing coastal development and protection. Our understanding of nearshore ocean environmental forces and their relation to the movement of sediment and beaches directly affects many of the 125 million citizens living within 50 miles of the U.S. coast who rely on the coastal resources and beaches for their living and recreation.

Over a third of the coastline of the contiguous states is rapidly changing—mostly eroding. This change places an increasing pressure on public administrators, who must make judgments about coastal land use, as well as on developers and engineers, who must gauge the economic and physical risks to homes, structures, harbor entrances, and to the rapidly diminishing public lands.

What makes the development of shoreline and coastal environmental measurement capability a matter of immediate concern, and even of national interest, is the present emphasis on cost sharing between the federal and local governments or public authorities for development and maintenance of coastal and port facilities and projects (such as deeper shipping channels, beach nourishment and protection schemes, and wave barriers). The adverse effects resulting from inaccuracies in planning, often stemming from inaccurate measurement and poor understanding of environmental forces and changes, are likely to have more public impact as local responsibilities for undertaking coastal projects increasingly press the taxpayers and local economies.

Over the past decade, remarkable advances have been made in the general field of measurement systems—sensing, processing data, and modeling. There is every reason to expect that such improvements would enable the engineer to respond more effectively to the pressures impinging on the use of coastal areas and on construction on and near the beach. However, the potential for such advances in coastal environmental measurement systems has not been fully realized. Accordingly, at the request of the U.S. Army Corps of Engineers, the National Research Council appointed the Committee on Coastal Measurement Engineering Systems to:

- assess the needs for coastal data for planning, design, construction, and maintenance;
- identify the areas where the theoretical underpinnings are inadequate to establish measurement needs;
- assess the availability and suitability of instrumentation to meet these needs; and
- provide recommended actions about where new or better instrumentation is needed, with a relative priority.

Two questions asked of the committee were fundamental to the conduct of its assessments and development of its recommendations. In identifying the needs for coastal data, the key question is, "What engineering requirements have significant influence on these data needs?" In regard to the role of modeling in analyzing and forecasting coastal changes and the relation between modeling and engineering measurement, the fundamental question posed to the committee was, "How does the capability and practice of modeling in the high-energy coastal waters influence the development of measurement systems?" The committee considered an evaluation of the development costs for specific measurement systems to be outside the scope of this study; however, the assessment of measurement alternatives does include an evaluation of the present state of development for various measurement systems and identifies the difficulties that must be surmounted in development.

The committee—in its assessment of coastal data needs, instrumentation, and analyses—addressed only the in-water aspects of the measurement of noncohesive sediment in this report, but chose to exclude cohesive sediments (such as clays and muds) in its assessment.

A committee of nine members provided expertise in coastal engineering, physical oceanography, sedimentology, and engineering for coastal and harbor dredging. In addition, representatives of four agencies provided much useful technical program and background information for the committee's consideration.

The committee reviewed measurement system development and witnessed several tests conducted by the U.S. Army Corps of Engineers during its 1986 SUPERDUCK Project at the Corps' Coastal Engineering Test Facility in Duck, North Carolina. In addition, the committee conducted a survey of over 30 coastal engineers and scientists from the United States, Canada, and Europe to obtain their views about measurement development needs and the associated engineering requirements and what new technology can be practically applied to improve present measurement practices. The questions and a summary of results are presented in the Appendix.

The committee met six times over a two-year period, identified the salient engineering concerns, reviewed the physical oceanographic processes occurring near the shore that could affect engineering activities, and identified measurements needed to understand these physical processes. The committee then determined how well those measurements meet design or modeling requirements and made recommendations regarding development. The organization of this report reflects this analytical process.

Contents

Executive Summary

Coastal scientists and engineers are faced with a wide variety of problems in the coastal zone. In most cases the resolution of these problems involves measurements of water and particulate motion and coastal processes—currents, waves, tides, bathymetry, sediment transport, and so on. These measurements may be needed for a variety of purposes:

- research into the fundamental processes,
- design data,
- input data for developing physical and mathematical models and for validating them,
- monitoring, and
- documentation of extreme events.

Some coastal engineering problems will present increasingly difficult challenges in the next few years. Examples of these problems are the rapid erosion of the barrier islands along the Atlantic and Gulf coastlines, the possible impact of sea level change on shore stability and structures; construction, protection, or preservation of some expensive coastal structures and developments; and the cost and impact of the extensive harbor entrance dredging.

Although no one has evaluated the total cost of coastal engineering works in the United States, much less defined the entire scope of such activity, we do know that the cost of maintenance dredging alone amounts to over one-half billion dollars in federal and local government funds annually, hurricane losses along beach areas exceed hundreds of millions of dollars, and more ordinary winter storms cause property damage in the tens of millions. The capability to understand and anticipate how and when coastal changes occur in and near the high-energy wave zone can significantly reduce the public and private costs and losses; the ability to measure change is directly related to this capability.

Unfortunately, many coastal processes are poorly understood, largely due to the difficulty of making good measurements. The processes represent a large range of space and time scales, from the smallest turbulence scales to sea level changes occurring over decades. Often a great deal of sensitivity and precision is needed in the instruments, yet they must function over an extended period of time in one of the most energetic and corrosive of ocean environments. Instrumentation in remote sites must operate unattended for weeks or years. Biological fouling can be a major consideration in subarctic regions. In some cases sensors do not exist to make some very important measurements—nearshore sediment transport near the seabed, for example. Only a few of the available coastal engineering measurement systems (e.g., tide gauges, current meters, wave gauges) can be bought off-the-shelf. Most systems are built in small numbers and are often "customized" for the particular measurement requirement.

With this background, this report sets out to answer the following questions:

- What are the coastal measurement needs, and what are the engineering requirements having a major influence on these needs?
- What is the relationship between engineering measurement needs and the use of physical and mathematical models for analyzing and forecasting coastal changes?
- What are the implications of the modeling capability and practices on development of measurement systems?
- What new technology can effectively be applied to improve present measurement practice, and what gaps will exist in measurement techniques and systems?
- What improvements in measurement techniques and approaches will have a significant influence in accuracy and cost of analysis and forecasting of coastal change?

The committee attempted to be as realistic as possible in preparing its conclusions and recommendations. Every effort was made to relate the measurement needs to realistic coastal engineering problems. In most cases, the measurements are made to define processes and their impact on the shore or a structure, existing or planned. The measurements may be used to characterize or model the particular process—such as sediment transport—or they may be deterministic, as in an actual measurement of a load on a structure. Coastal engineering problems are divided into four general features, according to where they occur: *shore areas, backshores, entrances*, and *harbors*. These problems are in turn treated in regard to the following coastal processes:

- kinematics and hydrodynamics of high-frequency flows, including wave and current motions with periods of five minutes or less, such as ocean waves;
- kinematics and hydrodynamics of low-frequency flows with periods of more than five minutes, including tides and storm surges;
- fluid/sediment interactions; and
- fluid/structure interactions.

In each general process category, the requirements, present capabilities, and needs are assessed. The status of existing models and the modeling requirements for measurements are treated as well.

To assist the committee in identifying the major coastal engineering problems, a questionnaire containing the above questions was sent to over 30 leading coastal engineers. In part, the conclusions reached by the committee represent their input.

The committee conducted this study to assess the needs and availability of suitable coastal instrumentation and measurement systems, and to provide recommendations regarding specific developments. The committee was also responsible for providing guidance on development priorities.

The committee agreed that there is a pressing need for the development of instruments and measurement systems to promote our understanding of coastal processes. Presently, the user community is small and cannot attract sufficient industrial interest in developing the needed technology. To stimulate this development, we need a commitment of resources at the national level, as well as a forum to provide information, collaboration, interaction, and coordination on measurement system development.

The committee recommends 19 specific steps for improving coastal instruments and measurement systems, each recommendation derived from a conclusion reached by a consensus of the committee members. Of the 19 recommendations, 4 were ranked as high-priority, 5 were ranked high-to-medium, 9 were ranked as medium, and 1 was ranked as medium-to-low–priority. The nine recommendations ranked as high-to-medium are regarded as essential to coastal engineering advancement in the rest of this century. The committee, being well aware that specific local or regional coastal problems may argue for a different ranking of the recommendations, would only remind the reader that these recommendations are based on a national point of view.

HIGH-PRIORITY RECOMMENDATIONS

Wave data and measurement techniques:

1. *Directional wave energy spectra* and their rapid dissemination to forecasters and researchers are needed; a national coastal measurement system to expand a small-area coverage now in place is recommended.
2. *Directional resolution improvements* are essential for more accurate forecasting of littoral processes—instrumentation techniques to measure wave directionality (2° to 5° accuracy) both in situ and remotely should be developed.

Sediment transport processes and their measurement:

3. High-resolution measurement of concentrated sediment motions near the mobile sea bed cannot now be made in the surf zone and tidal inlets; this capability should be developed.
4. Models of sediment transport are largely empirical and are poorly verified; improvements in understanding the underlying theoretical relationships and field tests (interactive) of existing models are needed.

HIGH-TO-MEDIUM–PRIORITY RECOMMENDATIONS

1. The internal dynamics of rubble-mound structures are not well understood by coastal engineers, as the number of divergent opinions about the causes of structural failure show. Both modeling and in situ measurements of such structures should be undertaken to enhance the basis for better and safer design.

2. The causes of breakwater failure are still not well understood. Core pressures in breakwater cross sections should be measured during storms, and modern pressure-sensing and signal transmission technology should be adapted to acquire and process such data.
3. Wave set-up process is not well quantified; measurements of wave forcing and sea-level response during storms are needed.
4. Sediment transport prediction is closely linked to understanding and predicting turbulence; instruments for measuring turbulence in the nearshore environment are needed, and related modeling capability should be developed.
5. Limited-area hydrodynamical circulation models (2-D and 3-D) need to be improved; this progress is dependent on developing low-cost current meters and associated telemetry systems to be able to verify and develop new models. Development of such meters is urged.

MEDIUM-PRIORITY RECOMMENDATIONS

1. Improve and verify, through field measurements, a 3-D current model for complex bathymetry.
2. Develop reliable current meters for measuring low-frequency currents in tidal inlets during storms.
3. Improve storm-surge models and verify them through field measurements development to enhance predictions of overland flooding.
4. Improve means to measure velocity profiles in energetic, rapidly varying flow fields to allow better estimates of boundary shear stress.
5. Determine ways to measure small-scale (centimeter to decimeter) changes in seabed topography to understand scour processes around structures.
6. Develop measurement capability to obtain cross-coastline profiles under high-wave conditions.
7. Develop and verify, through field measurements, an operationally useful numerical model for refraction/diffraction for general use in complex bathymetry conditions.
8. Improve and design for lower cost production of slope arrays to measure wave momentum in shallow coastal water.
9. Improve models of nonlinear wave and current interaction and wave interaction with the bottom and verify these models through field measurements.

A medium-to-low–priority recommendation identified the extension to deep water, seaward to the continental slope off the West Coast, of seismic pressure sensors, to be better able to quantify tsunami models and coastal tidal models; this action would improve tsunami forecasting in several Pacific and Alaskan areas.

The committee agrees that measurements are most needed under high-energy conditions and close to the interfaces (sea surface, bottom, and structure). Many of the processes of interest are subject to numerical modeling, but in many cases the data needed to specify initial and forcing conditions have been lacking. Many of the processes of interest are nonlinear and interactive and require relatively complex physics in simulation models. Advances in computer technology and modeling open the door to modeling some of these processes—if the data requirements for the models can be satisfied.

In short, recent developments in sensor technology, data telemetry, recording systems and computers offer promise of significant advances in the resolution of many serious coastal engineering problems in the next decade. To meet the recommendations of this report, a national commitment is called for—involving government departments and agencies, such as the U.S. Army Corps of Engineers and the National Science Foundation, as well as universities and industry—to develop the necessary instrumentation and measurement systems.

1

Introduction

Coastlines border 30 of our 50 states and Guam, Puerto Rico, and the Virgin Islands. Approximately 85 percent of the nation's population resides in these coastal states and possessions, with nearly 53 percent of the total U.S. population now living within 50 miles of a coast.[1]

Concurrent with this growing population is an increasing strain on economic, legislative, and political decision-making processes that attempt to maintain a balance between population pressures and environmental equilibrium. As an example, harbors are essential for linking our nation's land transportation systems to vital overseas trade routes. But few harbors, if any, have been built without a significant effect on adjacent shoreline configuration. The appropriate design, construction, and maintenance of harbors is still a major issue in coastal engineering.

Harbors are only one example of the growing need for coastal and ocean engineering research. Numerous other issues must be addressed before the nation can cope with the increasing pressures

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[1] Statistical Abstract of the United States, 1984. The population of all coastal counties and municipalities in 1984 (123 million persons) was 52.6 percent of the total U.S. population (235 million persons). A county is designated as being "coastal" if the geographic center of the county is 50 miles or less from the ocean or the Great Lakes.

being focused on its coasts. In a presentation made in 1976 at the Specialty Conference on Dredging and its Environmental Issues in Mobile, Alabama, Mr. W. H. Sanderson, Chief of Construction Operations Division 1 (Wilmington District), U.S. Army Corps of Engineers noted that, while dredging is one of the oldest forms of engineering works, the modern-day engineer faces practically the same ocean inlet and navigation problems that confronted settlers in colonial times in their efforts to gain and keep access to the open sea.

The long-standing problem of how to stabilize and maintain our harbor entrances and assure the use of navigational waterways continues to challenge coastal engineering. The size of the task is evidenced by the fact that maintenance dredging now costs the nation over half a million dollars annually. However, with the cost-sharing provisions of the Water Resources Development Act of 1986 (P.L. 99-662), related large-scale combined Corps of Engineers and local government research is searching for ways to reduce the cost of dreding while enhancing shore protection. One example of such research, which reflects the close relationship between dredging technology and coastal engineering, is the *feeder berm* concept. The feeder berm will take beach-quality material excavated from harbor entrances or offshore channels and place it at selected sites just off the beach where storm wave action would gradually move the material in the downdrift direction. This sediment movement would increase the volume of material available in the littoral zone, resulting in a more gentle underwater slope or gradient, and contribute to reducing shoreline erosion rates. The success of this innovative approach must be gauged largely by the ability of the engineer and researcher to measure coastal changes.

The drive to live and play near the water has led to urbanization, which has presented significant challenges for coastal engineers. Structures have been built on the beaches, in the dunes, on the cliffs, and even over the water. Developers have flattened dunes, built in natural cuts, and sliced through natural barriers. Canals have been carved and dredged in wetlands and lowlands, sometimes with little regard to circulation, potential erosion, and sediment disposal. Indeed, our society has often disregarded the forces of the sea and the natural phenomena associated with them. Now we must cope with the resulting environmental damage.

To repair this damage and prevent further destruction, coastal engineers require better and more complete data on coastal processes. Additionally, theoretical and modeling studies, requiring specific data sets, are needed to develop a better understanding of coastal processes and their effects on beaches, harbors, and structures. These data needs require that better coastal engineering measurement systems be developed and deployed.

According to the jointly sponsored National Science Foundation and Office of Naval Research report titled "Natural Hazards and Research Needs in Coastal and Ocean Engineering" (NSF, 1984),

> Each year in the United States, natural and man-made hazards in our coastal and ocean environs cost many lives and sometimes billions of dollars in loss of property and commerce. These losses can be reduced through engineering research which produces better understanding of the hazards and better ways of dealing with the physical and economic results of severe events.

Clearly instrumentation and measurement systems are required to provide the data and models necessary to the attainment of this "better understanding."

Reports and articles such as "Shrinking Shores," in *Time*, August 10, 1987, or "Bayside Owners Fight Erosion, Inevitable Tide," in *The Washington Post*, October 3, 1987, highlight the dilemma of coastal residents. The *Time* article indicates that development and poor planning have contributed to several coastal problems and cites examples of beach erosion undermining fashionable homes on Long Island, bluffs dropping out from under homes on the California coast, and beaches receding in the Carolinas at rates from a few feet to as many as 100 feet per year. Beach recession is further exacerbated by the episodic onslaught of tropical storms and damaging hurricanes. Adding to these conditions is the rise in relative sea level over the past 100 years.

Seldom can an accurate economic value be placed on the damage caused by winter storms on areas exposed to high-energy wave forces. The January 1988 storm that hit the Southern California coast was one exception; the coastal damage was estimated to cost $28 million. Equally important to the evaluation of the storm's effect was the ability to quantify the characteristics of that storm—to measure wave parameters and document beach erosion and benthic profile changes. This knowledge can be attributed partly to the in-place coastal wave monitoring program for the San Diego Coastal Region of the U.S. Army Corps of Engineers (COE, 1989). This system costs less than $500,000 to install; annual operating expenses are about $100,000.

We are hearing cries for environmental protection, for determination of cause, and for solutions. Calls for design skills in the construction of jetties, groins, seawalls, and other protective structures to hold receding beaches are commonplace. Some actions being taken are beach restoration and sand by passing by using weirs in jetties and using small dredges in channel areas to return sand to beach areas.

PREVIOUS RELEVANT REPORTS AND STUDIES

The growing awareness of coastal engineering problems has in the past decade resulted in a number of studies directed at specialized and general needs for future research and development. A comprehensive conference on ocean current measurements was sponsored by the Institute of Electrical and Electronics Engineers (IEEE, 1982). Recommendations from this conference indicated the need for hardware and software standards and a government-sponsored central testing and calibration facility. The National Research Council (NRC) Symposium and Workshop on Wave Measurement Technology (NRC, 1982) emphasized the need for long-term wave-recording systems to establish reliable wave statistics for engineering design. Additional NRC conferences have been held, including one on remote sensing of the ocean surface (NRC, 1986) and another on directional wave spectrum applications (NRC, 1982). The Institution of Civil Engineers (ICE, 1985) in England convened a panel in 1984 to assess the research and development requirements in coastal engineering. This panel concluded that the most common design requirement for coastal engineers is the need for good wave information, particularly directional information. Adequate knowledge of waves in deep water is necessary to forecast the impact of waves in shallow water.

The National Science Foundation (NSF) sponsored a workshop called "Shallow-Water Ocean Engineering Research: Research Needs and Facilities" in 1983. The NSF, in cooperation with the Office of Naval Research (ONR), also sponsored an ad hoc Committee on Natural Hazards and Research Needs in Coastal and Ocean Engineering, in 1984 (NSF, 1984). Both groups identified specific research needs that should be addressed.

The Shallow-Water Ocean Engineering Research workshop group identified needs in eight primary areas of research in coastal engineering. Within five of these eight research areas specific needs were identified for coastal instrumentation and measurement systems. These needs included the following:

AREA	NEED
breaking waves	• instrumentation to measure velocity fields in aerated water;
wave attenuation	• instrumentation for measurement of bottom shear stress;
coastal protection	• measurement of wave-impact forces on structures, • measurement of fluid flow in and around protection structures, • more wave data in vicinity of coastal structures, • more monitoring of submerged and detached breakwaters;
sediment transport	• instrumentation to withstand severe storm waves for high-energy-surf-zone measurement;
diffusion and mixing	• measurement in multilayer and reversing flow, • measurement of wind-induced shear and wave formation, • measurement of velocity gradients in the horizontal and vertical.

The Shallow-Water Ocean Engineering Research workshop group also stressed physical and mathematical modeling of coastal processes as a critical area for development.

The ad hoc Committee on Natural Hazards and Research Needs in Coastal and Ocean Engineering identified needs in five areas of field-related research. Within each of these five areas there were either specified or implied needs for coastal measurement systems.

Following is a summary of these needs:

AREA	
hazard assessment	• information about physical and statistical anatomy of natural hazards such as winter storms, hurricanes, and tsunamis,

	• long-term measurement of wind speeds, wave heights, and recurrence intervals, • instruments and techniques for measurement of physical phenomena in the surf zone and nearshore during high-energy events;
long-term studies	• long-term studies (years) to identify important slowly varying phenomena such as gradual changes in ocean sea level and shifting of geological features;
post-event surveys	• rapid response to measure post-storm damage to obtain data otherwise lost within a few weeks of the event;
prototype measurements	• accurate measurements of the response (stresses, motions) of seawalls, breakwaters, moored platforms, piers, pipeline ballast, and other structures.

Certain of the aforementioned research measurement needs have been investigated in recent cooperative field studies. The Nearshore Sediment Transport Study (Seymour, in press, 1989) provided two extensive sets of data on nearshore currents and surf-zone waves, bottom response, and sediment transport. The Canadian Coastal Sediment Study (NRC-Canada, 1986) was a research study designed specifically to investigate sand transport on beaches. The Nearshore Environment Research Center (Horikawa, 1988) project in Japan was a multi-institution study that incorporated field measurements in an attempt to develop numerical models for predicting beach evolution caused by coastal structures. DUCK '82, '85, and '86 (SUPERDUCK) were three multi-institution field experiments conducted at the Coastal Engineering Research Center (CERC) facility in Duck, North Carolina. DUCK '82 focused on storm-induced nearshore processes related primarily to morphologic response (changes in shape at the seabed). DUCK '85 was a more broadly based study to enhance fundamental understanding of nearshore processes under both low-and high-energy wave conditions. Finally, SUPERDUCK was conducted as an improved and expanded version of DUCK '85, intended to provide high quality, comprehensive sets of data to evaluate and improve numerical and analytical models of nearshore processes.

Common to all of these field studies was the use and testing of state-of-the-art measurement systems and techniques. Various findings emanating from these field studies provide useful input to the assessment of measurement needs undertaken in this report.

Specifically, there was an overall concern for better ways of measuring bed-load sediment transport, as well as for continuous measurement of suspended sediments in the vertical water column. Concern was expressed for improved methodology for making high-wave–energy surf-zone measurements on bathymetric, sedimentologic, and fluid dynamic parameters.

All of the preceding studies and committee recommendations focus attention on the urgent need for a well-coordinated national effort to develop coastal measurement systems. It is the intent of this report to integrate previous findings with a comprehensive evaluation of existing needs and capabilities in order to provide a specific set of conclusions and recommendations to the research and development community. It is hoped these recommendations and conclusions will spur expanded efforts to develop measurement systems for coastal engineering.

COASTAL ENGINEERING AND PROCESSES

The term "coastal engineering," as discussed in this report, has been limited to the inner continental shelf and nearshore zone, ranging from water depths that are just within the zone of wave shoaling to the shoreline, where the energy from these waves is dissipated. The report also addresses backshore engineering considerations where damage from storm surge often occurs. By restricting consideration to these zones, several critical coastal environments are not addressed, including estuaries and lagoons and the mid-to-outer continental shelf. Recent NRC reports have addressed some aspects of estuarine-lagoonal engineering; the mid-to-outer continental shelf presents engineering design problems somewhat different from those of the inner shelf–nearshore zone and is beyond the scope of this report. Successful engineering within this inner coastal zone is essential if people are to live there in harmony with the environment.

MEASUREMENT COMPLEXITIES

Diversity of Conditions

Processes in the open ocean show a broad uniformity over large (kilometers and more) space scales. The coastal zone, on the other hand, exhibits nonuniformity in the cross-shore direction because of wave shoaling, in the longshore direction because of changes in shoreline orientation and shoreline structures, and in every direction because of distributed shoals, bars, and irregular bottom bathymetry. The diversity of scales makes this environment unique, as does the overall high-energy characteristic of the coastal region. Coastal engineering measurement systems for the inner continental shelf and nearshore zone must be designed to accommodate the diverse space-time scales of processes and conditions that interact within this shallow-water column.

Measurement systems must be designed to characterize the broad, basin-wide atmospheric pressure systems driving waves toward the coast; other measurement systems must resolve[2] the much smaller, beach-scale processes—prediction of which is the ultimate goal of much of coastal engineering. Conditions in the coastal wave zone are exceedingly "noisy to measure"; that is, the signal-to-noise ratio there is often very low. Measurement systems must be fast enough to measure processes occurring within the few seconds of a single breaking wave while also acquiring accurate data over much longer time scales, including climate-change-induced occurrences like relative sea level change. Most of these measurement systems must survive the large forces accompanying breaking waves, strong tidal and nontidal currents, and high levels of sediment concentration within the water column. The combination of shallow water, high sediment mobility, eroding shorelines, and poor predictability—not to mention constantly changing wave conditions, currents, and bottom forms (small-scale topography features)—all make this environment a difficult one to monitor.

Winds, Waves, Currents, and Tides

The important driving forces in the coastal zone include winds, waves, currents, and tides. While local winds generate local waves and create higher water levels during storms, pressure systems thousands of kilometers from the coast create winds that ultimately may have a severe impact on the shoreline.

Waves are perhaps the outstanding characteristic of the inner shelf-nearshore zone. Waves change from their relatively predictable deep-water form once they encounter the shallow water of the shelf.

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[2] Resolution in measuring systems refers to the minimum unit or quantity that can be discerned. For example, on a ruler, one millimeter might represent the resolution limit. At the other extreme, atmospheric pressure gauges are not typically close enough together to resolve compact storms like tornados.

Complexities of bottom topography, currents (such as the Gulf Stream), and local winds mold these deep-water waves into forms that are poorly predictable in many important circumstances, such as during storms. The constant change in waves as they move into shallow water and interact with each other and the sea bottom or seabed combines with the time variation in wave conditions to make description and prediction elusive. Winds drive and modify surface currents. Waves, as they break and run up on beaches, drive currents that parallel the shore.

Tides also contribute to the complexity of the nearshore environment. Near the many coastal inlets characteristic of the Atlantic and Gulf coasts of the United States, tides alter wave height and direction and coastal currents in an intricate fashion. Varying tidal elevations (in some areas exceeding 10 meters) cause the waves to act on different parts of a beach during low tide and high tide; sometimes the high-tide position can reach inland several kilometers.

Topography

Coastal engineering measurement systems are used to monitor the shape of the shoreline and submarine topography. A central difficulty in predictions based on these measurements is the interrelation of physical forces such as wind, waves, currents, and tides and the resulting responses. A wave may alter the bottom topography in an area, and that change in bottom topography can in turn change the characteristics of the wave. A common example is the nearshore sandbar. Under certain wave conditions, a nearshore bar is formed by moving sediments from the beach out to deeper water, forming a local shoal. The presence of this shoal in turn changes the breaking characteristics of the incoming waves, causing them to break over the bar first instead of on the beach. This interaction or feedback is a limiting factor in our understanding of coastal processes. One cannot study waves by themselves, or bed forms by themselves, neglecting the other processes. Instead, this feedback requires the engineer to model or measure both the bed and the driving forces, a difficult theoretical and observational problem.

Summary of Measurement Complexities

The diversity of scales and the interactive nature of the water and shoreline complicate the design of coastal engineering measurement systems. Although measurement systems can be designed for specific conditions with some considerable success, it is doubtful whether a small number of instruments or techniques ever will be sufficient to make all the measurements coastal engineers require to perform their design tasks. The nature of the inner shelf-nearshore zone will require a diversity of techniques and approaches. Although some universal and versatile tools may be available for many coastal engineering applications, specialized tools always will be required to perform specific measurements or to provide predictions under certain conditions.

ANALYTICAL METHODS IN THIS STUDY

The purpose of this study was to identify the development needs for instrumentation and measurement systems in coastal engineering. The committee gathered the available pertinent literature and analyzed and synthesized the results. A large volume of information had to be organized into meaningful and defendable conclusions and recommendations. Since an understanding of coastal engineering requirements involves such a diversity of measurements and modeling applied to a wide variety of coastal engineering projects, a scheme or structure was needed to organize and focus the results of this review. Determining that the most important measurements are those that are most needed to solve coastal engineering problems, the committee agreed on a structural approach that proceeded along the path shown in Figure 1-1.

The committee saw this as a hierarchical analysis—that is, each engineering problem has a variety of processes that must be understood, generally requiring a variety of measurements which in turn are used in engineering design or modeling to produce an engineering solution. The following example illustrates the approach used.

ENGINEERING ISSUE: Design of a dredged harbor entrance channel.

IMPORTANT PROCESSES AND MEASUREMENTS:

PROCESS	MEASUREMENTS		
Sea Surface Motion and Level			
• Wave parameters	Direction; Height; Period	or	Directional; Wave Energy; Spectrum

• Tidal parameters	Elevation
• Currents	Magnitude; Direction
Storm Parameters	
• Storm conditions	Duration; Strength; Origin
• Runoff	Volume; Location
Sediment Movement	Type of sediment Volume Transport rate in suspension Transport rate by bed-load

From the literature and the individual experience of its members, the committee determined measurement and modeling capabilities in meeting the design requirements and, if necessary, identified the needs for further refinement or development.

Some measurements are, of course, more critical than others; some can be measured with confidence (tides) and others not well at all (bed-load sediment transport). Using this structured approach it was possible to see how each measurement requirement affected the solution to the engineering problem.

Another consideration of importance to the measurement evaluation process is the difference in need that may arise from assessment of an applied engineering versus a basic research requirement. For example, the resolution of velocity and direction required for measuring longshore current is much less than that required for determining similar phenomena on a small scale (e.g., shear or drag forces). Often the differences are not conflicting but simply represent immediate applied engineering needs versus the more subtle basic research requirements.

In reviewing physical processes in the high-energy shore area—such as wave breaking and its relation to wave-force effects, for example—the committee noted where our theoretical understanding is weak. A comprehensive identification and assessment of all areas where theory is in doubt would be a large undertaking. In its assessment the committee chose to highlight those areas that have the greatest impact on the data required for coastal engineering.

The remainder of this report applies the committee's analytical approach (shown in Figure 1-1) over the full range of coastal processes that must be considered and understood by the engineer and those who are responsible for developing the technical basis for decision-making about the use and protection of our beach and coastal resources.

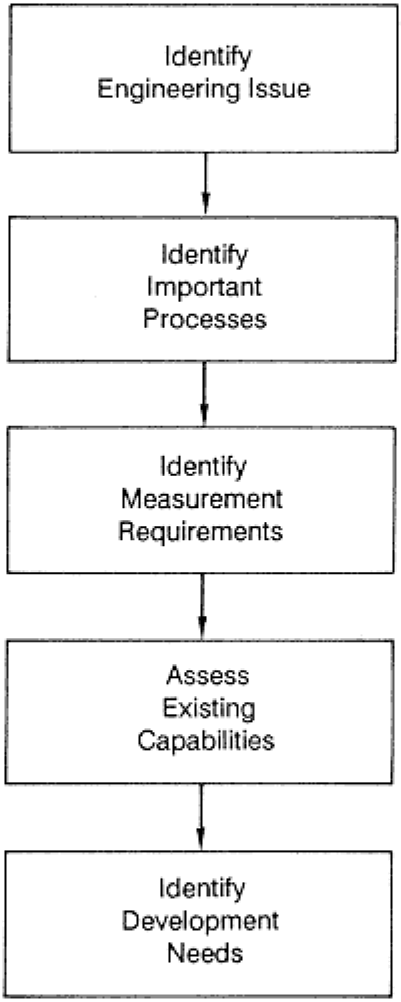

Figure 1-1
Structural approach to collecting infor mation on coastal engineering problems.

2

Coastal Engineering Applications

The coastal engineer operates in a dynamic, intricate, and multifaceted environment. Application of coastal engineering knowledge to the solution of problems is complicated by a host of physical and environmental factors. For example, in order to design and build a structure, engineers need a firm understanding of coastal ocean motions, sedimentation rates, stresses of the wave and water motion, and other forces on the shoreline and on the structure. Further complications result from the great range of ocean movement over space and time. Extreme events like breaking storm waves, storm surges, tides, and tsunamis add to the already complex nature of the coastal engineering discipline. To perform the job properly requires detailed and accurate information on the conditions under which a structure must perform and survive. Measurements and measurement systems are required to determine the range of influence, strength, and timing of the forces of nature in the coastal zone.

For this study, the committee first identified those issues or problem areas recognized as important to the engineering community; some issues are more urgent and must be given greater priority. Then it was necessary to identify and evaluate the state of knowledge of coastal processes related to each engineering issue. This evaluation in turn considered the state of theoretical development and analytical and numerical modeling in each coastal process area.

The latter consideration was necessary because modeling plays such an important role in coastal engineering.

ENGINEERING APPLICATION AREAS

The committee identified four major problem areas where coastal engineering skills must be applied. (See Figure 2-1, adapted from the Corps of Engineers' *Shore Protection Manual*, [1984].) The four engineering problem areas are identified simply as shorelines, backshores[1], entrances (or inlets), and harbors. These broad areas, either exclusively or in combination, encompass most coastal engineering problems, as defined by the U.S. Army Corps of Engineers.

Coastal Process Categories

Taken in the broadest sense, four categories of coastal processes act on the coastal areas identified in Figure 2-1. Two of these categories may be considered primary and the other two, interactive.

Primary processes consist of:

- kinematics[2] and dynamics[3] of high-frequency coastal water motions (periods of 0.1-5 minutes) and
- kinematics and dynamics of low-frequency coastal water motions (periods greater than 5 minutes).

Interactive processes consist of:

- fluid/sediment interaction and
- fluid/structure interaction.

In general, the short-period, high-frequency phenomena are related to wind-wave generated water motions; long-wave period, lowfrequency phenomena are generated, for example, by pressure effect, tidal motions, and such catastrophic events as slides, slumps, or earthquakes. The categories were specified because of the need to

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[1] "Backshore" is a general term referring to the area above and behind the normally active beach face. The backshore is typically affected only during storms or extreme high tides.

[2] "Kinematics" refers to the motions of a fluid element, in this case the trajectory of a small patch of water.

[3] "Dynamics" refers to the effects of external forces on fluid motion (effects on kinematics).

recognize spatial and temporal differences in the coastal measurement systems and instrumentation required for each category.

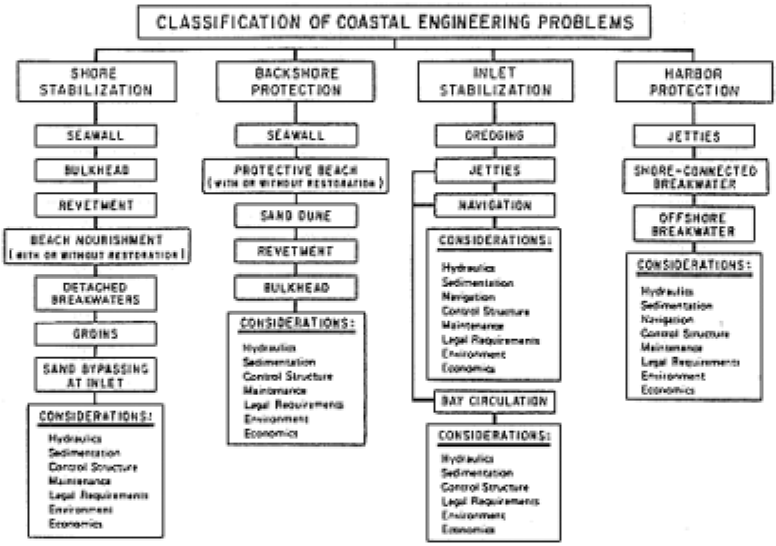

Figure 2-1
General classification of coastal engineering problems.

Coastal Features and Coastal Engineering Applications

Each of the four general coastal features previously categorized in Figure 2-1 and illustrated in Figure 2-2 (shoreline or shore, backshore, entrance inlet, and harbor) presents a distinct set of problems for instrumentation and measurement system development. Some measurement problems cross two or more features. The following paragraphs provide a brief overview of each feature or area of engineering application and emphasize a few perceived measurement goals.

Shore

Shore stabilization is a primary engineering goal along large sections of the U.S. coastline. Achieving this goal requires understanding the behavior of the shore or shoreline and effects adjacent to both hard engineering structures (e.g., seawalls, revetments, groins) and soft structures (e.g., beach nourishment). Basic to the knowledge required is an understanding of shore response to wave action and currents. Because present modeling capability to predict shoreline response is inadequate, measurements of the sediment transport rate, concentration, and distribution are necessary in both longshore and cross-shore directions. It is important to make these measurements under conditions of moderate-to-high-wave energy. Likewise, the ability to rapidly and accurately measure beach and nearshore profile changes under a broad range of wave-energy conditions is essential to verification of prediction models. An essential consideration for all of

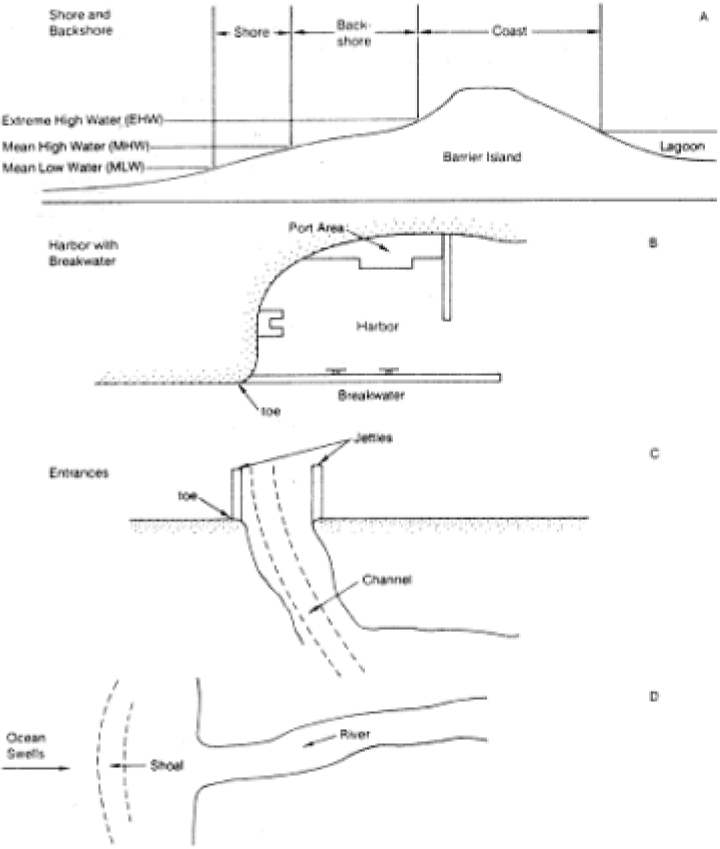

Figure 2-2
Illustrative examples of coastal engineering problems.

these measurements is the ability to carry them out successfully under high-energy episodic conditions associated with storms, because these energetic conditions result in maximum sediment transport.

The need for understanding shore processes is illustrated by the erosion of the shore at the Cape Hatteras Lighthouse on the Outer Banks of North Carolina. The 110-year-old historic tower is endangered by changes in the shoreline that have brought the high-water line to within 100 feet of the structure. A series of studies has sought to ascertain the reasons for past variations in the position of the shore, in order to forecast the future. But the basic understanding of shore processes is inadequate for reliable prediction of the rate of shoreline change during high-energy wave conditions (NRC, 1987).

Another factor in shoreline processes is relative sea-level change. Rising relative sea level exerts an inexorable pressure on most sections of the world's shoreline (but not all). For instance, many high latitude shoreline segments in Canada and Europe are emergent, contrasting with the U.S. shoreline which is primarily submergent. Whereas past relative sea-level rise in the United States has averaged about 30 cm per 100 years, this value exhibits considerable spatial variability.

Relative sea-level rise presents a future challenge to coastal engineers, but it is one that can be anticipated in engineering planning (NRC, 1987). If projections of increases in relative sea-level rise are correct, engineering projects designed for 25-50 year time scales will have to incorporate rising sea levels more directly into their design phase. Meanwhile, existing facilities and structures will have to be shored up to account for this long-ignored factor in the design equation. Nevertheless, unpredictable changes caused by coastal storms and hurricanes pose a greater concern than does the effect of sea-level rise.

Backshores

Much like shore stabilization, backshore protection requires an understanding of processes that vary in nature and importance from one location to another. Knowledge of dune, bluff, and beach response to extreme wind and wave events is essential to this understanding. Measurements of runup[4] and setup[5] under high-energy

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[4] "Runup" is the travel of waves up the face of the beach above the still water level.

[5] "Setup" refers to a general local increase in sea level caused by the momentum of breaking waves.

wave conditions and a knowledge of storm surge[6] histories are necessary. Measurement problems involving immersion, burial, and exposure of sensors may be more pronounced and problematic in these locations.

Unusually high lake levels along many shores of the Great Lakes during the mid-1980s provided an example of where backshore protection was paramount. When lake levels rise, backshores are likely to suffer damage from wave and current erosion during storms, especially when low-pressure systems combined with wind setup accentuate the already high water levels. Then, severe bluff and beach damage often result in significant environmental impact and property damage. The ability to measure wave direction and runup would support more reliable predictions of areas of greatest impact and how to safeguard them.

Entrances

Entrances include both natural inlets and constructed harbor mouths and channels. Stabilization of entrances is a primary engineering goal in certain natural and almost all constructed channels. The annual cost of maintenance dredging of inlets and harbors by the Corps of Engineers alone is rapidly approaching $400 million. A major measurement problem related to maintenance dredging of inlets and channels is the determination of transport and deposition of sediment during high-energy wind and wave events that frequently close navigation passages. This fact reinforces the need for measurements of sediment transport and concentration during high-energy tidal flows.

A good example of this problem is the entrance of the Columbia River leading to the major ports of Portland, Oregon, and Vancouver, Washington. At this entrance, a large curving sandbar often produces serious depth restrictions to the passage of ships as Pacific swells interact with strong river currents. The severity of navigation problems requires a specialized pilot for bar passage, separate from the river navigation pilot. Extensive studies of the pitching motion of ships crossing that bar under varying wave, tide, and current conditions (Wang and Noble, 1982) have verified the critical need to predict the movement of the shifting bar in order to avoid grounding or broaching.

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[6] Storm surge is increased sea level over a broad area caused by wind forcing.

Systems for diverting sand are being constructed to keep entrances open and to maintain sand nourishment to downdrift beaches. These systems require prediction of sand transport volumes that are dependent on local wave and current conditions. Presently, the use of sand diversion systems is severely limited by inadequate capability to predict sediment transport, largely owing to the lack of coastal engineering measurement systems.

Harbors

Design of safe, effective harbors with low operation and maintenance costs is another primary coastal engineering goal. Essential to achievement of this goal is an understanding of the stability of breakwaters formed from mounds of rock, the failure of concrete elements used to increase this stability, the leakage of wave energy through the breakwater, and scouring away by the waves of the sediments that form the breakwater's foundation. The cost of these structures is very large. Therefore, there is a strong economic pressure to improve prediction capabilities, thereby eliminating over-design. Measurement of wave forces on and within breakwater structures is required, as well as measurement of wave and current forces adjacent to and along the breakwaters. This is a particularly complex area of engineering, where theoretical development is sparse and empirical determinations are often based on indirect relations between wave forcing and structural response. Few measurements have been made of the forces and structural interactions on actual structures. Only recently have measurements been undertaken on the external structural elements. To the best of our knowledge no measurements internal to the structures have been made. This is an engineering area that requires development of specialized measurement systems.

A well-known example of this need is the failure of the harbor at Sines, Portugal. A massive breakwater constructed on the Atlantic coast was designed to provide a vast port and industrial complex. Before the structure was completed, a period of violent Atlantic storms produced waves that severely damaged the breakwater, destroying much of the capwall and roadway and preventing completion of ship berths planned for the lee side. Extensive investigation of the wave conditions that led to the Sines failure did not lead to a consensus judgment; rather, it resulted in 13 different opinions as to the principal cause of the breakwater damage.

3

Processes and Measurement Requirements

Coastal measurement systems designed for sensing the properties of waves and currents are usually categorized into one of two temporal domains: high-frequency and low-frequency. High-frequency wave and current motions are defined here as those with periods of five minutes or less and include both the gravity[1] and the infragravity[2] portions of the surface wave spectrum (see Figure 3-1). Low-frequency motions are defined here as those having periods greater than five minutes and range from tsunami to tidal or longer oscillation periods. The current velocity measurement techniques can be categorized as Eulerian or Lagrangian, and in situ or remotely sensed. Eulerian measurements are those collected by moored current meters measuring velocity at a fixed location. Lagrangian measurements are obtained by a tracer (drifter floats, dye, or tagged particles) following the current stream over a period of time. In situ measurements are obtained by placing instruments in the ocean. Remote-sensing measurements are those collected by "noncontact" methods from satellites, aircraft, ships, or ground stations, using electromagnetic

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[1] Gravity waves are those waves with lengths between their creats of a meter or so to a few hundred meters—typical of wind-generated waves.

[2] Infragravity waves have lengths of hundreds of meters to tens of kilometers and are usually driven by gravity waves.

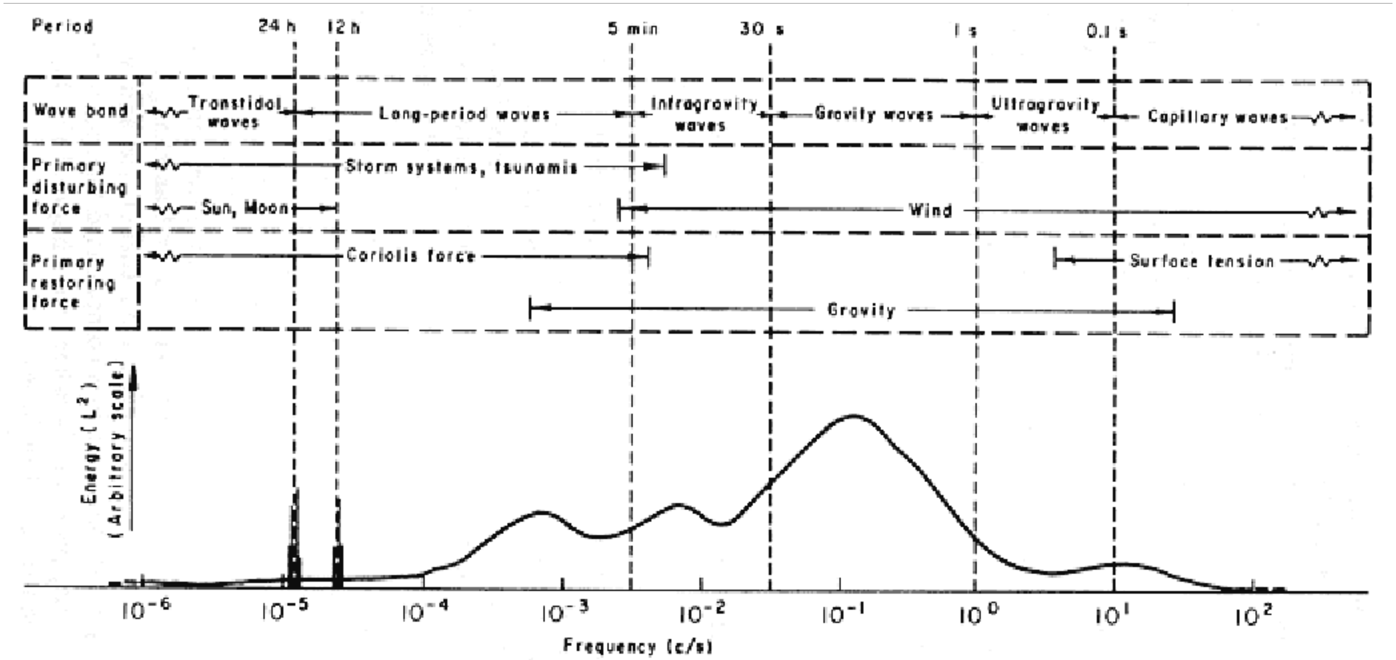

Figure 3-1
Approximate distribution of ocean surface wave energy illustrating the classification of surface waves by wave band, primary disturbing force, and primary restoring force. SOURCE: U.S. Army Corps of Engineers, Shore Protection Manual, 1984; after Kinsman, 1965.

radiation. Modern acoustic-Doppler current meters and similar sensors that sense current velocity using acoustic waves scattered from particles drifting with the current should be considered a combination of in situ and remote-sensing techniques.

After the hydrodynamic forces generated by high- and low-frequency waves are determined, the engineer and researcher must measure and understand the responses of the sediment particles to these wave and current forces. This chapter addresses the various measurement techniques used for determining sediment movement on scales from particle-size up to regions and locations from near (within a few centimeters) the seabed to the upper water column.

Finally, the engineer must be able to measure the effect of the hydrodynamic forces of the sea on structures in, or at, the wave zone. How structures, in turn, affect both hydrodynamics and sedimentary response also must be gauged if the engineer is to establish adequate design guidelines. This chapter also deals with these fluid structure interactions.

HIGH-FREQUENCY WATER MOTIONS

Processes

High-frequency motions in the coastal environment can be categorized as being wave-induced flows (including gravity and infragravity waves), turbulent flows, and averaged currents (that is, averaging the current in time for more than five minutes). Because Lagrangian measurement techniques generally do not lend themselves as well to high-frequency field measurements, only Eulerian systems are considered here.

In contrast to waves, currents are physically difficult to measure with a single instrument except in extremely simple cases. Spatial variation in waves primarily depends on the bathymetry, whereas current variation is influenced by the shape of both the bottom and the shoreline. Also, strong vertical variation in the current velocities can exist due in part to inhomogeneity in the water density caused by salinity and temperature variations, as well as changes caused by the viscous boundary layer effects on turbulence and velocity. Currents modify wave velocities in a complicated fashion when both are varying in time, particularly where the shape of the bottom is also changing as a result of this interaction.

TABLE 3-1 Summary of Data Needs for Coastal Engineering

1. SHORE STABILIZATION	3. INLET STABILIZATION
Sediment Characteristics	Sediment Characteristics
Grain size distribution	Grain size distribution
Concentration of suspended fraction	Packing density
Inlet Characteristics	
Near-bed transport rates	Bathymetry
Beach Characteristics	Net sediment flux
Beach profiles	Patterns of erosion and deposition
Local areas of deposition or erosion	Protective structures
Stabilizing structures	Hydrodynamic Characteristics
Hydrodynamic Characteristics	Wave height and steepness
Incident wave heights and steepness	Wave direction
Current velocities	
Wave direction	Bottom shear stress (wave/current interaction)
Velocities of wave-driven currents	
Velocities of other currents	
Bottom shear stress	
Turbulence characterization	
2. BACKSHORE PROTECTION	4. HARBOR PROTECTION
Sediment Characteristics	Sediment Characteristics
Grain size distribution	Grain size distribution
Beach Characteristics	Harbor Characteristics
Beach profiles	Bathymetry
Longshore sediment transport	Shoreline changes
Cross-shore sediment transport	Protective structures
Patterns of erosion and deposition	
Hydrodynamic Characteristics	
Wave direction	Hydrodynamic Characteristics
Wave height and steepness	Wave height and steepness
Wave runup	Wave direction
Storm surge	Current velocities
Tsunami runup	Bottom shear stress

Measurement Requirements

The proper design of a measurement system requires (1) knowledge of the expected environmental conditions at the measurement site, (2) appropriate design of the supporting moorings of platforms, and (3) the selection of suitable measurement devices. Each of these components, and their interaction, contributes significantly to the quality of the data, and a total system must be considered collectively. The requirements for precision and resolution of the data must also be considered.

The set of measurement requirements listed in Table 3-1 was established by assessing the engineering needs of each of the four application areas or features discussed in Chapter 2 (see Figure 2-1). The optimum spatial and temporal resolutions are specified for each measurement requirement (see Tables 3-2, 3-3, and 3-4) and existing sensing systems are identified for evaluation of their measurement capability. If the measurement capability of an existing sensing system failed to meet the necessary spatial and temporal resolution requirements, a need was then identified for instrument or system development.

Measurement Capabilities

Velocity Measurements—In Situ

A wide variety of physical measurement techniques incorporate current measurements taken at a point. A primary difficulty for nearshore velocity measurements is that oscillatory wave-induced velocities are generally present throughout the water column, superimposed on steady currents. In the wave, simple impeller (speed) and vane (direction) current meters were found to rectify the oscillatory velocity imposed by the waves, thereby biasing the results (e.g., McCullough, 1978). Vanes generally do not respond to wave motion rapidly enough to resolve direction accurately, giving "aliased" or noisy directional information. This condition has led to the development of a number of current meters that respond to wave motion and that have been adapted especially for shallow-water measurements. These instruments resolve the wave motion into velocity components at right angles to each other. Instruments include biaxial rotor vector-measuring current meter (VACM) (Figure 3-2), electromagnetic current meters (Figure 3-3), forward-scatter or backscatter acoustic-Doppler current profiler (ADCP) (Figure 3-4), and laser velocimeter. The Eulerian current meters have a relatively high capital cost per unit, ranging from over $4,000 for a meter to as much as $65,000 for a current profiler system, depending on the data recording and internal processing capability. Some of the difficulties and problems encountered with Eulerian measurement systems are biological fouling, corrosion, orientation uncertainties, disturbance of the flow fields by the instrument, bubbles, cavitation, extreme storm waves, and disturbance of sensors by fishermen.

Velocity Measurements—Remote Sensing

Remote-sensing techniques avoid many of the disadvantages of

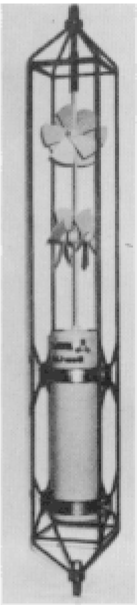

Figure 3-2
Davis-Weller Vector Measuring Current Meter, Model 630. SOURCE: EG&G Environmental Equipment Division, Burlington, Mass.

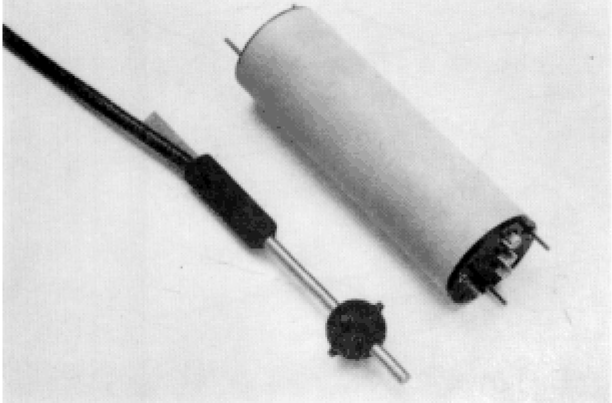

Figure 3-3
Electromagnetic Current Meter, Model 511.
SOURCE: Marsh-McBirney, Inc., Gaithersburg, Md.

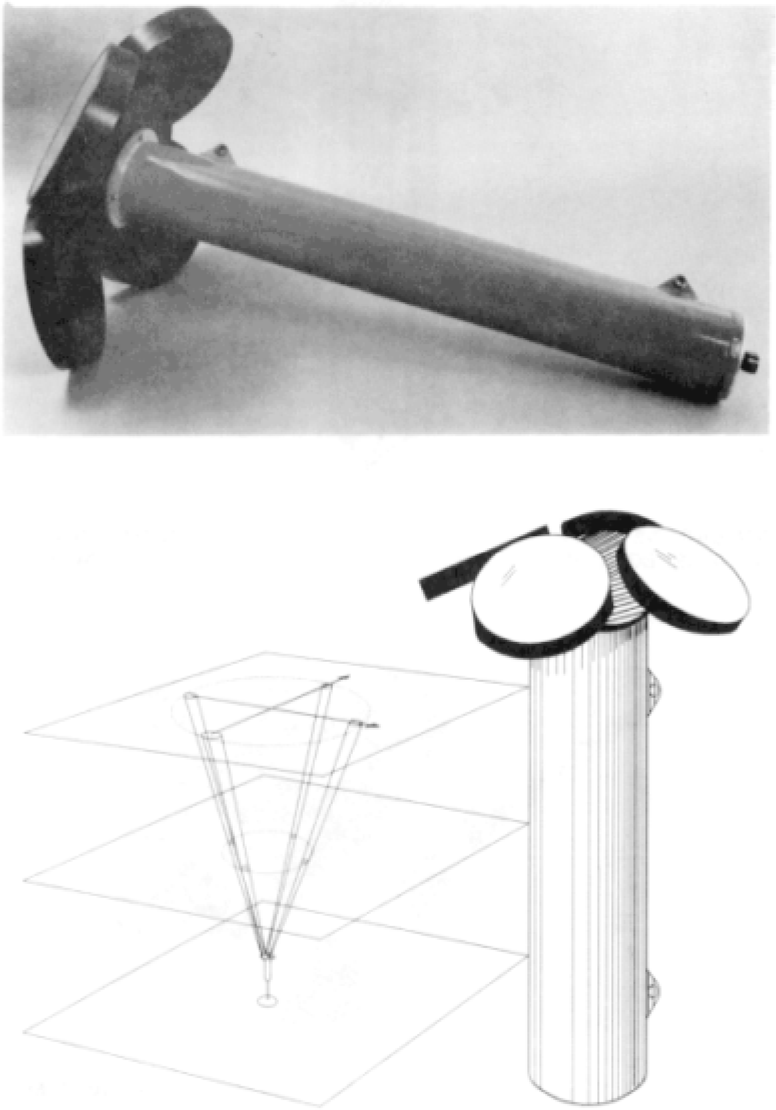

Figure 3-4
75-KHz Self-Contained Acoustic-Doppler Current Profiler.
SOURCE: RD Instruments, San Diego, Calif.

in situ measurements and have the advantage of generally providing rapid coverage of a wide area. The disadvantages in most techniques include sensing only of the surface currents (providing no information about the subsurface velocity profiles) and integrating over large areas so that the local gradients are filtered out.

One method for the remote sensing of currents relies on the scattering of radar signals from the sea surface. Current speed is determined from the Doppler shift (frequency change) in the scattered signal after a theoretical shift due to wave speed has been removed. The speed of the current in the direction of the radar beam is determined. Directional components are measured by turning the radar or using multiple radars. Synthetic Aperture Radar (SAR) uses a single radar mounted on a moving platform (plane or satellite), which allows good definition of currents over large areas. Other remote-sensing techniques are being developed, including optical systems, which offer additional capabilities for the future. Because of the large surface area observed by most of these systems, they are not generally applicable to the nearshore region, where currents change rapidly over short distances.

Wave Measurements—In Situ

A wide variety of wave-measuring devices for waves based on various physical principles have evolved, including direct, indirect, and remote techniques. Each technique has inherent advantages depending on the application. Desirable characteristics of any wave sensor should include good accuracy, linearity, ruggedness, dependability, and low cost. The utility of any wave sensor is highly dependent on the type of installation for which it can be adapted, such as bottom or pier mountings.

The most common direct measurement of the sea surface is by wave staffs (wires that penetrate the sea surface) that measure resistance, capacitance, or inductance. The disadvantages of wave staffs are that they usually require mounting on a rigid structure such as a tower or pier piling. In measuring plunging breakers there is a question as to exactly what is measured, because of multiple interfaces in the plunge portion of the wave. The influence of foam is unknown for direct wave sensors.

Other direct measurement techniques include acoustical devices directed up from beneath—such as inverted fathometers—and lasers and microwaves (infrared) looking down from above; both of these techniques are based on measuring the time for a pulse to travel from the sensor, be reflected off the surface, and return. Acoustical and electromagnetic methods have the advantage that they do not disturb the surface. The disadvantage of the inverted fathometer is that the speed of sound is a function of temperature and salinity, which can vary temporally and spatially over the vertical. Steep waves may not provide a good acoustic return mirroring exact surface configuration because of side-lobe reflection problems. The inverted fathometer does not work in the highly turbulent region near the surf zone due to scattering of the sound by turbulence and bubbles. Because of beam spreading, the sampled surface area may be wide and as a result, the signal return provides an area average depth; this may be an advantage or disadvantage depending on the intended use of the device. The inverted fathometer does offer the advantage that it can be mounted on the bottom, generally a much easier type of mounting than that required for a laser beam or microwave, which must be mounted from a structure looking down onto the surface.

Pressure sensors that provide indirect measurements of the wave surface generally have the advantage of ease of installation, durability, and low vulnerability to environmental forces. For this reason and because pressure sensor technology is highly advanced, they are a popular means of measuring the waves. The water column above the pressure sensor acts as a hydraulic filter, partially filtering out the high-frequency components of the wave spectrum. The wave spectrum is increasingly filtered as the depth of the sensor increases. A practical deep-water limit is approximately 20 m for placement of the pressure sensors to determine sea and swell waves. Some uncertainty exists concerning the performance of the sensors when the waves are quite steep (Forristall, 1982).

Nearshore direction characteristics are typically either measured locally in shallow water with "slope arrays" or measured in deep water with buoys and then transformed to the nearshore location. The important problem in predicting littoral sediment transport is that an accuracy of 1-3° is required to obtain good estimates. This means that the deep-water waves must be resolved to within 2-5° to obtain the desired nearshore directional accuracy after transformation.

Wave directional buoys are used primarily in deep water to measure the heave, pitch, and roll with accelerometers and an inclinometer. A second type of "orbit following" directional buoy, developed by ENDECO (Brainard and Gardner, 1982) infers the surface slope due to the forcing by the horizontal motion of water particles. The buoys have their own individual dynamic response functions, and the mooring also can influence the dynamic response of the buoys. Therefore, the dynamic response of the combined system of the buoy and mooring system must be known so that proper calculation of

TABLE 3-2 Assessment of Needs for Measurements of High-Frequency Motions

Measurement Objective	Accuracy Requirements	Measurement Technique	Capability	Need
Currents				
Longshore	±2 cm/s	Electromagnetic	I	2, 6, 7
cross-shore	5 Hz	Acoustic		
1-2°	Mechanical			
Turbulence	±1 cm/s	Acoustic	III	2, 4, 6, 7
	high-frequency	Hot film		
Water level				
Tides	±5 cm	Pressure, Mechanical	I	7
Storm surge	±5 cm	Pressure	I	7
Wave setup	±5 cm	Pressure	III	7
Wave runup	±5 cm	Photo/Video Electrical	I	4, 6, 7
Wave characteristics	0-15 m ±5%	Many	I	6, 7
Wave direction		Slope array	III	1, 2, 6, 7
deep water >> 10m	2-5°	Remote sensing		
shallow water	1-3°			
Breaker characteristics		Photographic	II	2, 6, 7
Meteorological				
Wind velocity	5%	Many	I	7, 8
Wind direction	10%	Many	I	7, 8

LEGENDS:

Need:

1 Major development
2 Improve information detail
3 Improve physics
4 Improve efficiency
5 Improve tuning
6 Special data needed
7 Verification needed
8 None

Capability:

I Good
II Adequate
III Possible but not satisfactory
IV None

surface displacement can be made. Buoys have not been used as reliably in shallow water as in deep water because of the demand placed on shallow-water surface moorings (large displacements, steep waves, etc.). Although buoys provide some directional wave information in deep water, these buoys do not give the high-resolution direction information often required for coastal engineering (see Table 3-2 to 3-4). More accurate, inexpensive inertial compasses based on optical interferometry should be available soon. These solid-state devices may give improved accuracy and reliability to the directional buoy measurements but will probably not improve the directional resolution.

TABLE 3-3 Assessment of Needs for Measurements of Low-Frequency Motions

Measurement Objective	Accuracy Requirements	Measurement Technique(s)	Capability	Need
Currents				
Offshore (10-20 m depth)	3 cm/s	EMCM, ATTCM, VACM, ADCM	III	3, 4, 5, 6
Nearshore	3 cm/s	(same as above)	II	3, 4, 5
Inlets	3 cm/s	(same as above)	III	3, 4, 5, 6
Radiation stress	10%	Slope array	II	5
Water level				
Offshore	10 cm relative	Pressure sensor, Remote altimeter	II	5, 6, 7, 8
Nearshore	10 cm absolute	Pressure sensor, Tide gauge	I	5, 6, 7, 8
Backshore	20 cm absolute	Pressure sensor, Float gauge	I	5, 6, 7, 8
Runup	0.3 m	Contact sensors, Photogrammetry	II	3, 4, 5
Wave setup	10 cm	Slope array	III	5, 6
Direction spec.	10%, 25°	Buoys, SAR, PUV, Slope array	II	3, 4, 6
Meteorological				
Wind velocity	5%, 10°	Many	I	6, 7, 8
Barometric pressure	1 mb	Many	I	6, 7
Morphological				
Bathymetry (large-scale)	5% or 0.5 m	Fathometer, Precise leveling	I	9
Bathymetry (small-scale)	0.3m	Fathometer, Precise leveling, Side-scan	III	2, 8

Measurement Objective	Accuracy Requirements	Measurement Technique(s)	Capability	Need
Natural topography	0.3 m	Precise leveling	I	8
Structures	0.3 m elevation 10% horizontal	Precise leveling, Photos	I	8
Vegetation	10% area	Photos	II	8
Water properties				
Temperature	0.1°C	CTD	I	7, 8
Salinity	0.1 ppt	CTD	I	7, 8

ACRONYMS:

EMCM electromagnetic current meter

ATCM acoustic travel-time current meter

VACM vector-averaging current meter

ADCM acoustic-Doppler current meter

SAR synthetic aperture radar

PUV pressure sensor combined with current meter

CTD conductivity (salinity)-temperature-depth meter

LEGENDS:

Need:

1	Major development needed
2	Improve information detail
3	Improve physics
4	Improve efficiency
5	Improve tuning
6	Special data needed
7	Verification needed
8	None

Capability:

I	Good
II	Adequate
III	Possible, but not satisfactory
IV	None

Slope arrays are designed to measure the directional wave characteristics in shallow water using three or more bottom-mounted pressure sensors (Higgins et al., 1981). Although the directional spectrum resolution is the same as a pitch and roll buoy, the wave momentum flux is well estimated. A measurement system comparable to the slope array is provided by using a pressure sensor and a two-component electromagnetic velocity sensor (PUV) (Grosskopf et al., 1983). An intercomparison of directional measuring capabilities for the buoys, slope arrays, and PUV was accomplished during the

TABLE 3-4 Assessment of Needs for Measurements of Fluid/Sediment Interaction

Measurement Objective	Accuracy Requirement	Measurement Technique	Capability	Need	Selected Reference
Sediment characteristics					
Grain size	silt-gravel	Bottom sampler	I	7	1
		Remote sensing	III	1	2
Particle density	2-6 g/cm^3	Bottom sampler	I	7	
Bulk density	1-4 g/cm^3	Bottom sampler	II	6	
		Nuclear density probe	II	5	3
Suspended sediment concentration	0-300 g/L	Optical	II	6	4
		Acoustic	III	1	5
		Water samplers	I	7	6
		Remote	III	2	7
Bed load		Samplers, traps	II	3	8
		Remote	IV	1	9
Sea level					
Wave characteristics	0-10 m ±5%	Pressure, staff, photo/video	I	7, 6	
		Wave riders	I	7, 6	
		Seismic	III	2	
		Other	III	1	
Wave direction	2-5°	Slope array	III	1	
		Remote			
Wave runup	±5 cm	Photo/video	I	7	
Breaker characteristics		Photographic	I	7	
Tides	±5 cm	Pressure	I	7	
		Mechanical	I	7	
Storm surge	±10 cm	Pressure	I	7	
Currents					
Nearshore circulation (large-scale)	±5 cm/s	Remote	III	1	
Longshore, cross-shore	±3 cm/s 10°, 5 Hz	Electromagnetic	II	7	
		Acoustic	II	7	
		Mechanical	II	7	
Boundary shear stress	±1 cm/s				
low-frequency		Current profile	II	7	
high-frequency			IV	1	
direct			IV	1	
Reynolds stress			III	7	
Radiation stress	±10%, 1 Hz				

Measurement Objective	Accuracy Requirement	Measurement Technique	Capability	Need	Selected Reference
Morphology					
Beach profiles					
small scale	1-5 cm	Hand survey	I	7	10
medium scale	±10 cm	Mobile survey	I	7	11
large scale	±50 cm or 5%	Photographic/ Remote	III	2	12
Bed profiles	±0.5 cm	Acoustic	III	2	13
Scour at structures	±30 cm	Side-scan sonar	III	2	

REFERENCES:

1 Gable, 1980
2 Schuman and Rea, 1981
Won and Smits, 1986
3 U.S. Dept. of the Interior, 1957
Anonymous, 1978
4 Bartz et al., 1978
Downing et al., 1981
5 Huntley, 1982
Kraus, 1987
6 Nielsen, 1984
Inman et al., 1980
7 Collins and Pattiaratchi, 1984
Thomas, 1980
8 White and Inman, 1987
Drapeau and Long, 1985
Downing, 1981
Salkield et al., 1981
9 Lowe, 1987
10 Aubrey and Seymour, 1987
11 Seymour et al., 1979
Clausner et al., 1986
12 Fraser, 1985
Kasischke et al., 1983
Smits and Won, 1987
13 Sallinger et al., 1986

LEGENDS:

Capability:

I Good
II Adequate
III Possible, but not satisfactory
IV None

Need:

1 Major development (new instrument)
2 Improve information detail
3 Improve reliability
4 Improve durability
5 Improve installation and use
6 More sensors, or lower data cost
7 None

ARSLOE[3] (Vincent and Lichy, 1982) experiment, and all methods gave similar results.

Recent developments in radiation stress (momentum flux) measurements include using differential pressure sensors to make direct measurements of the surface slope (Bodge and Dean, 1984) and using acoustic travel time to infer velocity gradients (Guza, personal communications).

Wave Measurements—Remote Sensing

Several techniques are available for remote sensing of waves and the sea surface, and more are under development. Remote sensing offers the advantage that the sensors can be mounted on movable platforms such as airplanes or satellites, and large areas can be measured rapidly. Other advantages are freedom from shore connection and the ability to sample extreme wind and wave conditions. The key disadvantage presented by using remote sensing of sea surface conditions is poor temporal coverage; observations of a series of events at an area are difficult to obtain by aircraft-mounted sensing.

Remote-sensing techniques are based on the scattering of electromagnetic radiation from the ocean surface, either coherently or incoherently. Early techniques utilized photography to determine surface slopes from sun-glint patterns. Stereoscopic photography was used to determine directional wave spectra, although this method proved to be cumbersome. Present image-analysis techniques make stereophotogrammetry a viable technique to estimate the directional spectrum.

Wave heights (but not directions) over the ocean are measured operationally using an altimeter aboard the Navy satellite GEOSAT. The altimeter measures wave height from the shape of the reflected radar pulse. NASA's plans for the next decade include a dedicated wave altimeter mission, TOPEX/POSEIDON, proposed for launch in 1991.

The airborne Surface Contour Radar (SCR), developed jointly by NASA and the Naval Research Laboratory (NRL), was designed

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[3] ARSLOE: Atlantic Remote Sensing Land-Ocean Experiment for sensor intercomparison, sensor development tests, and data wave-model verification; October 6 to November 30, 1980, offshore Duck, North Carolina. The tests were organized by the U.S. Army Corps of Engineers Coastal Engineering Research Center and the National Ocean Survey of NOAA.

to measure the directional wave spectrum (Walsh et al., 1986). An oscillating mirror scans a 0.85° × 1.2° pencil beam laterally to measure the sea surface elevation at 51 evenly spaced points within a swath approximately half the aircraft's altitude. Ground truth comparisons were made by a variety of slope-measuring buoys during the ARSLOE experiment, and reasonable comparisons were obtained (Walsh et al., 1986).

Synthetic Aperture Radar (SAR) has been operated from both aircraft and satellites. The imaging mechanism is complex, but the primary signal is that due to scattering from the centimeter-scale ocean waves. This signal can be accentuated at the crest of the long wave and may become the principal image for large waves (Harger, 1986). Thus, the SAR requires the presence of short waves of a few centimeters that result when winds are greater than approximately 3 m/s. Due to present resolution limitations, only significant wave heights greater than 1 m and wave lengths exceeding 25 m can be measured.

The SEASAT satellite system obtained a resolution of approximately 25-40 m using a 23-cm wavelength SAR to acquire radar images of the ocean surface in swaths 100 km wide and varying in length from 300 to 3,000 km. Vesecky et al. (1986) compared the results to intensive ship, buoy, and aircraft wave measurements during the Joint Air-Sea Interaction (JASIN) experiment. Comparisons between SAR and buoy estimates of wave length and direction agree to within about ±14 percent and ±10°. Correlations with buoy measurements suggest that significant wave height could be estimated to about ±1 m. SAR data from European and Japanese SAR-equipped satellites, to be launched in 1989 and 1991 respectively, will also provide valuable wave information.

During the space shuttle oceanographic mission in 1984, Shuttle Imaging Radar-B (SIR-B) SAR obtained images of the ocean surface. These were compared to those obtained from two aircraft scanning radars, the SCR and the continually scanning Radar Ocean-Wave Spectrometer (ROWS) (Beal et al., 1986). The ROWS obtains a high-resolution slope spectrum. A surface elevation spectrum can be obtained from all three systems.

High-frequency (HF) radars have been used to measure ocean waves (Barrick, 1982). These systems use polarized electromagnetic waves that are scattered from the ocean surface wave component in-line with the radar signal. Huang (1982) reports accuracies of ±8 percent for wave height greater than 1 m and ±7° for direction. Full directional information would require at least two radars looking in different directions.

Promising radar systems for coastal applications are broad-beam surface-wave radars. These systems can yield the same directional information as heave-pitch-roll buoys. An example is CERC's operational Coastal Imaging Radar System (CIRS), which is a shore-based X-band radar. The system is designed to obtain long-term statistics of wave direction and wave length, but does not provide wave height. It can operate unattended in all weather. Data can be collected up to 5.5 km off shore. Modal wave direction can be resolved within ±3° and wave length to 10 percent (COE, 1984).

Surface-scanning acoustic-Doppler sonar technology has demonstrated the ability to measure surface directional wave spectra (Pinkel and Smith, 1987). Doppler sonars mounted on the floating instrument platform FLIP have been used to scatter 75-kHz sound from the underside of the sea surface at range intervals of from 60 to 1,400 m. Complete wave directional information has been obtained from a single location using a pair of sonars aimed at right angles. Although some aspects of this technique are not fully understood, the observed motions are consistent with linear wave theory. This technology allows a single-point instrument in the open ocean to resolve wave direction as well as an array of conventional measuring devices 1,000 m in length.

Measurement Needs

Cost of installation, recording, and analysis can easily exceed the cost of the instrument; these cost considerations should be a part of instrument design and selection. The availability and experience in the use of microprocessors and other technologies can allow for preprocessing or analysis of the data in situ. New expanded storage media such as bubble memories, optical discs, and high-density digital tape allow for larger and more reliable recording capability. Satellites for telemetry links such as system ARGOS and improved ground telemetry can be used to obtain real-time data. Cable technology for data links to shore using fiber optics is rapidly advancing.

Waves

The National Research Council-sponsored symposium and workshop on wave measurement technology (NRC, 1982), which was mentioned earlier, assessed the needs, status, and future directions to be pursued. Operational and research needs were described in that NRC report. Five major research areas for wave data were described and, for the most part, these areas have been aggressively pursued in the intervening seven years as noted (in italics):

1. Properties of a sequence of large waves need to be studied, both in the field and theoretically. This phenomenon has been identified as a primary mechanism for damage to structures. The workshop participants recommended investigation of the nonlinear aspects of wave interaction. *This area of research has been aggressively pursued (see e.g., Elgar et al., 1985), but not all aspects of the problem still need to be solved.*
2. Understanding is lacking of wave interaction—particularly the nonlinear aspects of waves with currents, bottom bathymetry, and winds. *Progress has been made in the understanding of the weakly nonlinear evolution of waves due to shoaling (see e.g., Freilich and Guza, 1984), but our knowledge still needs to be greatly improved.*
3. Progress has been made on refraction/diffraction models, but a fully operational model is not available and field verification data are lacking. *This assessment is still true, although significant improvements have been made (see discussion in Chapter 4, wave-induced currents).*
4. There is a need to improve understanding and ability to measure extreme events and the effects of such events on structures and the nearshore environment. *This is still true, as long-term wave records are needed to establish reliable wave statistics.*
5. Improvement is needed in wave directionality measurement and analysis, both in situ and remote. *This is still a requirement today—see Chapter 6: Conclusions and Recommendations.*

Velocity

A need has been identified by this committee for a high-frequency turbulence measurement capability for application in sediment-laden or aerated waters that occur within the surf zone. Laser- and acoustic-Doppler measuring devices offer nonintrusive methods for measuring near the bed but need to be adapted for in situ application in the surf zone. These instruments offer promising areas for technology advances, as do improved recording and analysis systems.

At the 1978 IEEE conference on current measurements, subgroups made specific recommendations, most of which still apply today. One recommendation was that the engineering community sanction standardized testing methods and procedures. The idea of some sort of government-sponsored central testing and calibration capability, perhaps open to all who have a need, was proposed as a cost-effective service to the nation. It was agreed that there is a need for both hardware and software "standards" applied to the measurement of currents.

The need for standards and calibration facilities is exemplified by the continuing controversy over the capabilities of electromagnetic flow meters—the standard instrument used in the surf zone for the last decade (Aubrey and Trowbridge, 1985, 1988; Guza, 1988; Hamblin et al., 1987; Doering and Bowen, 1987).

The remote sensing of waves and currents is an area that requires more development and holds promise for obtaining simultaneous measurements over a broad area.

A question was raised in 1978, and is still valid today, as to who should underwrite the cost of research and development of new ideas in current-measurement technology. Should government or industry bear the cost of instrument development? A problem for manufacturers is the small volume in a specialized market. Manufacturers continually must incorporate technological advances or risk being noncompetitive. A new current-meter concept can quickly make older meters obsolete.

LOW-FREQUENCY WATER MOTIONS

This section addresses long-period phenomena, at time scales of five minutes to years or decades. Classifications of such phenomena are shown here:

Classification	*Range of Period*
Tsunami[4]	5 minutes to 1 hour
Harbor seiche	1 to 10 minutes
Shelf wave	minutes to hours
Astronomical tide	semi-diurnal to annual
Storm surge	hours to days
Seasonal sea level	1 to 12 months

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[4] A tsunami is a long wave generated by vertical movement of the ocean floor caused by an offshore earthquake. In the past, tsunamis were often referred to as "tidal waves" although they have nothing to do with astronomical tides.

Long-term sea level	years to decades
Ground-water intrusion	years to decades

Concerns with such phenomena include navigation of inlets to harbors (tidal currents), backshore and harbor protection (tsunamis, storm surges, tides, and long-term changes in sea level), and berthing of vessels (tidal range and harbor seiches).

This report does not address the inner harbor wave motions as these are not considered normally to be a shoreline, high-energy measurement concern. Tides are global and ever-present, whereas tsunamis are of local origin and rare in occurrence but can have significant impact on shorelines and backshores. Storm surges, while also event-related, are as frequent as the intense storms that cause them and are of major concern to localities on the Atlantic and Gulf of Mexico coasts. Pacific coastal regions of the United States are less affected by storm surges because the narrow continental shelf inhibits surge. Measurements of the strength and tracks of storms are needed for use both in design of sea walls and other protective works and in evaluation of risk to coastal communities. Shelf waves excited by longshore winds, or seasonal and long-term changes in sea level or land level, compound such considerations.

Measurements Requirements

The most predictable of the low-frequency water motion phenomena are the astronomical tides, at least for those coastal locations where long-term tide data are available. Storm surge prediction (either in real time or in the hindcast mode) demands accurate wind velocity information characterizing the storm in space and time. It also demands accurate bathymetric data near shore, and land elevations in the backshore if overland flooding is an important consideration. Numerical models for storm surges need water-level data during storm events and adequate astronomical tide data to verify the models. Longshore current data, particularly for currents at key locations such as inlets, are valuable, if not indispensable, for refining the model algorithm for computing the friction between the water and the seabed.

Existing water-level data for verification and possible improvement of model performance are generally not adequate for two reasons: lack of a sufficient number of tide gauges within backwater regions and lack of combination of tide gauges and wave gauges in regions offshore of the breaker zone during storm events. The water-level evolution during a storm depends on the integrated effect of the wind stress and atmospheric pressure, and indirectly on the wind-induced surface waves that produce a low-frequency water-level anomaly near shore (referred to as "wave setup"). The next-generation storm surge models need to allow for this phenomenon using computationally efficient numerical models of waves. Verification of such model upgrading requires water-level and wave data to infer the contribution of wave setup to the total rise in sea level near shore. Bottom pressure gauge data at the continental shelf break also would be useful in fine-tuning the outer boundary conditions that are used in present surge models.

Another area for improvement in coastal flooding surge models is the effect on the flow caused by vegetation and other natural or constructed obstructions. The effect of vegetation on wind-wave propagation over flooded land is addressed by Camfield (1977) and in a report of the National Research Council (NRC, 1977). Verification of the proposed methodologies and their extension to low-frequency flow impedance is largely lacking because of insufficient data on prototype conditions. The requirement is for strategically placed wave and water-level gauges on both sides of such natural obstructions during storm events. Although such information is highly site-specific, it is a necessary step in the development of models that might be applied to different generic classes of natural and constructed obstructions. Photogrammetric techniques (using photography in surveying) together with in situ surveys would be useful in attempting to develop a measure of the extent and effect of such overland morphological features.

In the design of coastal protection structures or in the evaluation of risk of flooding for coastal communities, the data on high-water-level events at any particular location are usually inadequate to determine the probability that a water-level anomaly will exceed a given value in a given period of time (e.g., 50 years). In the absence of data for coastal regions where storm surges constitute the main threat (combined with tide), the historical behavior of storms can be employed together with surge models to give reasonably meaningful estimates of such probability (NRC, 1983; Office of Chief of Engineers, 1986). Good storm data for the region are needed to validate the storm surge model used to simulate flooding. Evaluation of risk for coastal communities threatened by tsunamis is much more difficult because of the lack of adequate data on seabed motions associated with the seismic events that cause tsunamis. Seismic data themselves yield quantitative information on the location and magnitude of the event, but are not sufficient to determine whether a tsunami has been generated (Murty, 1977; Van Dorn, 1984). Data required for proper characterization of the source are those derived from benthic (deep-water) pressure gauges such as those in the Pacific Ocean (Gonzalez et al., 1987; Eble, 1988), well away from the influence of continental shelf, and in harbors, where most tide gauges are located.

Long-term changes in sea level, whether due to a change in the land level (subsidence, uplift) or climatic conditions, are important in designing to mitigate possible flooding scenarios over time spans of several decades (NRC, 1987). The long-term change not only adds directly to water elevations due to surge, but also affects such things as wave climate and seawater intrusion into aquifers. The measurement requirement is for accurate long-term tide gauge data where sea-level changes are of concern. Satellite-based measurement systems such as Very long Baseline Interferometry (VBI) and Differential Global Positioning Systems (DGPS) show great promise for measuring relative sea-level changes accurately and rapidly (Carter et al., 1986).

Measurement objectives related to engineering needs are summarized in Table 3-3, and specific accuracy requirements for each measurement objective are given.

Measurement Capabilities

The capability for most of the required measurements exists as shown in Table 3-3 (capability I, II, and III). For water level, both stilling-well tide gauges and bottom-mounted pressure gauges are generally adequate to measure sea-level variation with time periods of a few minutes or more (capability I and II). However, for variations with periods of months or longer, the accuracy of pressure gauges may be inadequate due to instrument drift. If sea-level changes are to be corrected for barometric pressure or water density, these data must also be available.

Currents associated with low-frequency phenomena can be measured by a variety of means including tracking of drifters, in situ current meters, and remote acoustic-Doppler systems. The Lagrangian tracking methods are well suited for measurements offshore during normal weather conditions. However, for measurements during storm conditions, the existing capability is marginal in terms of ruggedness, reliability, installation, and portability. For measurements in channels, the bottom-mounted acoustic-Doppler current-meter systems appear to have the most promise (Lhermitte, 1981). In theory, acoustic tomography could be a useful technique. However, practical limitations may preclude the use of acoustic tomography in shallow water as there are many unanswered questions concerning the stability of acoustic paths and the signal processing required to resolve currents in shallow water. Electromagnetic and acoustic techniques have been rated, therefore, as capability level III—passable, but not yet satisfactory. Modeling of low-frequency motions requires much data for validation of the models, including the shape of the bottom contours. Not only is large-scale bathymetry required for modeling needs, but also small scale features (such as bedforms), primarily for modeling bottom frictional terms.

Nearshore bathymetry data can be obtained by fathometer (acoustic travel-time measurement); however, precision leveling is required to provide a known elevation or bench mark for reference. The existing capability (level I) is quite adequate to determine the general bottom shape, but the capability for determining small-scale features relevant to bottom roughness is only marginally adequate (capability level III). Bed forms (periodic or quasi-regular changes in the elevation of the sea floor) having length scales from centimeters to hundreds of meters and amplitudes of centimeters to meters are difficult or impossible to measure during storms, when they are changing rapidly. Existing technology does not permit these measurements to be made during high-energy events; nominal development may permit improved estimates of the time scales of motion of some of the larger bed-form features (see the section on fluid/sediment interactions, later in this chapter). Clearly, improved modeling capability verified by observations would provide the best means for simulating the effects of bed-form changes in the near future.

Measurement Needs

The major needs for quantifying low-frequency motions in the nearshore and backshore regions are adequate coverage and strategic placement of sensing devices for water level, waves, and currents during normal tidal regimes and during storm- or earthquake-induced anomalous events. "Strategic placement" means that which will allow inferences to be drawn in terms of such phenomena as wave setup, sea-level differentials across inland flooded areas containing extensive and variable vegetation, and volume flow into or out of harbors or estuaries. Acquisition of such data during event-related phenomena such as storms and tsunamis requires real-time capability, including the possibility of placement of portable sensing equipment. The development needs are for suitably rugged yet reliable sensing devices for currents and waves under storm conditions. Table 3-3 summarizes these needs.

FLUID/SEDIMENT INTERACTIONS

One of the ultimate goals of coastal engineering research is to understand and to predict shoreline stability and morphological changes in response to the variety of processes that occur in the coastal environment. The engineer must understand the processes to be able to undertake projects that address such concerns as beach nourishment, sedimentation associated with coastal structures, erosion-accretion patterns along exposed coasts or in the vicinity of inlets or navigational channels, and sediment response associated with dredging activities. The coastal engineering data needs listed in Table 3-1 reflect the breadth of problems in which sedimentation plays an important role.

From a physical point of view, sedimentary processes are the result of fluid/sediment interactions, or more specifically, the response of sediment particles to the forces produced by shoaling waves, tides, coastal currents, and winds. Sedimentary processes are among the most important but least understood aspects of the coastal environment. In studying sediment transport phenomena, quantifying the total sediment movement under a variety of conditions is the ultimate goal. A distinction is often made between *bed-load* transport—those grains sliding, rolling, or moving within several grain diameters of the seabed—and *suspended-load* transport, those grains suspended by fluid turbulence. In extremely high-transport situations, grain-to-grain collisions, rather than fluid turbulence, become the dominant suspending mechanism, and a grain-dispersed layer is maintained within 10 to 15 cm of the seabed. For this document, the distinctions between these transport modes are not critical, and distinction is made only between suspended and near-bed transport.

Nearshore sedimentation research generally has been limited by technology and the inability to monitor sediment transport on time and space scales commensurate with the physical causes. As a result, progress in sedimentology has lagged behind advances in our understanding of the other physical mechanisms operating in the nearshore environment. At the same time, as conceptual and theoretical modeling of nearshore sediment response has continued to evolve, the need for appropriate field measurements has continued to grow.

Field investigations of various aspects of fluid/sediment interactions encompass a wide range of efforts. Thus, a broad demand is placed on instrumentation and sensor capabilities. A review of recent literature (e.g., Greenwood and Davis, 1984; Edge, 1985; Kraus, 1987) suggests that, within the classifications shown earlier in Figure 2-1, sediment-related field studies fall into three broad categories: *regional, site-specific* , and *process-oriented*.

The regional category of field investigation includes broad-scale or reconnaissance-level investigations that, for example, require information on (1) regional patterns of circulation, suspended sediment, bed morphology, and longshore bar geometry; and (2) noncorrelated parameters such as wave climatology, sediment accumulation volumes, and shoreline changes. Because of the large area involved, remote-sensing devices would be appropriate to these investigations. Typical examples include use of time-lapse photography to map spatial and temporal changes in longshore bar morphology relative to wave conditions (Holman and Lippman, 1987); correlation of Land-Sat images for detecting the nearshore surficial suspended-sediment concentration field with various physical processes thought to cause resuspension (Fedosh, 1987); and comparison of historical changes in beach profile with storm wave predictions (e.g., Dick and Dalrymple, 1984; Brampton and Bevan, 1987).

The site- or project-specific category of field investigation includes studies designed to (1) obtain empirical information on local processes, (2) test or use hypotheses to explain local beach changes, or (3) investigate gross cause-and-effect relationships between fluid motions and sediment response at a location of interest. Excellent examples of site-specific studies relate to human intervention with the nearshore, e.g., the shoreline effects of reduced flooding in the Nile River (Inman and Jenkins, 1985), studies of massive sediment injections at San Onofre, California (Grove et al., 1987), and sediment infilling at dredged channels, as is observed in many harbors.

The process-oriented category of field investigation relates to fundamental sediment-transport research. Specific theoretical relationships are investigated at the sediment-particle scale of inquiry, and the goals may have longer-term implications related to sediment-transport theory and future applications. Studies of this nature may or may not have immediate application to coastal engineering problems but represent potential advances to the field. Historically, experimental research has been carried out in wave tanks or flumes; however, field experiments are beginning to be used to test specific hypotheses, to support improved numerical modeling efforts (e.g., Mason et al., 1987), and to carry out fundamental fluid/sediment research in the nearshore zone (e.g., Seymour, 1987; Hanes and Huntley, 1986; Beach and Sternberg, 1988).

Instrumentation requirements are substantially different for these three categories of study. The first category, regional-scale investigation, requires less precise quantitative information covering broader geographical areas. In contrast, process-oriented sediment-transport research requires a wide variety and large number of instruments deployed in precise arrays to document detailed relationships. Study areas are selected on the basis of research interest and place great demand on collection of field data. Site- or project-specific studies fall between the other two categories in requirements for instruments and data collection and may rely, for example, on selected point measurements or long-term measurements of bathymetry.

Measurement Requirements and Capabilities

The measurements required to fulfill coastal engineering needs are extremely varied. This variety can be illustrated by reviewing the major engineering problems defined earlier in Figure 2-1 and Table 3-1 and considering the primary measurements needed to address fluid/sediment interactions (summarized in Table 3-4). The measurement requirements listed under backshore protection (in Table 3-1) emphasize spatial-scale (wide area) monitoring rather than local sensing. Inlet stabilization requires measurements to be made within entrance channels and includes estimates of sediment transport and flux, especially in relation to infilling channel entrances. Transport of cohesive sediment (clays and muds) in nearshore regions was not considered in this report, and readers are directed to the report on Sedimentation Control to Reduce Maintenance Dredging of Navigational Facilities in Estuaries (NRC, 1987) for a review of cohesive sediment transport. Harbor protection refers to measurements designed to investigate sedimentation associated with major protective structures and the adjacent seabed.

The various measurement requirements tabulated in Table 3-1 have been grouped by category in Table 3-4, which emphasizes the variety of measurements used to address coastal engineering sedimentation problems. Included with each measurement requirement is a suggested measurement performance (resolution or range), a commonly used measurement technique, a designation of present instrument capability, the related development need, and selected references for the sediment and seabed morphology categories.

From Table 3-4 it is seen that, generally, methods for measuring waves and currents are operational and are capable of measuring over the full range of environmental conditions (capability I, II). In contrast, methods for measuring various aspects of sediment characteristics and coastal morphology are in various developmental stages and their full potential has not been realized (capability III, IV). In some cases, measurements are only possible under low-wave conditions (e.g., diver-operated samplers), while in other cases, measurement techniques are lacking (e.g., fast response near-bed sediment-transport sensor). As a result, sediment transport in the nearshore zone is inferred from other measurements (e.g., currents, waves), rather than measured directly.

Measurement Needs

The measurement capability ratings shown in Table 3-4 indicate that many of the sediment and bed-morphology-related measurement techniques and some flow and wave measurements related to fluid/sediment interaction are limited in their present capabilities. The present major measurement deficiencies in fluid/sediment interaction studies include the following.

Near-Bed Sediment Transport

While recent advances have been made on rugged solid-state optical sensors capable of measuring suspended sediment concentrations in the surf zone (e.g., Downing et al., 1981; Huntley, 1982), a technology does not presently exist to measure sediment concentrations or change occurring in the near-bed region (within several centimeters of the seabed). Sediment concentration increases toward the seabed; measurements in this area are fundamental to our understanding of total sediment transport. Although nearshore sediment-transport studies using sand tracers and traps have been used, the long time-response of the measurement (minutes) does not match the wave-forcing period. Prototype acoustic devices that record grain impacts in the near-bed region (Downing, 1981; Salkield et al., 1981) have been constructed and deployed. However, an operational solid-state device that can monitor bed-load transport in the near-bed zone is not presently available.

Acoustic devices for detecting suspended sediment concentration profiles are presently being developed and operated in a variety of laboratories. Although there are some basic problems with the operation of these sensors in the coastal zone (e.g., strong response to bubbles, limited response to fine sediment), they are perceived to have significant potential. Acoustic backscatter devices are being developed to provide high-resolution profiles of suspended sediment, either looking downward to the seabed, upward into the lower water column (Lynch et al., 1987), or throughout the water column (see summary in Kraus, 1987). Acoustic-Doppler devices have been proposed for monitoring fluid sediment flows within centimeters of the seabed (Lowe, 1987), thus suggesting a means to estimate bed-load transport. Multifrequency acoustic devices have the potential of resolving grain size characteristics of suspended load. These devices are evolving rapidly, and they show high potential. Their adaptability to the high sediment concentration and entrained air bubbles common to the nearshore environment, however, is yet to be established.

Fluid Turbulence

Turbulent velocity fluctuations and the related transfer of momentum are the actual mechanisms that maintain sediment suspension within the surf zone. Turbulent fluctuations occur from fluid shear and from breaking waves. Classical sediment-transport theory is based on boundary shear-generated turbulence. Some present sediment-transport models used in the surf zone consider only forced turbulence from boundary shear, while others consider turbulence from breaking waves to be more important. In all cases, knowledge of turbulent characteristics in the surf zone is almost totally lacking, and existing means to quantify fluid turbulence are inadequate.

Methods for measuring turbulence in other fluid environments (including areas of the continental shelf outside the surf zone) have been developed. These include hot film anemometers (e.g., Gust and Weatherly, 1985), acoustic travel-time current sensors (e.g., Williams and Tochko, 1977), and laser-Doppler velocimeters (e.g., Agrawal et al., 1988). Thus, some forms of technology exist that have potential application. Preliminary measurements of turbulence in the surf zone have been made using hot film probes (George and Flick, 1987).

Bathymetry

Requirements for measuring bathymetry exist on several scales. On a large scale, the ability to monitor beach profile changes quickly with 10-15 cm accuracy over the range of fair weather and storm conditions is necessary to understand a wide variety of nearshore problems. These include problems related to beach nourishment, long- and short-term beach erosion/accretion, longshore trapping efficiencies, channel sedimentation rates, and total sediment budgets. On a smaller scale, methods are required to monitor changes in seabed elevation caused by scour and erosion at a given point on millimeter-to-centimeter scales. Measurements of this accuracy are necessary for sediment-transport research directed toward predicting seabed stability and determining the relationships between sediment transport and changes in beach morphology.

Present methods for measuring beach profiles include wading survey techniques (Aubrey and Seymour, 1987), tractor- and sled-mounted transducers, and the motor-driven CRAB device operated by the Corps of Engineers at the Duck, North Carolina, Field Research Facility. These techniques provide approximately similar resolution (10-15 cm) but are limited in operation to low-wave conditions, such as wading survey techniques, or are large devices that cannot be easily moved from site to site, such as CRAB. Instruments for measuring small-scale bathymetric changes at a point are presently under development (Sallenger, 1989; personal communication). These instruments use miniature, high-frequency echo sounders that are mounted within the water column and "look" downward toward the seabed. The signals are noisy because of bubbles and high sediment concentrations, but these difficulties are being considered and development is proceeding.

Directional-Wave Characteristics

The partitioning of total sediment flux into cross-shore and longshore components is dependent on the direction of wave propagation in shallow water. Since waves generally break at low angles to the beach, a difference of 1° to 2° in the estimated wave direction can significantly change the computed longshore sediment flux rate. Consequently, improved wave directional resolution is required in measurement systems for sedimentation assessment and forecasting. This measurement requirement is also important for other aspects of coastal engineering, as discussed earlier in this chapter.

Spatial-Scale Observations

Several nearshore engineering functions, such as beach protection and beach nourishment planning and engineering, require data from simultaneous observations over large sections of the nearshore or coastal zone with methods that may be less accurate or precise than the site-specific requirements discussed in the preceding sections.

Remote-sensing techniques have been developed, over the past decade, that may provide significant potential for application in the surf zone. These techniques rely on satellite, airborne, and ground-based sensors that can rapidly scan or observe a variety of parameters. Examples showing some limited application of these remote-sensing methods include determination of nearshore bathymetry from airborne systems and the use of satellite imagery detecting nearshore turbidity to map coastal circulation patterns. Generally, remote-sensing technology has been developed for use in other fields; however, many of the specific methods have potential for coastal engineering applications. Some examples are briefly summarized in Table 3-5, which also includes some of the in-water acoustic and photographic methods discussed in the foregoing sections. Large-scale spatial averaging may limit the usefulness of some of these technologies in the surf zone.

Since no agency or institution exists that coordinates or systematically funds instrument development, the needs of the coastal engineering community have been addressed historically on an individual basis as dictated by funding for field research. Most of the major cooperative field studies—e.g., NSTS, C^2S^2, Duck '85, SUPERDUCK, etc.—(Kraus, 1987) have been responsible for coordinating moderate development efforts carried out by individual participants. This ad hoc approach has been effective in the sense that instrument development is closely tied to scientific needs. It may not, however, provide adequate or long-term funding and facilities for developing some of the major instrument systems listed in the foregoing discussions.

TABLE 3-5 Remote-Sensing Instruments, Techniques, and Potential Application in Surf Zone

Instruments	Potential Application
Deployment: SATELLITE/AIRCRAFT	
Altimeter	Geostrophic currents, wave and storm surge characteristics
Scatterometer	Sea state
SAR (Synthetic Aperture Radar)	Sea state, wave spectrum, wave direction
Radiometer (microwave) Color scanner	Suspended sediment distribution
Deployment: AIRCRAFT	
SCR (Surface Contour Radar)	Sea surface
ROWS (Radar Ocean-Wave Spectrometer	Directional wave spectrum
AOL (Airborne Oceanographic Lidar)	Surface waves and bottom topography
SLAR (Side-Looking Airborne Radar)	Mapping
ALM (Airborne Electromagnetic Method)	Coastal bathymetry
Deployment: GROUND-BASED	
CODAR (OSCR)	Coastal circulation
SLR (Side-Looking Radar)	
Cameras: time lapse and time exposure; (photographic and video imaging)	Wave runup, breaker conditions, low-frequency wave characteristics, bar morphology
Techniques	
Deployment: IN WATER	
Acoustic backscatter	Suspended sediment concentration, flux, bed-load transport characteristics, local scour and deposition, turbulent and suspended sediment field.
Laser Doppler	
Acoustic Doppler	
Acoustic tomography	

FLUID/STRUCTURE INTERACTIONS

Structure Types and Measurement Requirements

Coastal structures can be divided into the following categories:

- Breakwaters
- Elevated platforms, on piles or cylinders

- Seawalls and bulkheads
- Jetties and groins
- Dredged entrance channels into harbors
- Navigation aids
- Artificial islands.

Design of each of these types of structures requires knowledge of environmental forces sufficient to establish criteria for location, materials that should be used, and dimensions. These criteria may come from physical models, or, if the physics and mathematics are understood well enough, from numerical models.

Breakwaters

The purpose of a breakwater may be different in one location than in another location because of different reasons for reducing wave energy. Some of these purposes are to:

- provide quieter water in an entrance channel for safe navigation,
- provide a calm harbor for loading and unloading cargo or passengers from ships,
- protect the shore from wave damage during storms, and
- reduce beach erosion or accumulate sand.

Breakwaters can be properly designed only with site-specific data about the wave spectrum—both for significant and maximum waves—and wave grouping, information on runup and overtopping, shock pressures exerted by breaking waves, the effect of the breakwater on currents, the intensity of air bubbles during storms, and the engineering characteristics of bottom sediments at the seabed and for some depth below.

Breakwaters are of various types. The most common is the rubble mound, faced with large stone or concrete units of different shapes. Caisson breakwaters, made of rows of hollow boxes (of concrete, usually) reflect wave energy, since long-period narrow-spectrum waves can cause significant scour. Design of these breakwaters requires specific knowledge of the erodibility characteristics of the local seabed.

Composite breakwaters, partly caissons and partly rubble, have been built in many configurations, most notably in Japan. These structures are characterized by a vertical wall near the top so that impact forces are usually a critical design consideration.

Another variety of breakwater is that composed of a line or lines of sheeting, sheetpiling, or connected cylinders, forming a vertical wall. This design also requires detailed information about the foundation materials below the seabed and also about scour resistance in front of the structure.

Any of the foregoing types of breakwaters may be built with different top elevations, depending on the need to prevent, or to allow, overtopping during storms that are so violent that vessels would not be entering. Still lower top elevations may be built as submerged breakwaters designed to reduce the height of waves, but not to absorb or reflect all wave energy.

A special class of structures is floating breakwaters. Their effectiveness depends on their width as compared with the wave length of incoming waves. Consequently, they are mainly suitable for relatively short waves, such as those usually occur in marinas and other small-boat harbors. They offer advantages, compared to bottom-mounted breakwaters, in sheltered deep water or in regions of unusually high tide ranges. A literature search by the Corps of Engineers Waterways Experiment Station (WES) shows a wide variety of designs for floating breakwaters, including arrays of tires, boxes, baffles, and diaphragms (COE, 1982).

A working group of PIANC (Permanent International Association of Navigation Congresses) has been established to analyze 163 breakwaters from many parts of the world in efforts to find common factors among breakwaters that have contributed to their success or failure, consider model tests, evaluate safety factors, and propose ways to respond to engineering and construction problems. This assessment is still underway, but it is clear from such reviews, as well as from experience in the analysis of several failures, that more information is needed about the progress of shock pressure waves through the armor and core materials.

Elevated Platforms

Elevated platforms supported by piles or cylinders embedded in the sea bottom have been extensively used and researched. Wave forces on the cylinders have been measured, and the body of data is sufficient for design, except for the magnitude of shock pressures for breaking waves. Better knowledge is needed about the effect of groups of piles on the scouring of the seabed. Examples of this lack of understanding are demonstrated by the effect of pilings used in construction of several research piers over the past decade (for example, at the Corps of Engineers facility, Duck, North Carolina, and Scripps Institution of Oceanography) that have caused unexpected deepening near the pier. In addition, predictions of scour depth as a function of wave climate and the engineering properties of the beach soils and subsoils are not possible with any great accuracy at this time.

The measurement of the height of storm wave crests is a critical requirement for safe design. Many tests and observations of behavior of oil industry platforms have shown the need to maintain the elevation of the underside of the deck above the crests of the highest waves, to avoid excessive impacts.

Seawalls

The design of seawalls and bulkheads along the shore requires the same kinds of measurements of wind and wave forces as breakwaters, with added emphasis on wave overtopping and the effects of impounded rainwater on the landward side.

Jetties and Groins

Jetties and groins are physically similar to breakwaters but are built perpendicular to the shoreline. In the United States, jetties are structures protecting and stabilizing the entrances to harbors, although the term "jetty" is used more broadly elsewhere. Groins, by interfering with the transport of sand along the shore, are used to attempt to stabilize the shoreline position. Design problems for these structures are similar to the design problems for breakwaters.

Entrance Channels

Dredged entrance channels into harbors may be considered coastal structures with negative elevation. In designing entrance channels, information is required about the source and movement of sediments that tend to fill up these channels and impede shipping. In addition, entrance channels may cause adverse environmental effects in the form of downdrift erosion when sediment supplies are cut off. The relations between current velocity, wave climate, grain size, distribution of sediments, and turbulence are not clearly understood.

Navigation Aids

Navigation aids to guide ships and boats are a broad class of coastal structures. They may be fixed or floating and consist of buoys, lights, ranges, markers, and communications stations (acoustical, visual, radar, or radio). Measurements of environmental forces such as those developed by wind, current, and ice are important to the effective design of navigation aids and their supporting structures.

Artificial Islands

The creation of land in the ocean for terminals, airports, and other activities has been advanced, particularly by the Japanese, during the past two decades. The fill is typically contained within a conventional breakwater structure so it presents no unique design problems.

Measurement Capabilities

To measure the dynamics of wave/structure interactions, a variety of instrumentation may be required, including the following:

- Fast response pressure sensors
- Strain gauges
- Tensiometers
- Accelerometers
- Anemometers
- Water-level gauges
- Current meters
- Bathymetric and topographic measurement systems
- Optical motion indicators, remote sensing.

Measurement requirements, capabilities, and needs have been summarized in Tables 3-6 and 3-7 for application to structures of two general types: fixed position (rubble mounds, solid blocks, or vertical-walled caissons) and floating breakwaters. These structures may be located on shorelines, harbor entrances, or channels. In situ instruments, imbedded in rubble-mound structures, can present data-logging problems because of the susceptibility of cables to damage.

TABLE 3-6 Assessment of Needs for Measurements of Fluid/Structure Interaction (Fixed-Position Structures)

Measurement Objective	Accuracy Requirements	Measurement Technique	Measurement Capability	Operational Need
Profile movement:	10 cm	Survey	III	
external	10 cm	Survey + strain gauge	II	5, 6
internal	5 cm	Inertial	IV	1
Water level				
Wave characteristics	10 cm	Pressure + wave riders	I	3, 6
Wave direction	5°	Slope arrays + photos	III	2
Wave runup		Photos	II	5
Wave reflection		Photos	II	2, 6
Wave transmission		Photos	II	6
Wave overtopping		Photos, Acoustic	II	5
Pore pressures		Pressure gauge	III	1
Currents				
Toe of structure	10 cm/s	Acoustic	II	4
Inside structure	10 cm/s	Acoustic	II	5, 6
Forces				
Mooring	± 10%	Strain gauges	I	5, 6
Torsional	±10%	Strain gauges	I	5, 6
Seismic	±10%	Strain gauges	I	5, 6

LEGENDS:

Capability:		Need:	
I	Very good	1	Major development
II	Adequate	2	Improve information detail
III	Not adequate	3	Improve reliability
IV	None	4	Improve durability
		5	Improve installation and use
		6	More sensors or lower data cost

Measurement Requirements

Erosion at the Base of Rubble-Mound Structures

If the foundation soils are eroded by storm waves, causing the sediments to move seaward, the undermining will cause raveling of the slope and loss of material. To counteract this effect, the base areas are often reinforced with a berm or placed in a previously excavated trench to prevent scour. However, the effectiveness of these erosion-prevention techniques so far has not been accurately measured. Physical models do not adequately reflect the scale relationship between foundation sediments and rubble or armor materials. Prototype measurements of waves and currents, scour, and transport

TABLE 3-7 Assessment of Needs for Measurements of Fluid/Structure Interaction (Floating Breakwaters)

Measurement Requirement	Measurement Capability	Measurement Needs
Wave data		
Currents, instantaneous	Sensors, Adequate; at toe, none	At toe; installation
Time series, in storms	Adequate	Improved reliability
Stochastic	Adequate	Improved reliability
Heights	Adequate; at toe, none	At toe; installation
Directions	Inadequate	Better resolution
Pore pressures, core and foundation in storms	Sensors, Adequate	Durable installation
Velocity in interstices	None	Installation, none
		Development and installation
Rate of overtopping	None	Development
Transmission through reflection, in 3 dimensions	Adequate	Better spatial coverage
	Partial	Development
Runup	None	Development
Air content of breaking waves	None	Development
Ice forces	None	Development
Storm currents, toe	Sensors, Adequate; Installation, none	Installation
Seismic forces	Adequate	Improvement
Structure data		
Cross section, as built	Poor, especially for rubble	Development
Movement of units	Poor	Development
Internal strain	Adequate, outside	Improvement
Floating structures		
Mooring forces	Adequate	
Torsional stresses	Adequate	Improvement
Ice forces	Adequate	Improvement

are required; numerical and physical models need to be developed on the basis of these measurements.

Shock Pressure Implosion

When a wave breaks directly against a rubble slope, or against a concrete wall embedded within it, the shock pressure rapidly penetrates the interstices. These shock pressures are suspected of being involved in rearrangement of the structure and breaking of concrete units. Measurements are needed of the pressure gradients that exist at the peak of such implosions, and of the movement of individual elements of concrete, stone, gravel, and sand as they are jostled by the impacts.

Storm Surge

During the height of a storm, mean sea level may rise considerably as a result of the combined effects of wind setup, reduction in barometric pressure, and tides or seiches. This brings the zone of maximum wave action nearer to the top of the structure, where the structure is often the most vulnerable. There are few reliable measurements available at this time of the structural impact or the structural response, so that models are of questionable value.

Loss of Fine Particles

Under the cyclic action of waves, fine particles in the breakwater may work their way through the gaps in the armor (these channels are called piping), or subarmor, and escape. Progressive piping may then cause cavities within the breakwater and loss of support for materials above, leading to eventual reduction of the crown elevation and allowing detrimental overtopping. At present, there is no technique for detecting and locating internal cavities and piping; such information could affect design and material selection criteria.

Overtopping

If sufficient "green water" crosses the top of the rubble mound, the crests can attack the structure and flood the interstices at the roadway or crown. Both tests and prototype experience show that flows that overtop are more likely to cause damage. In fact, breakwater "roundheads," or ends, are known to be most vulnerable and are often designed with heavier units or flatter slopes, or both. Repeated overtopping is thought by some to be a dominant factor in structural failure. Better measurements of wave/structure interaction are needed.

Armor Decomposition

Wave attack, sun and salt, heat and cold (and perhaps ice), and the impact of smaller stones—and movement of units themselves—all cause gradual deterioration of stone or concrete. The rounded corners of old armor units attest to this effect. As the units become more spherical they become less stable and shift position. Efforts have been made to build scale models with units of softer material, to reproduce this effect, but these efforts have not been wholly satisfactory. A long-term monitoring program of armor decomposition would provide needed information.

Multidirectional Waves

When waves from different directions approach a breakwater, convergence of crests can produce a local breaking wave far larger and steeper than the average conditions. There is a need for more directional wave measurements in the vicinity of breakwaters.

Breakwater Stability

Impact of concentrated wave energy against any structure at the top of a rubble mound can precipitate a loss of slope stability. A rubble-mound slope has been characterized as an incline close to the failure point. For reasons of economy, slopes are often made as steep as is believed to be practical; there is a lower factor of safety common to the design criteria for rubble-mound structures than for steel and stone structures. There is a need for more measurements of rubble-mound breakwater—on prototype and model rubble-mounded structures—in order to improve understanding of stability coefficients.

Summary

Instruments are available to measure many parameters related to interaction between water and structures. Some parameters cannot be measured, largely because the sensors and data links have not been successfully deployed in the harsh environment of a stormy sea. Measurements that are needed but cannot yet be measured adequately on fixed structures are

- the types and directions of breaking waves attacking structures,
- the nature of movement of different structural components during storm conditions,
- pore pressure within the interstices and in the foundation,
- wave transmission and reflection,
- torsional stresses in floating structures,
- scour depths as they progress during storms,
- the air content of water at contact points,
- the velocity of wave crests,
- the amount and nature of overtopping, and
- the amount of wave runup.

The priority research areas are those that will lead to more rational design of coastal structures. This research focuses on measurement of the pressures and forces, not only external but also internal, from storm waves at the instant of breaking on structures, so that the behavior observed can be understood and predicted. To undertake much of this research it will be necessary to develop installation methods for mounting instrumentation on or in structures and to recover the data.

4

Modeling Coastal Systems

Modeling coastal processes can be a subject worthy of extensive discussion, and it is certainly a topic of rapidly growing interest—for both researchers and engineers. This chapter, however, addresses only the relation between modeling and coastal measurement and is therefore limited in scope.

Mathematical models are useful, if not indispensable, tools in the analysis, synthesis, and interpretation of field or laboratory measurements in the coastal environment. Models are often a useful tool for identifying significant gaps in data as well as for completing missing data in a data series. A model may be based on purely statistical considerations, on purely physical principles, or both, and generally involves a finite number of parameters whose values must either be stipulated or inferred from the measurements. Models used in the analysis of data are usually, but not exclusively, diagnostic models (see the following section), while models used in estimating future changes are usually some form of predictive model. Engineering requirements dictate what one wishes to predict, whether it be changes in beach bathymetry or in hydrodynamic forces on a structure under given design storm conditions. Measurements are clearly indispensable information for verification of models, but at the same time models can be extremely useful in identifying the appropriate type of data that ought to be obtained.

Modeling and measurements should work hand in hand. A model allows one to assess the sensitivity of some result to changes in certain input data. For example, a study of the sensitivity of coastal flooding models was made by Jennings (NRC, 1983). As expected, the parameterization of the storm was the most critical factor. However, a number of other inputs were listed. Among these, doubling the bottom friction factor caused errors of greater than ±3 feet in the scale flood elevation, while increases of 1 foot in all land elevators resulted in peak flood elevation changes of only 0.3 feet.

A model may also indicate that measurements ought to be made at a certain minimal spatial or temporal scale. An example of the latter exists in the Coastal Upwelling Experiment (CUE), sponsored by NSF during the mid-1970s, which involved field measurements of currents and water density along the continental slope region of Oregon and Northern California. The initial data were taken at rather coarse spatial resolution, with no unusual results. Numerical model experiments by Wang and Mooers (1976) predicted that a narrow subsurface jet flowing counter to the surface currents could exist. Subsequent field measurements at much closer spacing disclosed that a subsurface narrow countercurrent jet indeed existed. The lesson to be learned is that data gatherers and modelers must coordinate their efforts to achieve the most meaningful results. If some natural scales in space and/or time exist related to the physical phenomena under study, then sampling must take such scales into account to avoid biasing or misinterpreting the measurements.

When one makes measurements, either in the laboratory or in the field, the strategy is nearly always based on some preconceived notion of a process (i.e., a model), whether it be purely conceptual or highly quantitative. Physical models as discussed in the following section should be understood to be quantitative mathematical relationships among several variables and involving one or more parameters that characterize some physical, chemical, or biological process. In contrast, laboratory physical models are scaled-down versions of a prototype system in which one employs some scaling considerations. Both field measurements and laboratory measurements are essential means of verifying, based on physical principles, a mathematical model or of providing the essential parameters that are not known a priori.

In this section a general discussion is given of the relevance of models to the requirements for making or improving coastal measurements. This is done in the context of recognized limitations that exist in both models and measurements. Mathematical models require input data to drive them, and their predictions relate, with varying degrees of sensitivity, to such input data. Information about model sensitivity can be useful in determining the accuracy or resolution needs for basic measurements. By making models an integral part of the measurement system, the strengths of measurements and of models can offset the limitations of each. Mathematical models are limited in accuracy by:

- the completeness and accuracy of rendition of the physical processes that are included in the model,
- the accuracy and resolution of the required data (e.g., initial conditions, forcing data, morphological data, physical parameters), and
- the spatial and temporal resolution of the model.

Field and laboratory measurements are limited by:

- the accuracy of sensing devices and recording systems,
- the accuracy of location of sensors,
- the influence of the presence of some instruments on the process they are intended to measure,
- the spatial and temporal resolution of the measurements, and
- the completeness of the measurements in terms of the physical process being studied (i.e., have all the pertinent variables been observed to characterize and interpret the process adequately?).

The second limitation listed under "mathematical models" is very dependent on the measurements. The third limitation is primarily related to the first. A model can usually be made to a finer grid scale than the measurements and can sometimes indicate where measurement locations are most effective. Where the model grid size is a concern is in the ability of the model to deal properly with physical processes that are important at scales too small for this grid size. Such subgrid scale processes must be represented in some ad hoc manner in the model. The classical example is the effect of those turbulent processes that are too small in scale for the adopted average grid scale of the model. One must always adopt some form of closure hypothesis for the subgrid-scale turbulent stresses and mixing processes. The adequacy of the ad hoc closure hypothesis must rely on comparison of model results with measurements from specially designed experiments. This is where laboratory-scale physical modeling methodology is of paramount importance.

The real strength of the measurements, aside from inherent observational errors and limited ability to handle small-scale features, lies in the simple fact that the measurements contain all of the physics. The strength of the model, when properly tuned, is that it can be used as a diagnostic tool to help interpret the discrete measurements. This is particularly true of dynamic systems with many variables. For example, not only does the model provide a rational interpolator, it also provides the means to compute quantities usually not measured directly, like stresses, transport rates, energy fluxes, and energy density.

PHYSICAL MODELS

Physical models, including hydraulic models, are generally used when flow conditions of a prototype system are not amenable to mathematical analysis. The inability to mathematically model a prototype system may be due to (1) the nonlinear character of the equations of motion, (2) an inability to characterize turbulence or dissipation, (3) complex geometries or interconnected flow passages, or (4) hydraulic elements that are not susceptible to physical description. Physical models are applied for prediction of prototype behavior or for studying details of a system that are not easily observed in nature.

Two major problems encountered in physical modeling are (1) maintaining equivalence between model and prototype and (2) making proper interpretation of model data. These two problems are inherently linked because both geometric and dynamic similarity must be achieved before model data can be considered quantitatively valid. Obtaining geometric similarity (all dimensions scaled proportionally) does not guarantee dynamic similarity. Therefore, the assumption that a physical model that looks like a small-scale version of the prototype does in fact respond in a dynamically correct sense is unsound. In many cases, scaling one of the dimensions (say the vertical dimension) differently from the others will actually improve the model's performance.

An additional problem in physical modeling is the limited representation of the forcing function. In many cases, the directional spread of waves is omitted or no wind is included.

Once similarity is established in a model, the model must then be calibrated. Calibration is the procedure of adjusting model parameters until the model can satisfactorily reproduce measured prototype behavior. Model calibration is, therefore, directly dependent on the type and quality of measured prototype field data. Furthermore, model verification requires a suitable quantity and range of prototype data so that the model can be checked against data not used for calibration.

Initial construction of a physical model to achieve geometric similarity is highly dependent on the density and resolution of bathymetric data available. Usually physical models are constructed with horizontal dimensions constrained by the space available for the model. In an undistorted model, this constraint usually results in small model depths, especially at the coast and in harbors. Unless the bathymetric data from the prototype had a high vertical resolution, calibration of the model may be impossible. If a distorted model is constructed where vertical exaggeration is imposed with respect to prototype dimensions, the necessary resolution of prototype bathymetry may be relaxed somewhat. However, the lack of rapid high-resolution bathymetric measurement systems usually results in physical models being poorly calibrated—or, if calibrated, they are seldom verified owing to the low number of detailed surveys.

Calibration and verification of similarity between model and prototype requires detailed field measurements of the spatial and temporal distribution and variability of velocity fields. Present technology such as acoustic-Doppler current meters may be able to acquire the necessary prototype data at a point, but large numbers of these sensors are required to verify model similarity.

In most models pressure and average velocity are in similitude (Froude similitude). The problem is in achieving similitude of forced turbulence and boundary layers, which affect quantification of sediment transport; at present, providing similitude of suspension is not possible. Lacking the ability to use similitude models, the sediment transport must be empirically estimated though calibration of the model by comparison with observed full-scale results in nature that are obtained through improved field measurement systems.

MATHEMATICAL MODELS

Long-Period Waves and Currents

With the possible exception of tsunamis, all models of waves having periods in excess of five minutes neglect effects of vertical acceleration of the fluid, although allowing for slow rise or fall of water level. The Coriolis force associated with the earth's rotation is also important for periods greater than a few hours. Tides and storm surges differ primarily in the nature of the forcing; both are adequately modeled using the averaged-over-depth equations of motion with appropriate incorporation of bottom stress. Some models of tides or storm surges allow for vertical variation of velocity in a parametric manner; others are full three-dimensional models.

Models of storm surges and of slowly evolving circulation on the continental shelf or in estuaries demand adequate information on the spatial distribution of wind stress and on barometric pressure versus time in order to drive them. The modeling of hurricane-induced storm surges generally employs an auxiliary storm model for the inclusion of the wind stress and pressure fields associated with such storms (NRC, 1983). The main difference between the storm surge and wind-driven circulation models is that the latter generally allows for effects of water density stratification. For shelf waters or estuaries with both horizontal and vertical variations of density, proper rendition of currents demands a full three-dimensional model in which density, as well as the current structure, are dependent variables.

Aside from the foregoing differences in physics, the various models of low-frequency hydrodynamics differ mainly in domain (area of effective coverage), resolution, optimization, and numerical implementation. With the exception of global tide models and ocean-scale circulation models (excluded from consideration here), the model domain is generally of limited area with open lateral boundaries, at which appropriate forcing and/or radiation of energy can be allowed. One of the troublesome aspects of model domains with open boundaries is in making sure the boundary conditions employed at the open boundaries are compatible with physical processes being simulated within the interior of the model domain.

The state of the art in modeling of tides and storm surges for limited domains is generally adequate. The needs are primarily in the adequacy of data for verification and in fine tuning of such models. Some deficiencies of course do exist; these were alluded to in Chapter 3 in connection with storm surges. One is the need for proper modeling of wave setup with attendant need for data to verify this component of water-level anomaly. Another is the need to properly address the coupling of short- and long-wave dynamics (wave/current interaction), which is important in nearshore circulation and in the quantification of bottom stress.

Modeling of circulation at estuarine or shelf scale is still a developing field of research. Here the requirement for adequate measurements of currents in three dimensions, for verification and tuning of such models, is vastly more demanding on available resources. The problem is compounded by joint forcing due to winds, tide/current interaction, and effects of density stratification as controlled by river input and seaward boundary conditions.

Of all the phenomena that fall in the low-frequency category, tsunamis are unique in the sense that the forcing is unknown for most events. While the epicenter of a given event is known, the spatial configuration and amplitude of the ground motion at the seabed is generally not known. The modeling techniques are fairly well advanced, including allowance for weak dispersion effects that are important in long-range propagation from the source to distant coastlines. In principle, one could use measured response at tide stations to "back out" what the unknown source characteristics are; this is similar to what geophysicists do in estimating the structure of the earth's interior from seismic data. Such inverse methods for recovery of cause from effect demand receiver data that have minimal contamination by local effects. Unfortunately, nearly all tide station data (with the exception of benthic pressure gauges) are heavily contaminated (distorted) by local resonant effects that render inverse methods virtually meaningless because the available models cannot be that site-specific.

Table 4-1 summarizes the types and objectives of models pertinent to low-frequency motions, the existing techniques, needs, and example references.

Waves and Wave-Induced Flows

Estimation of nearshore waves is the design information most often needed for addressing coastal engineering problems. Waves are a primary consideration for measuring design forces on ocean structures; waves are also the most important agent for littoral sediment transport and are responsible for driving the currents in the nearshore. The primary requirement for accurate prediction of littoral transport and nearshore currents is high-resolution directional wave information. Adequate input is obtained by directly measuring radiation stress in shallow areas using a slope array.

The drawback of this approach is that its measurement location is site-specific, making it costly to obtain information over a

TABLE 4-1 Modeling of Low-Frequency Motions

Model Type	Objectives	Technique	Needs	References
Storm force	Wind and pressure	Empirical,		Graham and Nunn, 1959; Schwerdt et al., 1979.
		Parametric	2, 3	Forristall, 1980.
	Drag coefficient	Empirical,		Garratt, 1977.
		Parametric	8	Huang et al., 1986; Reid and Whitaker, 1976; Wu, 1985.
Storm surge	Water level	Numeric 2-D	2, 4	Butler, 1980; Jelesnianski, 1972.
	Current profile	Parametric,	3, 7	Butler, 1980; Forristall, 1974, 1980; Forristall et al., 1977.
		Numeric 3-D	7	Heaps, 1974; Leendertse and Liu, 1975; Sheng, 1983.
	Inundation	Numeric 2-D	1, 6, 7	Butler, 1980; Jelesnianski and Chen, 1981.
Tide	Water level and volume flux	Numeric 2-D	2, 4	Butler, 1980; Leendertse, 1984.
	Current profile	Numeric 3-D	3, 7	Heaps, 1974; Leendertse and Liu, 1975; Sheng, 1983.
	Global model	Numeric 2-D	2	Hendershott, 1977; Schwiderski, 1980.
Tsunami	Water level	Analytic	8	Many
	Generation	Numeric	1, 6, 7	(2-D), Hwang and Divoky, 1972. (3-D), Mader, 1984.
	Propagation	2-D	2	Hwang and Divoky, 1972; Kim et al., 1987.
	Local response	2-D	2, 7	Houston, 1978; Vastano and Reid, 1970.
	Source energy	Inferential	1, 6, 7	Van Dorn, 1984.
Wave/current interaction	Wave-induced currents	Numeric	1,2,6,7	Vermulakonda et al., 1985; Wu et al., 1985.
	Bottom stress	Analytic	3, 6, 7	Grant and Madsen, 1979.
	Wave setup	Empirical	1, 6, 7	CERC, 1984.
Estuarine circulation	Currents	Numeric 2-D	2, 6, 7	Butler, 1980.
		Numeric 3-D	2, 6, 7	Blumberg, 1975; Leendertse and Liu, 1975; Sheng, 1982.
Shelf circulation density	Currents and	Numeric 2-D	2, 6, 7	Brink and Chapman, 1985; Brink et al., 1987.
		Numeric 3-D	2, 6, 7	Leendertse and Liu, 1975; Liu and Leendertse, 1987.

LEGEND:

Need:

1 Major development needed
2 Improve information detail
3 Improve physics
4 Improve efficiency
5 Improve tuning
6 Special data needed
7 Verification needed
8 None

large section of shoreline. As pointed out in Chapter 3, an alternative approach is to measure or hindcast waves in deep water and to refract the wave information to shallow-water locations. This approach requires highly accurate deep-water wave directional information (which we are not presently capable of measuring or hind-casting) and refraction of the waves to shallow waters using models that have not been adequately verified. Another approach is to use inverse techniques of refracting a number of shallow-water wave measurements (not necessarily with high directional resolution) back out to deep water to determine the deep-water wave directional spectrum. The distributed shallow-water wave sensors act as a wave antenna. The completeness of directional information in deep water increases with the number of shallow-water wave locations. Again, the inverse technique requires an accurate refraction model. Therefore, to predict nearshore waves and wave-driven currents, models are required for wave forecasting and wave refraction and diffraction and for nearshore dynamical models, as described in the following discussion.

There has been considerable renewed interest in wave forecasting in the last decade. This interest primarily stems from the requirement for improved forecasting for offshore oil facilities. Wind/wave prediction was recently reviewed by Sobey (1986) and an intercomparison of various models was accomplished by the Sea Wave Modeling Project (SWAMP) (Sea Wave Modeling Project Group, 1985).

Wave-forecasting models can be divided into three categories: (1) the older empirical approach (based on dimensional analysis), (2) the modern numerical discrete spectra, and (3) parametric approaches (both based on the radiative transfer equation). The numerical models can be further categorized in terms of how the nonlinear wave/wave interactions are treated. The first-generation numberical models, evolved in the early 1960s, decouple the wind/sea generation and propagation of the directional wave spectrum. They do not redistribute energy nonlinearly within the spectrum. These models are still in use today for global wave prediction (e.g., the U.S. Navy) because of computational efficiency.

Extensive field measurement of wave growth under carefully selected uniform fetch-limited wave conditions became available in the late 1960s and early 1970s (Mitsuyasu, 1969; Hasselman et al., 1973). The analysis of these data showed the importance of the nonlinear wave/wave interaction to feed energy into the low-frequency end of the spectrum, rather than direct wind forcing. The second generation models evolved to include the nonlinear coupling. The newer generation models either parametrically redistribute the wind/sea spectral energy and use a discrete spectral representation for swell components or use a discrete representation for both the swell and wind/sea. The models were tested for various wind conditions by SWAMP (1985). It was concluded that the first- and second-generation models gave significantly different answers in the development of the wind/sea variances for fetch and duration cases and in the shape of the spectrum. Deficiencies existed in establishing the nonlinear energy transfer parameters that largely control the shape and the growth of the wind/sea spectrum. The deficiencies were particularly evident for extreme conditions of rapidly changing winds. Under these conditions, the present parameterization contained insufficient information to describe the wide variety of spectral distributions that arose (SWAMP, 1985).

A group of international scientists formed the Wave Model Development and Implementation Group (WAMDI) in response to the SWAMP recommendations. A third-generation model resulted that integrates the basic transport equation describing the evolution of the two-dimensional ocean wave spectrum without additional ad hoc assumptions regarding the spectral shape. The source functions describing the wind input, nonlinear transfer, and white-capping dissipation are prescribed explicitly. The only tuning was two parameters in the dissipation functions set to reproduce the observed fetch-limited growth of the fully devolved Pierson-Moskowitz spectrum (a spectrum widely employed in deep-water wave analysis). Improved agreement over the earlier models was obtained comparing the model output to a variety of North Atlantic and North Sea storms and Gulf of Mexico hurricanes (WAMDI, 1988).

Shallow-water wave modeling has not received the same attention as deep-water forecasts but appears to give comparable results. The greatest deficiencies appear to be in the transition between deep and shallow water, where generation and refractive effects on the propagation and wave damping are important. A spectrum (referred to as the TMA Spectrum) has been developed by Bouws et al. (1985) for this purpose and requires further testing.

Wave Refraction and Diffraction Modeling

As a train of swell waves is propagated into shallow water, the wave speed changes with varying water depth. Along the crest of a wave, the part of the wave in deeper water moves faster than the part in shallower water. As a result, the wave bends to align with the contours, and wave refraction occurs. Refraction and shoaling due to depth are important for determining the distribution of wave energy along a coast. Observations indicate that refraction has significant influence on the erosion and deposition of beach sediments. Wave trains can also be refracted by ocean currents.

The refraction problem has been modeled using several approaches. Based on the theoretical formulation, the four commonly used methods are (1) Snell's law, (2) ray theory, (3) mild-slope elliptic equation, and (4) parabolic equation approximation.

Snell's law modeling employs classical optical refraction principles and generally is applied to simple geometries (straight and parallel bottom contours). Ray theory follows a certain element of the incident wave field (a section of wave crest for regular waves) as it approaches the shore along a "ray," which is its trajectory. This method determines the wave height and direction of wave propagation along the ray in an efficient manner. The drawback in ray models is their inability to incorporate the diffraction process. The ray models may cross and cause locally large (infinite) wave heights which are not realistically attainable. The mild-slope equation is a 2-D approximation to the equation of motion that can be solved for combined refraction and diffraction. The forward parabolic approximation method is a fast wave model limited to forward-propagating waves and does not account for reflection. For steep slopes, an iterative scheme must be used to solve the parabolic equation. Recently, practical alternatives for linear wave propagation problems have been developed and applied to solve the mild-slope equation (Ebersole, 1985; Kirby and Dalrymple, 1983; Liu and Tsay, 1983; Ito and Tanimoto, 1972).

If combined refraction/diffraction is the dominant physical process of wave propagation and wave transformation, the foregoing mathematical models may give adequate results for different engineering purposes. Due to the respective applicability of the models, a series of model verification tests is needed. A practical problem is specifying the grid spacing in the models. The determination of appropriate grid scale for bathymetry in refraction models is unsolved and can be critical to the results.

For simple bathymetries, the wave refraction models have been verified using detailed laboratory data (Whalin, 1972; Tsay and Liu, 1982). On the other hand, there has not been an adequate model verification of wave propagation using field data to date. Given the importance of wave refraction analysis to coastal engineering projects, this is a major deficiency.

Breaking Waves

Dynamical wave forcing occurs when there is a change in momentum, which is primarily due to wave breaking. Wave breaking is identified by foam and overturning of the wave face. Nearshore breaking is a transient process associated with shoaling of the waves that results in a steepening and eventual instability of the wave. Breaking waves are a principal mechanism for the redistribution of mass and momentum over both the vertical and the horizontal. The kinematics and dynamics of breaking waves are highly complex and are only crudely modeled. The exact criteria for the onset of breaking are not understood. Kinematic instability occurs when the water particle velocities near the crest exceed the speed of the crest and the wave is observed to break. The influence of infragravity wave velocities and wave reflection on wave breaking is unknown. Wave breaking is one of the least understood phenomena (Thornton and Guza, 1986) and is critical to the various dynamical models and wave-force problem. While substantial progress has been made in understanding the mechanisms that cause breaking in deep water (Tanaka, 1985; Longuet-Higgins, 1984, 1985), the theoretical basis for analysis of shallow-water breaking is not well understood. Wave-breaking processes need to be studied both in the field and laboratory, and theoretically. In particular, understanding of the processes has been slowed by the lack of quantitative measurements, particularly in the field.

Wave-Induced Nearshore Currents

Under the action of waves, nearshore currents, including longshore currents, mass transport, undertow, and rip currents, are formed. These currents are responsible for the direction and magnitude of the net coastal sediment transport. As waves refract and shoal and eventually break, there is a change in wave-induced momentum that must be balanced by a slope in the mean water level or an increase in the bottom shear stress and concomitant nearshore currents. The wave-induced momentum is commonly referred to as radiation stress (Longuet-Higgins and Stewart, 1962); recent advances in nearshore dynamics are based on this concept. Analytic solutions for longshore current (Bowen, 1969; Thornton, 1970; Longuet-Higgins, 1970) have established that the driving force for the longshore current is a component of the radiation stress tensor, S_{xy}. On the other hand, rip currents can be produced by longshore variation in wave setup (owing to variable wave height and resulting normal radiation stress terms). These earlier nearshore current models were for monochromatic incident waves over simple topographies.

The nearshore environment is complex. Waves are random and the beach topography is three-dimensional; a numerical model is necessary for predicting two-dimensional or three-dimensional nearshore dynamics. Using a finite difference scheme, Noda (1974) and others developed steady linear nearshore current models. Including the nonlinear inertial terms and the turbulent mixing terms, successful modeling results were obtained (Ebersole and Dalrymple, 1979; Wu and Liu, 1985). The latter model was verified with field data (Wu et al., 1985) for waves with a narrow spectrum on a beach with nearly parallel bottom contours. A random wave description using a probabilistic wave height distribution was used in a longshore current model by Thornton and Guza (1986), which agreed well with field measurements. All these modeling and experimental results are for the two-dimensional case, and the secondary currents, due to the vertical nonuniformity of the wave-induced velocities as observed in the surf zone and near breaking, are not considered. Due to imbalances in the momentum fluxes in the vertical and nonuniform flow, a strong seaward flow (undertow) is generated above the bottom boundary layer. This undertow appears to exist between the shoreline and the breaker line.

In a recent study on the interaction of the undertow and the boundary layer flow, Svendsen et al. (1987) proposed a two-layer model in a surf zone. It was found that field measurements were needed to supply information about the breaker heights and the empirical parameters for the solution. It appears that further progress depends on measurements to obtain a better understanding of the vertical structure of waves and turbulence.

Infragravity Waves

As waves traverse the surf zone, the frequency of the peak shifts to lower frequency. As the sea-swell waves dissipate due to breaking, the low-frequency infragravity waves (see Figure 3-1) are amplified.

The infragravity waves are identified as either reflected long waves (surf beat) or edge waves propagating alongshore. The infragravity waves are omnipresent. They have been shown to be important for nearshore processes because of potentially large velocities in the swash area (Guza and Thornton, 1982) and have been hypothesized as the cause of morphological changes alongshore and of cross-shore bars (e.g., Carter et al., 1973; Holman and Bowen, 1982).

Generation mechanisms proposed could be the result of preferential forcing offshore by nonlinear wave/wave interaction (Gallagher, 1971), surf-beat forcing (Longuet-Higgins and Stewart, 1962), generation by time-varying break-point (Symonds et al., 1982), or through resonant tuning by the bar from a broad-spectrum offshore forcing (Symonds and Bowen, 1984). Existing models for infragravity wave generation in the surf zone are not well verified and need to be developed to incorporate better physics for infragravity wave dissipation. The interaction of sea-swell waves with infragravity waves in the nearshore needs to be investigated. Although some generation mechanisms have been proposed and utilized in initial models, the level of understanding is not well developed and field measurements are required for model development and verification. Measurement of longshore variation in setup, radiation stress, and related morphology is necessary for further development of these models.

Swash Zone

A highly dynamic area is the swash zone, the area where the water edge runs up and down the beach face. Here the amplitude of the infragravity waves is at a maximum, the waves finally dissipate, and the bottom is highly variable due to the energetics of the fluid motion. To model the swash properly, the moving edge of the water surface running up and down a sloping bottom needs to be included. Permeability, the internal pressure, and the flow field within the sandy bottom of the swash zone influence the swash dynamics and are important to the sediment movement.

Sediment Transport

Mathematical modeling of sediment transport has progressed significantly over the past decade, but basic theoretical and modeling questions still remain. Predictive mathematical models for sediment transport are in routine operational use; however, lack of verification over a broad range of conditions makes their predictions questionable. Coastal engineers need improved models of nearshore sediment transport to perform engineering tasks effectively and to bring this aspect of their discipline up to the level attained by our understanding of other processes (surface gravity waves, infragravity waves).

Major field experiments have been directed at improvement of our knowledge of sediment transport (NSTS*, C^2S^2**, for instance), yet we still are not able to predict this transport with sufficient accuracy to meet many engineering needs. This difficulty arises from the interaction of the driving forces (waves, currents) with the sediment that they are moving. Once the sediment moves and achieves a new form (profile, roughness), this affects the driving forces, changing their characteristics and thus changing the equilibrium form of the sediment. This feedback makes modeling difficult. Further complications arise because of the nonlinear terms in the sediment and fluid flow equations. For instance, in shallow water, bottom friction plays an important role in the momentum balance. The form of the bottom friction term is nonlinear; that is, friction is not linearly related to velocity. In addition to velocity, bottom friction is related to the grain size of the bed, to the roughness of the bed, to the interaction of steady or quasi-steady currents with waves, and to their relative directions. Although models have been developed to account for some of these nonlinear effects (e.g., Smith, 1977; Grant and Madsen, 1979, 1982), these models assume the nonlinear interaction of a linear wave and a current. In shallow water, waves themselves become nonlinear, creating a nonlinear interaction between a nonlinear wave and a current. No adequate models for these effects have yet been developed. In summary, the prediction of sediment transport in shallow water is complicated by

- interaction of the sediment with the driving forces,
- the mobility of the bed (it is not stationary),
- the nonlinear character of waves in shallow water,
- lack of understanding of turbulent momentum balances in shallow water, and
- lack of incorporation of cohesion or biological binding effects.

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* National Sediment Transport Study.
** Canadian Coastal Sediment Study.

In spite of these limitations, progress has been made in modeling sediment transport in the nearshore zone. Some of these models are described below.

Sediment Entrainment

Sediment resting on the bed must be entrained by the fluid before being transported. The entrainment potential can be represented as a critical shear stress at the bed required before the sediment leaves the bed. Alternatively, this entrainment quantity can be nondimensionalized as a critical criterion for the threshold of initiating transport. The threshold function depends on grain size, grain size distribution (whether unimodal or multimodal), biological activity (organisms can be either stabilizing or destabilizing), and cohesion (both mineralogical and other chemical effects).

Previous work on sediment entrainment has been mostly empirical (e.g., Madsen and Grant, 1976; Komar and Miller, 1975, 1973; and Inman et al., 1976). The latter investigators all assumed sediment of uniform grain size, although some discussion of mixtures of grain sizes has been included in the literature (e.g., Kamphuis, 1975; Madsen and Grant, 1975, 1976). Little comprehensive treatment of nonuniform grain sizes has been available for oscillatory flows. Finally, some recent work has expanded on the role of biological effects and cohesion on sediment entrainment (Jumars and Nowell, 1984; Nowell et al., 1981).

Near-Bed Sediment Transport

Near-bed (or bed-load) transport occurs near the bottom and incorporates as a dynamically important element grain-to-grain contact and collisions for its sustenance. Since the precise definition of *bed*-load transport has been debated, we refer instead to *near*-bed transport where grain-to-grain interactions are important dynamically. Available models for near-bed transport take many forms. Although it is not possible to review all models of transport, some are summarized briefly here. These models all suffer from lack of inclusion of adequate physics of near-bed turbulence, the interaction of waves and currents, and field verification. Major steps forward in this modeling require improved understanding of momentum exchanges within the thin (order of 10 cm) wave boundary layer (the layer closest to the bottom, which is stationary at the bed and moving at approximately the wave-driven flow at the top).

Near-bed transport equations come in many different forms. Near-bed transport integrated in the cross-shore direction is exemplified by the commonly used equations to predict total longshore sediment transport under wave-induced currents. Here, quasi-empirical and often dimensionally incorrect equations are derived to represent the integrated transport across the surf zone. The most commonly used of these is the CERC longshore transport equation (COE, 1984), as well as those of Komar and Inman (1971) and others. These integrated forms rely heavily on field observations to set one or more coefficients. In practice, the U.S. Army Corps Districts modify these coefficients, which are intended to be universal, to match some subjective input, such as position of a nodal point in longshore transport or total transport trapped in a tidal inlet.

A second popular approach to sediment transport has been the energetics approach (Bagnold, 1963; Inman and Bagnold, 1963; Bailard, 1981). These models assume that a fraction of the dissipated wave energy is available to move sediment. By setting the fraction of dissipated energy involved in sediment transport, one can calculate the total transport. As shown by Aubrey (1978) and others, incorporation of a nonlinear wave or a steady current can result in net sediment transport (instead of just oscillatory, zero-net transport under a linear wave).

A third type of approach to sediment transport has been to relate various sediment parameters to the driving forces, using empirical relationships. Popular are those relating transport rate to the threshold parameter (Meyer-Peter and Muller, 1948; Ackers and White, 1973). These methods have been tested in a variety of field settings, against themselves and against other transport formulations. Although the authors commonly reach conclusions about the advantages of one particular method, field data generally are inadequate to draw true conclusions. CERC uses the Ackers and White formulation for much of their sediment transport calculations (e.g., Vermulakonda et al., 1985), in spite of lack of good field or laboratory evidence supporting its use in oscillatory flow.

A fourth method used to calculate near-bed transport is the probabilistic method derived by Brown (1950) and Einstein (1972) for steady flows. Madsen and Grant (1976) expanded this work to include oscillatory flow. Although just as well tested perhaps as other methods, few models use the probabilistic approach of Einstein and Brown.

Suspended Sediment Transport

The debate about the relative importance of near-bed versus suspended-load transport in the nearshore zone continues unabated. Field data are only now beginning to quantify the importance of suspended-load transport, although lack of concurrent measurements of near-bed transport make it difficult to examine relative quantities of near-bed versus suspended load. As with all sediment-transport models, various approaches have been applied to examine suspended-load transport. The basic concept behind much of the modeling is that fluid turbulence is required to keep sediment in suspension; the primary force acting to remove sediment from suspension is gravity. Whereas in near-bed transport grain-to-grain interactions are important, for suspended load, fluid/grain interactions predominate. Models differ in how they represent mathematically the turbulence or maintenance forces.

A heuristic model of suspended-load transport was derived by Dean (1973) to examine suspended sediments in the surf zone. More complicated models involving turbulence explicitly have been proposed by a large number of investigators (Beach and Sternberg, 1988; Grant and Madsen, 1979; Glenn, 1983; Smith, 1977; Soulsby, 1988). These models use eddy diffusion to represent the turbulence that maintains the sediment in suspension. More complicated models incorporate different representations of turbulence. Prime among these are the so-called higher-order closure models, where turbulence production is calculated (e.g., Mellor and Yamada, 1974; Adams and Weatherly, 1981; Sheng, 1982). Computational complexity increases with the higher order closure models. So far, too little data have been collected to evaluate these models adequately, particularly for shallow-water, nonlinear wave conditions. Most application and evaluation has taken place on midcontinental shelf areas or in estuaries.

Another common method for modeling suspended-sediment transport is based on observations. Some representation of the driving force is related empirically to observed sediment concentrations. These measurements are always time-integrated, because of the difficulty some researchers have in sampling rapidly enough. Examples of these methods include Inman et al. (1980) and Kraus et al. (1988).

Beach Morphology

Prediction of the morphology of a beach under given conditions, and of changes in that morphology as driving forces change, has been a major activity of nearshore researchers because of its importance to coastal engineering. For designing structures in the nearshore, evaluating potential for amphibious landings, or designing beach restoration projects, the behavior of the beach profile is critical. This long history of interest has resulted in a variety of approaches to profile prediction, some of which are well-tested under limited conditions.

The initial work on beach morphology was empirical (Bascom, 1951; Aubrey, 1978, 1979; Birkemeier, 1985), relating changes in profiles to some aspect of the driving force. Wright et al. (1985) describes the changes in the general shape of a beach in response to the driving force. Closely related to this empirical modeling is inferential modeling, where hydrodynamic patterns are related loosely to possible profile configurations. An example of inferential modeling is an article by Holman and Bowen (1982) that relates theoretical interference patterns of surface gravity and infragravity waves to possible shoreline configurations.

Energetics models of beach configuration have been developed based on the initial work of Bagnold and coworkers (Bagnold, 1963; Inman and Bagnold, 1963). These later models (e.g., Aubrey, 1978; Bowen, 1980; Bailard, 1981) relate the equilibrium slope to a potential transport of sediment related to the driving forces by an energetics argument

Other models of beach planform change have incorporated a variety of assumptions. Early analytical models were derived by Pelnard-Considere (1956) and later discussed for more general situations by Larson et al. (1987). Dean (1977) has derived a model that has been expanded (Perlin and Dean, 1983) to enable prediction of shoreline changes out to various depths, based on an equilibrium profile concept. Swart (1974, 1977) has derived extensive models for profile response under varying wave conditions based on observations in the North Sea. CERC recently has implemented its own shoreline response model based on a number of these previous studies (e.g., Perlin and Dean, 1983). Sunamura and Horikawa (1974), Watanabe (1982), Kraus and Harikai (1983), and Nishimura and Sunamura (1987) propose different models of beach morphology change.

Bed Forms

Bed forms are responsible for much of the transport of sediment in the inner continental shelf-nearshore zone, and as such might be incorporated in the earlier section on near-bed transport. However, bed forms are important contributors to the momentum balance of nearshore circulation, so they deserve an independent mention. Bed forms are the response of a deformable sand bed to hydrodynamic shear stresses applied at the surface of that bed. Rarely is a bed perfectly flat; instead it will have some scale of structure superimposed on it. Prediction of these bed forms, and how they respond to different wave and current forcing, is essential for predicting circulation and sediment transport in the nearshore zone.

Bed-form prediction schemes are largely empirical in nature and have addressed both steady and oscillatory flows. Early work includes that of Southard (1971), Clifton (1976), Komar (1974), and Rubin and McCulloch (1979). Later work used a threshold-of-transport representation to examine stable conditions for the existence of bed forms. Included in this work is that of and Miller and Komar (1980), Greenwood and Sherman (1984), and Dingler and Inman (1976). Finally, dimensional analysis has been applied to bed-form prediction to obtain stability criteria. Included in this aspect is work by Dingler and Inman (1976) and Yalin (1977), among others. Dynamical models for bed forms are sorely lacking. Existing bed-form models are useful for limited scales of bed forms (ripples, dunes, and sand waves). Some of the largest-scale bed forms are poorly predicted (large sand waves or sandbanks, submarine bars), leaving a large gap in the ability of coastal engineers to make accurate calculations in certain environments.

Bed-form prediction ability also is weak in combined steady and oscillatory flows. The effects of combined waves and currents of various relative magnitudes and directions on bed forms have yet to be modeled theoretically or observed adequately in the field.

MODELING FORCES ON STRUCTURES

The state of the art in modeling of wave forces on offshore commercial platforms is a highly developed technology. A review of the literature with respect to wave forces on fixed tubular members and submerged tanks of dimensions comparable to the wave length is given by Dean and Dalrymple (1984). Both deterministic and stochastic spectral methodologies exist for estimation of wave loading. The newer technology addresses nonlinear coupled models of wave/structure interaction for compliant structures in deep water and floating tethered structures (e.g., Crandall, 1985; Jeffreys and Patel, 1982; Basu, 1983; Niedzwecki and Sandt, 1986).

In striking contrast, the design of breakwaters, jetties, and groins is based largely on highly empirical methods and past experience (CERC, 1984). The internal fluid/solid and solid/solid dynamic stresses created by large waves striking and possibly overtopping such structures is poorly understood. At present there is no capability for measuring and modeling the internal dynamics of rubble-mound structures.

5

Data

Any measurement program produces data. However, several important aspects of collection are necessary to make such data useful. These include calibration and standards, quality control, data processing, analysis, and archiving. In some cases there are quite formal programs for these procedures—for example, routine weather observations and ocean hydrographic data. These data, in most cases, are handled in a prescribed manner from the time they are collected until they are archived. The sensors must meet some established calibration and standard; quality control procedures are specified; the data are transmitted to the operational centers in a prescribed format, and finally they are archived in a specific way. Those who need the information can usually obtain it in a standard format. This is not the case for coastal engineering data.

The data requirements for coastal engineering research and design efforts are diverse. A partial list of quantities of interest is shown in Table 5-1.

A variety of sensors and instrumentation is required to make these measurements. Some are relatively standardized, such as a tide gauge, for which there are formal calibration procedures and standards, and the data are handed to the archiving center in a prescribed way. However, for other measurements, there are a variety of competing sensors and virtually no calibration or standards; quality control is highly variable. In many cases, the data are collected and analyzed by an investigator or agency and the only place the data may be seen, before they are archived in a file cabinet, is in a publication. This lack of standards for archived data has an impact on the usefulness and validity of coastal engineering data, which are typically expensive to obtain.

TABLE 5-1 Quantities of Interest in Coastal Engineering

Measurement	Units
Deep-water wave height and direction	m, degrees
Shallow-water wave height and direction	m, degrees
Current speed and direction	cm/sec, degrees
Bottom friction	dynes/cm^2
Wave forces	dynes
Beach profiles	m
Suspended sediments	gm/cm^3
Sediment transport	gm/sec
Bed-load transport	gm/sec
Sea level	m
Wind speed and direction	m/sec, degrees
Water temperature and salinity	T°C, S ppt
Breaker zone and type	no units

QUALITY CONTROL

Quality control is fundamental to good science and engineering. Poor data can lead to wrong conclusions and bad designs. If the data are to be used in a model simulation, poor quality data may lead to bad model output. However, quality control is particularly difficult with some of the measurements needed by coastal engineers. First, there may be no accepted calibration procedures or standards. In many cases, the instrument is a one-of-a-kind creation; in other cases, there are no calibration facilities where the conditions of the coastal zone can be simulated. For example, it is well established that impeller current meters provide different readings in oscillating flows than in steady flows. In a wave field such as the surf zone, impeller current meters would not be a good choice for measuring currents. However, even if a suitable impeller meter were found, it would be difficult to establish calibration standards and facilities. Even the electromagnetic current meter, which is commonly used for nearshore measurements in wave fields for many applications, is only calibrated routinely for zero velocity by placing it in a container of still water.

All observations contain errors. These can usually be attributed to one or more of several factors, e.g., sensor response or calibration, telemetry, recording, processing, or archiving. For a discussion of quality control, the data can be divided into two categories, (1) operational data and (2) research data.

Operational data are collected on a routine and continuing basis by engineers to meet their requirements. Examples are winds, waves, and water level at a particular location to support the design requirements for a structure. These data are normally collected with standard off-the-shelf instrumentation that has been designed specifically for that application, such as cup anemometers, pressure wave gauges, and float tide gauges. The operating principles, calibration, standards, and data from these instruments are quite well understood. Government agencies use these instruments routinely to meet their responsibility for environmental monitoring.

Research data, on the other hand, are collected on a very different basis. In this case, the instruments are frequently one-of-a-kind, or, at most, a small production run designed for a special purpose. A hypothetical example would be an instrument designed to measure the boundary friction at a particular site for a short period of time. Normally, only the investigator who owns, and may have built, the instrument is experienced in its use.

No widely accepted standards or calibration facilities exist for such instruments, and the data are frequently unique and require special processing and archiving. These data are generally considered to belong to the investigator who collected the data until such time as the results of the investigation are published.

Quite different quality control is exercised on these two classes of data. For operational data, there are standardized procedures from the time the data are collected until they are archived. For research data there may be no standard quality control procedure and the data may never be formally archived.

The committee has concluded that there is an urgent need to introduce quality control in coastal engineering measurements, but how this can be accomplished is not clear.

Capabilities for Quality Control

Quality control requires good instrumentation, careful calibration of all components of the system from sensor to recorder, careful data handling, and finally, archiving. Quality control is a procedure that is exercised at each step along the way to include experimental design, sensor selection, sensor calibration, telemetry, recording, processing, and archiving.

The evolution of digital electronics, sensor technology, telemetry, and recording systems has enhanced our capability to exercise quality control, in some cases in a highly automated fashion. At the same time, these and other recent technical advances generate data at a much greater volume, making the quality control problem comparably larger. Unfortunately, in coastal engineering the measurement requirements are so diverse and difficult that formalized quality-control procedures are not prevalent. The ultimate use of much data is as an input to a model. As computer technology has progressed the models have become more and more demanding of data, not only in quality but also in quantity. In many cases model requirements for quality-controlled data cannot be satisfied.

In general, the techniques are available to provide the necessary quality control, but this capability is not being used with respect to coastal engineering data. Part of the reason for this is that the data are often collected by individuals who have only a limited objective in mind for the data. Additionally, the measurement environment is detrimental to instruments, and maintenance is difficult and costly, particularly for long-term measurements. Coastal engineering measurements are often site-specific, and their application to other problems is limited. Finally, the lack of a comprehensive archiving procedure for coastal engineering places no pressure on the investigators to exercise strong quality control measures.

Quality Control Needs

There is a need to establish formal quality control procedures for many coastal engineering measurements. This will require agreement on the measurements, calibration and standards, recording, processing, and data archiving. This has not been done in the past for a variety of reasons. The Corps of Engineers has recently begun to develop procedures for their coastal wave measurement program. However, there are many other types of coastal engineering data for which no quality control procedures have been established.

The following needs are identified:

- Comprehensive data bases are required to solve many coastal engineering problems. They may be comprehensive in that a variety of measurements is collected simultaneously, or in that the measurements are collected over a wide geographical region continuously. There is a need to develop a comprehensive historical quality-controlled data base to support engineering design and modeling.
- There is a need to improve real-time acquisition and quality control of coastal engineering data.
- Quality, quantity, and timeliness of the data entering the data base should be improved.
- Support is needed for development of quality-control procedures and the necessary tools and procedures to deal with coastal engineering data as part of coordinated long-term research planning.
- Calibration standards and methods should be established for as many coastal engineering measurements as possible; wave data should be given first priority.
- Provisions should be made for real-time access to coastal engineering data by a variety of users.
- Procedures should be developed for identifying coastal engineering data appropriate for archiving and for entering new data into the system conveniently. Appropriate quality control must be applied to both of these functions.
- Efforts should be made to acquire good data bases from other countries.

STANDARDS AND CALIBRATION

Standards and calibration are fundamental to scientific data collection. Unfortunately, in the high-energy, shallow-water coastal zone, there are often no suitable standards or calibration facilities for a particular sensor. Tide gauges, pressure sensors, current meters, and temperature and salinity instruments are examples where standards and calibration facilities exist. However, for many other quantities such as sediment concentration, turbulence, radiation stress, and bed load, none exist. In these cases, the only "standard" may be that the measurements are taken by other systems, or that they satisfy theory, or are repeatable.

Unfortunately, in many cases, little or no thought is given to standards and calibration of coastal engineering measurements. To be sure, it is a difficult problem, but unless it is addressed, the risk of costly mistakes will remain high.

DATA ASSIMILATION AND SYNTHESIS

As emphasized at the beginning of this section, the product of a measurement system should be (1) a set of data, along with an assessment of its accuracy; (2) controls for the quality of data; and (3) the data-base management for their and use in engineering applications. The initial motivation for collecting some of the data may be for special engineering or research goals; other data may be part of an ongoing program for acquisition of certain standard measurements to build knowledge of the coastal oceanic and atmospheric climate. The types of data and their accuracy can vary greatly. Much data will be from direct in situ measurements in the water column; some may be indirect measurements made by remote techniques. This report has identified a number of such indirect measurements made by remote techniques, including those using acoustics (e.g., Doppler and tomographic methods) and electromagnetic sensing via satellites or aircraft (e.g., laser, infrared imagery, drogue tracking, or radio altimetry). The kinds of information inferred from these remote-sensing systems include elevation of the sea surface or seabed relative to the sensor, sea surface temperature, and currents.

The in situ direct measurements from fixed sensors can give added information on currents, pressure, and other properties within the water column, at sampling rates that are limited only by the inherent time constant of the sensor and of the recording and/or telemetry system. When recorded at suitable sampling rates at a single location, pressure or sea surface elevation data can quantify surface waves (but not their direction), tsunamis, tides, and storm surges. Similarly, the sensing of fluid velocity at given rates, and with given spatial resolution, determines its usefulness to studies of circulation, wave kinematics, or turbulence.

It should be noted that there are a number of data types for quantifying waves and currents over a wide spectrum of frequencies and for inferring information about sediment transport, erosion, and deposition in the coastal zone. Each type of measurement has inherent error bounds that depend on sensor type, the energy level of a given event, and the frequency spectrum of the event. A great range exists in the spatial and temporal resolution of measurements and, in many cases, there is a trade-off between accuracy and resolution (either spatial or temporal).

Faced with this variety of measurement data, which portrays different things, at different times, in different places, and with different accuracy and resolution, how can one synthesize at least portions of this data base so as to give a description of coastal zone dynamics more meaningful than that derived from any individual set of measurements? One answer is to use models that relate the different variables in a physically acceptable manner. For data that are not synoptic, and especially for data taken to quantify small-scale and/or high-frequency processes like turbulence, the synthesis is largely a matter of the contribution by these data to the proper representation of processes that cannot be resolved adequately in predictive models, such as bed stress and sediment dynamics. The committee sees this approach as an iterative tuning process between model adequacy and data adequacy.

The foregoing interactive synthesis for model development was discussed throughout Chapters 3 and 4. The kind of data synthesis that was not highlighted in those chapters relates to the problem of combining different types of data in a more direct diagnostic manner, so as to give a description of a synoptic field. Examples include synthesis of wind field or water circulation in the nearshore zone, thereby providing better spatial resolution and suppressing individual measurement errors. An example of this synthetic approach was pointed out to the committee by Richard Seymour (personal communication). His example pertains to the problem of estimating wind fields in the nearshore zone where data are not generally available from the National Weather Service (NWS) of NOAA. Such information can be important in nearshore generation of surface waves and surges. Basically, the methodology is the following:

> Suppose some auxiliary measurements of wind velocity are made in the nearshore zone to supplement those made at land stations and those from offshore meteorological buoys and ships at sea. It is well known that wind velocity and sea-level atmospheric pressure gradients are related in a deterministic manner and hence, the assimilation of the additional nearshore wind velocity measurements with the barometric pressure and wind information available from NWS can

yield a blended description of the wind field in the nearshore zone, which is an improvement on that deduced from the NWS data alone.

Another example is related to nearshore circulation (low-frequency horizontal flow of water, but outside of the zone where rip currents are active). If one adopts the hypothesis that the flow is quasi-steady, then the circulation field can be represented in terms of a stream function (the analog of pressure in the case of the wind field). It is then possible to combine all the data on low-frequency horizontal current measurements (for a reasonably synoptic period) to estimate the stream-function and therefore the circulation. The data may include direct in situ measurements from fixed current meters at a few locations, Lagrangian drifted data, and sea-level and satellite-derived imagery of surface temperatures—all of which are related to the stream-function. The methodology, when carried out objectively, requires representation of the unknown stream-function. Specific examples of the technique as applied to oceanographic measoscale eddies are given in Vastano and Reid (1985) and McWilliams et al. (1986).

Other examples could be given that involve more complex techniques of information theory and objective analysis, which are beyond the scope of this report. It suffices to conclude this section by citing the principle that the whole can often be better than the sum of the parts, provided that the parts are compatible with an appropriate diagnostic or prognostic model. Thus we return to a theme inherent in the text of this report: Both models and data are essential elements of a coastal engineering measurement system.

6

Conclusions and Recommendations

The Committee on Coastal Engineering Measurement Systems conducted this study with three objectives in mind: (1) to assess the needs for coastal data, (2) to determine the availability and suitability of instrumentation to meet these needs, and (3) to provide recommendations regarding specific development of coastal instruments and measurement systems. Because the modeling function has a fundamental role in analyzing and forecasting coastal changes, the committee was requested also to assess how the capability and practice of modeling of processes in the high-energy coastal waters influence the development of measurement systems. The committee was also responsible for providing guidance on measurement development priorities.

The committee agreed that there is a pressing need for development of instruments and measurement systems. There is a need for a commitment at the national level to stimulate and coordinate development of measurement systems and techniques. Presently, those who use instrumentation and measurement systems—both scientists and engineers—are few in number and operate at such limited funding that industry interest in developmental technology is also slight. Yet the benefits that might accrue from more timely and accurate data can be of major value to national, state, and local coastal management interests. These interests are just beginning to be influenced by recent changes in public law that place major responsibility on local government to finance coastal works, which put increasing emphasis on the validity of the environmental impact estimates for coastal development and have extended the federal government's economic involvement in coastal erosion.

A federal laboratory with extramural funding capability could serve the purpose of coordination and support for a national program. The committee recognized that, at present, development of instruments and measurement systems is carried out on a small scale and is usually driven by individual research needs. Therefore, availability and suitability of existing systems is often unknown to much of the potential user community. Thus, a need exists for a forum to provide information, collaboration, interaction, and coordination on measurement systems development.

The committee agreed to 19 recommendations regarding specific development of coastal instruments and measurement systems. The committee used the procedure schematically represented in Figure 6-1, and recommendations were derived from a conclusion reached by a consensus of its members. Each committee member ranked these recommendations and prioritized them as high, medium, and low, based upon their perception of the need and expected benefits to be gained in solving coastal engineering challenges from a national perspective. These individual priorities were integrated to arrive at a consensus prioritization, accepted by the entire committee.

Of the 19 committee recommendations, 4 were ranked as having high priority. Of the remaining 15 recommendations, 5 were ranked high-to-medium, 9 were ranked medium, and 1 was ranked medium-to-low priority. It is the committee's feeling that the 4 high-priority recommendations need to be supported at the national level in the immediate future. The 5 recommendations ranked high-to-medium are also regarded as essential to coastal engineering advancement for the rest of this century. The remaining recommendation, categorized as being medium-to-low priority, is important but applies to more limited areas of the coast.

The four sections that follow present the prioritized recommendations of the committee. Each recommendation is preceded by the specific related conclusion reached by the committee.

HIGH-PRIORITY RECOMMENDATIONS

CONCLUSION: Wave direction measurement techniques, either for

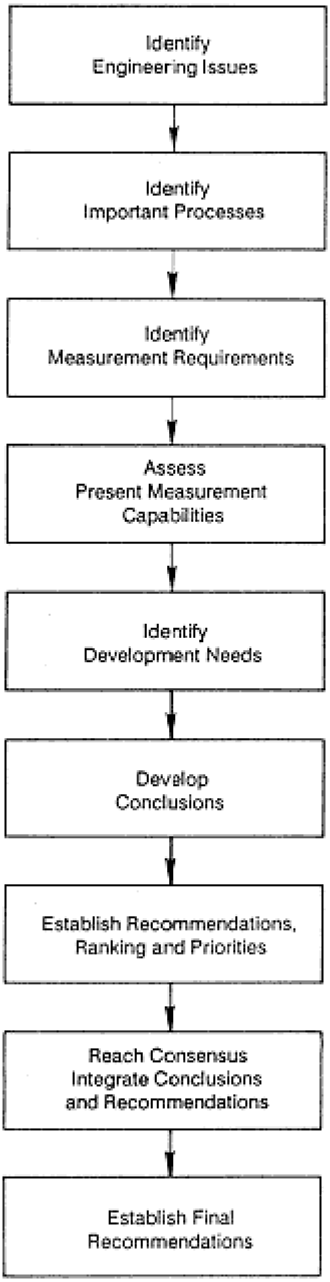

Figure 6-1
Analytical process for development of conclusions and recommendations.

deep or shallow water, do not provide the necessary resolution for accurate prediction of littoral processes.

RECOMMENDATION: It is recommended that both in situ and remote-sensing systems, including radar and acoustic techniques, be explored and developed.

CONCLUSION: There is a need for a U.S. coastal observation data base on height, period, and direction of ocean waves.

RECOMMENDATION: It is recommended that a permanent national system be established for the measurement and timely dissemination of nearshore wave data to include height, period, and direction.

CONCLUSION: Sediment-transport modeling (conceptual and mathematical) in the nearshore zone is largely empirical and poorly verified.

RECOMMENDATION: It is recommended that programmatic emphasis be placed on theoretical improvement and rigorous field testing (in an interactive fashion) of existing sediment-transport models, while more physically based models are derived and field-tested.

CONCLUSION: There is no existing capability to reliably measure high-concentration sediment motions, especially within the region immediately above the mobile bed.

RECOMMENDATION: It is recommended that high-resolution sediment transport measurement systems be developed for use in high-energy wave environments such as the surf zone and tidal inlets.

HIGH-TO-MEDIUM-PRIORITY RECOMMENDATIONS

CONCLUSION: There is a need for the development of both measurement and modeling capability for understanding the internal dynamics of rubble-mound structures.

RECOMMENDATION: It is recommended that mathematical modeling efforts be undertaken in combination with in situ measurements on the dynamics of rubble-mound structures.

CONCLUSION: Mechanics of breakwater failures are poorly understood because of the unknown nature of the deformations and displacements of pieces of material in rubble-mound structures.

RECOMMENDATION: It is recommended that simultaneous measurements of pore pressures in breakwater cross-sections be recorded during storms. Pressure-measuring devices of adequate sensitivity are available, but means of deployment, protection, and transportation of data to safe off-site observation stations need development.

CONCLUSION: More and better data are needed on wave setup during storm events.

RECOMMENDATION: It is recommended that measurements of wave forcing and sea-level response be made during storm events to quantify wave setup.

CONCLUSION: Improved understanding and prediction of fluid turbulence is essential to improve prediction of coastal flows and sediment transport.

RECOMMENDATION: It is recommended that significant effort be directed toward developing instrumentation for measuring turbulence in the demanding nearshore environment. Concurrently, turbulence modeling must be extended to enhance prediction of turbulence under conditions of waves, currents, and a movable bed.

CONCLUSION: Adequate current data are needed for verification and further development of two-dimensional and three-dimensional limited-area circulation models.

RECOMMENDATION: It is recommended that development of low-cost current meters and associated telemetry or recording systems be undertaken to provide a feasible means of obtaining data vital to the verification and further development of two- and three-dimensional hydrodynamic models in the coastal region.

MEDIUM-PRIORITY RECOMMENDATIONS

CONCLUSION: There is a need for improved three-dimensional models of nearshore currents.

RECOMMENDATION: It is recommended that an improved three-dimensional nearshore current model, including improved description of breaking waves and swash, be developed for complex bathymetry, and that the necessary three-dimensional field data be acquired to verify the model.

CONCLUSION: Quantification of tide and storm-surge phenomena requires measurement of currents in tidal inlets to supplement information on water levels.

RECOMMENDATION: It is recommended that efforts be made to develop reliable current meters, which can be deployed during either normal or storm events, for measuring low-frequency currents in tidal inlets. The use of acoustic-Doppler profilers, tomography, or electromagnetic methods for monitoring volume transport in channels and inlets needs to be explored.

CONCLUSION: Existing storm-surge models that allow for overland flooding of tidal flats and upland vegetated areas are based on ad hoc methodology. Adequate field data do not exist to calibrate storm surge models.

RECOMMENDATION: It is recommended that further development of storm-surge models be directed at improving the physical basis and numerical implementation for overland flooding. A program of field measurement should be conducted to provide data sets for calibration and verification.

CONCLUSION: There is currently no well-tested proven capability to measure, or to estimate accurately, boundary shear stress beneath combined waves and currents in shallow water.

RECOMMENDATION: It is recommended that acoustic travel time, acoustic-Doppler velocimeter, or laser-Doppler velocimeter techniques be improved so that adequate velocity profiles can be obtained in energetic rapidly varying flow fields. Alternative technology (optical methods, hot-film), which may provide estimates of boundary shear stress under a broader spectrum of environmental conditions, should be pursued.

CONCLUSION: Measurement of small-scale (centimeter to decimeter) changes in bed topography are needed for understanding local scour around structures and bottom roughness.

RECOMMENDATION: It is recommended that nonintrusive (remote) techniques be developed to measure local scour and bed forms under a variety of wave conditions, including storm events. Higher resolution side-scan sonars, buried differential pressure sensors, and other acoustic, optical, and laser techniques should be explored for this application.

CONCLUSION: There is currently a capability to measure bathymetry across the coast under low-to-moderate wave conditions. Present techniques for measuring bathymetry across the coast cannot be used under high storm-wave conditions.

RECOMMENDATION: It is recommended that technologies for measuring nearshore bathymetry be improved to allow measurements under higher wave conditions. Development efforts should evaluate both remote-sensing methods and in situ optical and acoustic technologies for estimating beach profile changes over a full range of oceanic conditions.

CONCLUSION: There is a need for development and field verification of an improved operational model for refraction/diffraction.

RECOMMENDATION: It is recommended that an efficient, computationally fast, operational numerical model for refraction/diffraction be developed for the general case of complex bathymetry.

CONCLUSION: Specially dense measurement of wave-radiation stress (wave momentum) is needed in shallow coastal water to provide long-term, reliable, accurate data for predicting littoral processes.

RECOMMENDATION: It is recommended that slope arrays be improved to lower costs, by making them more compact or by utilizing self-recording or telemetry to eliminate shore cables. Other techniques should also be pursued, such as combined pressure sensor and velocity meters (PUV) and shore-based radars.

CONCLUSION: Coupled short-wave/long-wave models are needed to increase predictability of complex nearshore flow fields, particularly around tidal inlets. Improvement must be made in the physical understanding of nonlinear wave/current interaction and wave interaction with the bottom. Detailed velocity measurements in the field are required to provide data sets to validate these models.

RECOMMENDATION: It is recommended that existing short-wave/long-wave coupled models incorporate more complete physics. Particular emphasis should be placed on modeling complex fluid/bottom interactions near tidal inlets. Measurement programs should be initiated to provide wave height and measurements in sufficient detail to test these models.

MEDIUM-TO-LOW-PRIORITY RECOMMENDATIONS

CONCLUSION: Quantification of tsunami models, coastal tide models, and shelf circulation models requires deep water pressure gauge measurements at Pacific locations, seaward of the continental slope.

RECOMMENDATION: It is recommended that the benthic pressure measurement program be expanded to include a West Coast array.

DEVELOPMENT NEEDS

In the previous sections of this report we have identified several unsolved problems in coastal engineering. These problems exist due in part to our limited understanding of some of the processes important in coastal engineering. Our understanding is limited in some cases because of the measurement difficulties that are encountered in the coastal zone. This is indeed a difficult measurement environment, with a wide range of space and time scales to be resolved. High data rates are needed to resolve the short-period processes, and long recording times are needed to resolve the long-period processes. Since many of the processes of interest are two- or three-dimensional, the simultaneous operation of several sensors is also necessary.

Often, measurements are needed in remote locations where instrumentation systems must operate in an automatic mode. Until recently data had to be telemetered from a sensor to a recording site via cable through the surf zone. It was difficult to get long-term measurements because of cable failures, even though experience with West Coast wave measurements has shown that properly designed cables can survive many years. Recent advances in telemetry and data acquisition systems have overcome some of these problems.

Measurements are most needed under high-energy conditions and close to the interfaces (sea surface, bottom, and structure). Remote-sensing techniques using radar and acoustic techniques may provide some means to improve such measurements. Many of the processes of interest are subject to numerical modeling, but in many cases the data needed to specify initial and forcing conditions have been lacking. Many of the processes of interest are nonlinear and interactive and require relatively complex physics in simulation models. Advances in computer technology and modeling make it feasible to model some of these processes if the data requirements for the models can be satisfied.

In summary, recent developments in sensor technology, data telemetry, recording systems, and computers offer promise of significant advances in the resolution of coastal engineering problems in the next decade.

Appendix: Survey Findings

The following findings stated below summarize the responses received from a survey of 24 scientists and engineers in the United States, Canada, and Europe who are engaged in activities covering all aspects of coastal measurements discussed in this report.

1. Coastal Engineers need to improve the spatial and temporal characteristics of their measurement programs. This should include, but not be limited to, better area coverage and longer term monitoring programs, as well as measurements under specific conditions. These efforts are inhibited by:

    - the high cost of equipment and logistics,
    - the reliability of available equipment, and
    - the available technology.

2. Remote sensing from land-based, airborne, and satellite systems holds promise for meeting certain coastal engineering requirements. However, there is no concerted effort to apply this technology to coastal engineering problems.
3. Coastal engineers have a better understanding of noncohesive sediment processes than cohesive sediment processes. Additional research needs to be directed toward cohesive sediment processes.

4. Longshore and cross-shore sediment-transport processes are poorly understood. Direct rather than indirect measurement techniques are needed. Acoustic and laser technologies appear to hold promise, but need further development, testing, and evaluation.
5. High-resolution, deep-water, directional wave spectra measurements are required to support a number of coastal engineering requirements. These are not possible on a routine basis with available technology. Technological development is needed.
6. Coastal engineers have almost no measurements of important processes in the surf zone under storm conditions. This is an essential requirement that demands significant research and development.
7. Coastal engineers can predict the environmental impact of coastal structures only under a few conditions. Beach replenishment and restoration are poorly understood. Little hard data are available, and recordkeeping is poor.
8. In recent years process-oriented experiments have improved our knowledge of important coastal processes (C2S2, NSTS, DUCK, SUPERDUCK). More emphasis needs to be placed on process-oriented experiments in various locations under various conditions.
9. More measurements of these coastal processes are needed:

    - mean currents under wave conditions,
    - wave-induced apparent stress,
    - turbulent stress,
    - wave trough vs. wave crest, and
    - longer term series.

10. Several other countries are active in coastal engineering research. Some are actively considering the issues of coastal engineering measurement requirements (Canada and the United Kingdom). Efforts should be increased to foster the exchange of information.
11. Many coastal processes are poorly understood. Engineers and scientists need to work together to resolve important needs.

References

Ackers, P., and W.R. White, 1973. Sediment transport: new approach and analysis. Proc. Am. Soc. Civil Eng., J. Hydraul. Div., v. 99, p. 2041-2060.

Adams, C.E., Jr., and G.L. Weatherly, 1981. Suspended sediment transport and benthos boundary-layer dynamics. In: C.A. Nittrouer, ed., Developments in Sedimentology, v. 32, pp. 1-18. Elsevier, Amsterdam.

Agrawal, Y., F. Diaz, and D.G. Aubrey, 1988. Use of laser anemometry in shallow coastal systems. Proc. Conf. Uses of Laser Anemometry, Lisbon, Portugal, June 1988.

Anonymous, 1978. Sediment Density Gauge, Model 3563: Manual. Troxler Electronic Laboratories, Inc., Research Triangle Park, North Carolina.

Aubrey, D.G., 1978. Statistical and dynamical prediction of changes in natural sand beaches. Ph.D. thesis, Scripps Institution of Oceanography, University of California, San Diego, p. 194.

Aubrey, D.G., 1979. Seasonal patterns of on/offshore sediment movement. J. Geophys. Res., v. 84, pp. 6347-6354.

Aubrey, D.G., and R.J. Seymour, 1987. Methods of position control and beach face profiling, Part A, Chapt. 3, Measuring the nearshore morphology. In: R.J. Seymour, ed., Nearshore Sediment Transport. Plenum Press, New York.

Aubrey, D.G., and J.H. Trowbridge, 1988. Reply. J. Geophys. Res., v. 93, pp. 1344-1346.

Aubrey, D.G., and R.J. Trowbridge, 1985a. Kinematic and dynamic estimates from electromagnetic current meter data. J. Geophys. Res., v. 90, pp. 9137-9146.

Aubrey, D.G., and R.J. Trowbridge, 1985b. Reply to comment on: Kinematic and dynamic estimates from electromagnetic current meter data. J. Geophys. Res., v. 93, pp. 1344-1346.

Bagnold, R.A., 1946. Motion of waves in shallow water—interaction between waves and sand bottoms. Proc. R. Soc., London, Ser. A., v. 187, pp. 1-15.

Bagnold, R.A., 1963. Mechanics of marine sedimentation. In: M.N. Hill, ed., The Sea, v. 3, pp. 507-528. Interscience, New York.

Bailard, J.A., 1981. An energetics total load sediment model for a plane sloping beach . J. Geophys. Res., v. 86, pp. 1938-1954.

Barrick, D.E., 1982. Status of HF radars for wave-height directional spectral measurements. In: Measuring Ocean Waves. National Academy Press, Washington, D.C.

Bartz, R., J.R.V. Zaneveld, and H. Pak, 1978. A transmissometer for profiling and moored observations in water. Soc. Photo-Optical Instrumentation Eng., Ocean Optics V, pp. 102-108.

Bascom, W.N., 1951. The relationship between sand size and beach force slope. Trans. Am. Geophys. Union, v. 32, pp. 866-874.

Basu, A.K., 1983. Response of guyed tower to wave loading. Proc. 2d Int. Offshore Mech. Arctic Eng. Symp., Houston.

Battjes, J.A., and J.P.F.M. Janssen, 1978. Energy loss and set-up due to breaking of random waves. Proc. 16th Int. Conf. Coastal Eng., pp. 569-587. American Society of Civil Engineers, New York.

Beach, R.A., and R.W. Sternberg, 1988. Wave-current interactions in the inner surf zone and their influence on suspended sediment transport. Proc. IAHR Symp. Mathematical Modelling of Sediment Transport in the Coastal Zone, pp. 156-165.

Beach, R.A., J.R.V. Zaneveld, and H. Pak, 1978. A transmissometer for profiling and moored observations in water. Soc. Photo-Optical Instrumentation Eng., Ocean Optics V., pp. 102-108.

Beal, R.C., D.G. Tilley, D.E. Irvine, E.J. Walsh, F.C. Jackson, D.W. Hancock III, D.E. Hines, R.N. Swift, F.I. Gonzalez, D.R. Lyzenga, and L.F. Zambresky, 1986. A comparison of SIR-B directional ocean wave spectra with aircraft scanning radar spectra. Science, v. 232, pp. 1531-1535.

Birkemeier, W.A., 1985. Time scales of nearshore profile changes. Proc. 19th Int. Conf. Coastal Eng., pp. 1507-1526. American Society of Civil Engineers, New York.

Blumberg, A.F., 1975. A numerical investigation into the dynamics of estuarine circulation, Chesapeake Bay Institute Report No. 91, Baltimore, Maryland.

Bodge, K.R., and R.G. Dean, 1984. Wave measurement with differential pressure gauges, Proc. 19th Int. Conf. Coastal Eng., pp. 755-769. American Society of Civil Engineers, New York.

Bouws, E., and J.A. Battjes, 1982. A Monte Carlo approach to the computation of refraction of water waves. J. Geophys. Res., v. 87(C8), pp. 5718-5722.

Bouws, E., H. Gunther, W. Rosenthal, and C.L. Vincent, 1985. Similarity of the wind wave spectrum in finite depth water, 1. Spectral form. J. Geophys. Res., v. 90(C1), pp. 975-986.

Bowen, A.J., 1969. The generation of longshore currents on a plane beach. J. Mar. Res., v. 27, pp. 206-215.

Bowen, A.J., 1980. Simple models of nearshore sedimentation: Beach profiles and longshore bars. In: S.B. McCann, ed., The Coastline of Canada, Paper 80-10. Geological Survey of Canada, Ottawa, Ontario, Canada.

Brainard, E.C., II, and D.L. Gardner, 1982. Wave track and waverider heavy buoy intercomparison at the entrance to the Columbia River. In: Oceans '82 Conference Record. Industry, Government, Education—Partners in Progress, pp. 861-866. Institute of Electrical and Electronics Engineers, Piscataway, New Jersey.

Brampton, A.H., and S.M. Beven, 1987. Beach changes along the coast of Lincolnshire, U.K. (1959-1985). In: Proc. Coastal Sediments '87, New Orleans, Louisiana, pp. 539-554. American Society of Civil Engineers, New York.

Brampton, A.H., and R.W. Sternberg, 1988. Suspended sediment transport in the surf zone: response to cross-shore infragravity motion . Mar. Geol., v. 80, pp. 61-79.

Brink, K.H., and D.C. Chapman, 1985. Programs for computing properties of coastal trapped waves and wind-driven motion over continental shelf and slope. Tech. Rep. WHOI-85-17, p. 99. Woods Hole Oceanographic Institution, Woods Hole, Massachusetts.

Brink, K.H., D.C. Chapman, and G.R. Halliwell, 1987. A stochastic model for wind-driven currents over the continental shelf. J. Geophys. Res., v. 92, pp. 1783-1797.

Brown, C.B., 1950. Sediment transportation. In: H. Rouse, ed., Engineering Hydraulics, p. 1039. Wiley, New York.

Butler, H.L., 1980. Evolution of a numerical model for simulating long period wave behavior in ocean-estuarine systems. In: Estuarine and Wetland Processes with Emphasis on Modeling, Marine Science Series, v. 11. Plenum Press, New York.

Camfield, F.E., 1977. Wind-Wave Propagations Over Flooded, Vegetated Land. Tech paper no. 77-12. U.S. Army Corps of Engineers, Coastal Engineering Center, Fort Belvoir, Virginia.

Carter, W.E., and D.S. Robertson, 1986. The application of geodetic radio interfermetric surveying to the monitoring of sea level . Geophys. J. R. Astron. Soc., v. 87, pp. 3-13.

Carter, T.G., P.L. Liu, and C.C. Mei, 1973. Mass transport by waves and offshore sand bedforms. J. Waterways, Harbors, Coastal Eng. Div. Proc. Am. Soc. Civil Eng., v. 2, pp. 165-184.

Clausner, J.E., W.A. Birkemeier, and G.R. Clark, 1986. Field Comparison of Four Nearshore Survey Systems. Miscellaneous paper no. CERC-86-6. U.S. Army Corps of Engineers.

Clifton, 1976. Wave-generated structures—a conceptual model. In: R.A. Davis and R.L. Ethington, eds., Beach and Nearshore Processes. Special Publication 24, pp. 126-148. Soc. Econ. Paleontal. Mineral.

Coastal Engineering Research Center (CERC), U.S. Army Corps of Engineers, 1984. Shore Protection Manual. CERC Report MR-83-10. U.S. Army Corps of Engineers, Vicksburg, Mississippi.

Collins, M.B., and C.B. Pattiaratchi, 1984. Identification of suspended sediment in coastal waters using airborne thematic mapper data. Int. J. Remote Sensing, v. 5, p. 635.

Copeland, G.J.M., 1985. A practical alternative to the mild-slope wave equation. Coastal Eng., v. 9, pp. 125-149.

Crandall, S.H., 1985. Non-Gaussian closure techniques for stationary random vibration. Int. J. Non-Linear Mech., v. 20.

Dally, W., R.G. Dean, and R.A. Dalrymple, 1985. Wave height variation across beaches of arbitrary profile. J. Geophys. Res., v. 90(6).

Dean, R.G., 1973. Heuristic models of sand transport in the surf zone. Proc. Conf. Eng. Dynamics in the Surf Zone, pp. 208-214. Institution of Engineers, Sydney, Australia.

Dean, R.G., 1977. Equilibrium beach profiles: U.S. Atlantic and Gulf Coasts. Tech. Rep. No. 12. University of Delaware, Newark.

Dean, R.G., and R.A. Dalrymple, 1984. Water Wave Mechanics for Engineers and Scientists, p. 353. Prentice-Hall, Englewood Cliffs, N.J.

Dick, J.E., and R.A. Dalrymple, 1984. Coastal changes at Bethany Beach, Delaware, Proc. 19th Int. Conf. Coastal Eng., Houston, pp. 1650-1667. American Society of Civil Engineers, New York.

Dingler, J.R., and D.L. Inman, 1976. Wave formed ripples in nearshore sands , Proc. 15th Int. Conf. Coastal Eng., Honolulu, pp. 2109-2126. American Society of Civil Engineers, New York.

Doering, J.C., and A.J. Bowen, 1987. Skewness in the nearshore: a comparison of estimates from Marsh-McBirney current meters and colocated pressure sensors. J. Geophys. Res., v. 92.

Downing, J.P., 1981. Particle counter for sediment transport studies. J. Hydraul. Div., Am. Soc. Civil Eng., v. 107, pp. 1455-1465.

Downing, J.P., R.W. Sternberg, and C.R.B. Lister, 1981. New instrumentation for the investigation of suspended sediment processes in the shallow marine environment, Mar. Geol., v. 42, pp. 19-34.

Drapeau, G., and B. Long, 1985. Measurements of bedload transport in the nearshore zone using radioisotopic sand tracers. Proc. 19th Conf. Coastal Eng., Houston, pp. 1252-1265. American Society of Civil Engineers, New York.

Ebersole, B.A., 1985. Refraction-diffraction model for linear water waves. J. Waterway, Port, Coastal, and Ocean Engineering. v. 111. no. 6., pp. 939-953. American Society of Civil Engineers, New York.

Ebersole, B.A., and R.A. Dalrymple, 1979. A Numerical Model for Nearshore Circulation Including Convective Acceleration and Lateral Mixing. Department of Civil Engineering, University of Delaware, Newark.

Eble, M.C., F.I. Gonzalez, and E.N. Bernard, 1988. Deep ocean observations of three recent tsunamis in the Gulf of Alaska. Abstract; EOS, 69: 44, November, 1988, p. 1245.

Edge, B.L., ed. 1985. Proc. 19th Int. Conf. Coastal Eng., Houston, p. 3282. American Society of Civil Engineers, New York.

Einstein, H.A., 1950. The bed-load function for sediment transport in open channel floor. Tech. Bull. 1026, p. 78. SCS, U.S. Department of Agriculture, Washington, D.C.

Einstein, H.A., 1972. A basic description of sediment transport on beaches. In: R.E. Meyer, ed., Waves on Beaches and Resulting Sediment Transport, p. 462. Academic Press, New York.

Elgar, S., R.T. Guza, and S.J. Seymour, 1985. Wave group statistics from numerical simulations of a random sea. Appl. Ocean Res., v. 7, pp. 93-96.

Fedosh, M.S., 1987. Segregating sediment resuspension processes with averaged Landsat data. Proc. Conf. Coastal Sediments '87, New Orleans, pp. 98-112. American Society of Civil Engineers, New York.

Forristall, G.Z., 1974. Three-dimesional structure of storm generated currents. J. Geophys. Res., v. 79, pp. 2721-2729.

Forristall, G.Z., 1980. A two layer model for hurricane-driven currents on an irregular grid. J. Phys. Oceanogr., v. 10, pp. 1417-1438.

Forristall, G.Z., 1982. Subsurface wave-measuring systems. Measuring ocean waves. Proceedings of a Symposium and Workshop on Wave-Measurement Technology. National Academy Press, Washington, D.C.

Forristall, G.Z., R.C. Hamilton, and V.J. Cardone, 1977. Continental shelf currents in tropical storm Delia: observations and theory. J. Phys. Oceanogr., v. 7, pp. 532-546.

Fraser, D.C., 1985. Airborne electromagnetic bathymetric survey and data analysis, Cape God, Massachusetts, area. Contract No. N6230684-C-0013. NORDA.

Freilich, M.H., and R.T. Guza, 1984. Nonlinear effects on shoaling surface gravity waves. Phil. Trans. R. Soc. London, Ser. A, v. 311, pp. 1-41.

Gable, C.G. (ed). 1981. Report on data from the Nearshore Sediment Transport Study experiment at Lendbetter Beach, Santa Barbara, California, January-February 1980. University of California Institute of Marine Resources. Ref. No. 80-5. Scripps Institute of Oceanography, La Jolla, California. 314 pp.

Gallagher, B., 1971. Generation of surf beat by non-linear wave interaction. J. Fluid Mech., v. 49(1), pp. 1-20.

Garratt, J.R., 1977. Review of drag coefficients over oceans and continents. Monthly Weather Rev., v. 105, pp. 915-929.

George, R.A., and R.E. Flick, 1987. Nearshore Turbulence: Velocity measurements in unsteady two-phase flows. EOS, v. 69: 44, p. 1248. Trans. American Geophysical Union.

Glenn, S.M., 1983. A continental shelf bottom boundary layer model: The effects of waves, currents and a movable bed. Ph.D. thesis, WH oq-83-6, p. 336. Woods Hole Oceanographic Institution, Woods Hole, Massachusetts.

Gonzalez, F.I., E.N. Bernard, and H.B. Milburn, 1987. A program to acquire deep ocean tsunami measurements in the North Pacific. Conference. Coastal Zone '87, May 26-29, 1987, pp. 3373-3381. Waterways Division, American Society of Civil Engineers, Seattle, Washington.

Graham, H.E., and D.E. Nunn, 1959. Meterological considerations pertinent to standard project hurricane, Atlantic and Gulf coasts of the United States. National Hurricane Research Project Report No. 33. U.S. Department of Commerce , Washington, D.C.

Grant, W.D., and O.S. Madsen, 1979. Combined wave and current interaction with a rough bottom. J. Geophys. Res., v. 84, pp. 1797-1808.

Grant, W.D., and O.S. Madsen, 1982. Moveable bed roughness in unsteady oscillatory flow. J. Geophys. Res., v. 87, pp. 469-481.

Greenwood, B., and R.A. Davis, Jr., eds., 1984. Hydrodynamics and Sedimentation in Wave-Dominated Coastal Environments. Mar. Geol., 60(1/4), p. 473.

Greenwood, B., and D.J. Sherman, 1984. Waves, currents, sediment flux, and morphological response in a barred nearshore system. In: B. Greenwood and R.A. Davis, Jr., eds., Hydrodynamics and Sedimentation in Wave-Dominated Coastal Environments. Mar. Geol., v. 60, pp. 31-61.

Grosskopf, G., D.G. Aubrey, M.G. Matti, and M. Mathieson, 1983. Field intercomparison of nearshore directional wave sensors. J. Ocean Eng., IEEE, Vol. OE-8, No. 4, pp. 227-271.

Grove, R.S., C.J. Sonu, and D.H. Dykstra, 1987. Fate of massive sediment injection on a smooth shoreline at San Onofre, California. Proc. Conf. Coastal Sediments '87, New Orleans, pp. 531-538. American Society of Civil Engineers, New York.

Gust, G., and G.L. Weatherly, 1985. Velocities, turbulence, and skin friction in a deep-sea logarithmic layer. J. Geophys. Res., v. 90 (C3), pp. 4779-4792.

Guza, R.T., 1988. Comment on: Kinematic and dynamic estimates from electromagnetic current meter data. J. Geophys. Res., v. 93, pp. 1341-1344.

Guza, R.T., and E.B. Thornton, 1982. Swash oscillations on a natural beach. J. Geophys. Res., v. 87, pp. 483-491.

Hamblin, F.F., Y.M.R. Marmoush, F.M. Byoce, and A.A. Smith, 1987. Field evaluation of an electromagnetic current meter based vertical profiler. J. Geophys. Res., v. 92, C11, 11, pp. 876-872.

Hanes, D.M., and D.A. Huntley, 1986. Continuous measurements of suspended sand concentration in a wave dominated nearshore environment. Cont. Shelf Res., v. 6(4), pp. 585-596.

Harger, R.D., 1986. The SAR image short gravity waves on a long gravity wave . In: D.M. Phillips and K. Hasselman, eds., Wave Dynamics and Radio Probing of the Ocean Surface. Plenum Press, New York.

Hasselman, K., T.P. Barnett, E. Bouws, H. Carlson, D.E. Cartwright, K. Enke, J.A. Ewing, H. Gienapp, D.E. Hasselman, P. Kruseman, A. Meerburg, P. Miller, D.J. Olbers, K. Richter, W. Sell, and H. Walden, 1973. Measurements of wind-wave growth and swell decay during the Joint North Sea Wave Project (JONSWAP). Dtsh. Hydrogr. Z., A 8(12).

Heaps, N.S., 1974. Development of a three-dimensional model of the Irish Sea. Rapp. P.-V. Reun., Cons. Int. Explor. Mer., pp. 147-162.

Hendershott, M.C., 1977. Numerical models of ocean tides. In: The Sea, v. 6, pp. 47-95. Interscience, New York.

Higgins, A.L., R.J. Seymour, and S.S. Pawka, 1981. A compact representation of ocean wave directionality. Appl. Ocean Res., v. 3(3), pp. 105-112.

Holman, R.A., and A.J. Bowen, 1982. Bars, bumps, and holes: Models for the generation of complex beach topograhy. J. Geophys. Res., v. 87, pp. 457-468.

Holman, R.A., and T.C. Lippman, 1987. Remote sensing of nearshore bar systems: making morphology visible. Proc. Conf. Coastal Sediments '87 , New Orleans, pp. 929-944. American Society of Civil Engineers, New York.

Horikawa, K., ed., 1988. Nearshore Dynamics and Coastal Processes. University of Tokyo Press. Tokyo. 522 pages.

Houston, J.R., 1978. Interaction of tsunamis with the Hawaiian Islands calculated by a finite-element numerical model. J. Phys. Oceanogr., v. 8, pp. 93-102.

Huang, N.E., 1982. Survey of remote sensing techniques for wave measurement. In: Measuring Ocean Waves. National Academy Press, Washington, D.C.

Huang, N.E., L.F. Bliven, S.R. Long, and P.S. DeLe, 1986. A study of the relationship among wind speed, sea state, and the drag coefficient for a developing wave field. J. Geophys. Res., v. 91, pp. 7733-7742.

Huntley, D.A., 1982. In situ sediment monitoring techniques, a survey of the state of the art in U.S.A. Report No. C2S2-1, p 35. Department of Oceanography, Dalhousie University , Halifax, Nova Scotia, Canada.

Hwang, L.S., and D.J. Divosky, 1972. Tsunami generation. J. Geophys. Res., v. 75, pp. 6802-6817.

Inman, D.L., and R.A. Bagnold, 1963. Littoral processes. In: M.N. Hill, ed., The Sea, v. 3, pp. 529-553. Interscience, New York.

Inman, D.L., and S.A. Jenkins, 1985. The Nile littoral cell and man's impact on the coastal zone of the southeastern Mediterranean. Proc. 19th Int. Conf. Coastal Eng., Houston, pp. 1600-1617. American Society of Civil Engineers, New York.

Inman, D.L., C.E. Nordstrom, and R.E. Flich, 1976. Currents in submarine canyons: An air-sea-land interaction. Ann. Rev. Fluid Mech., v. 8, pp. 275-310.

Inman, D.L., et al., 1980. Field measurements of sand motion in the surf zone. Proc. 17th Int. Conf. Coastal Eng., Sydney, Australia, pp. 1215-1234. American Society of Civil Engineers, New York.

Institute of Electrical and Electronic Engineers (IEEE), 1982. Proc. IEEE 2d Working Conf. Current Measurement. Tech. Report 82 CH 1704-6. Institute of Electrical and Electronic Engineers, New York, New York.

Ito, Y., and K. Tanimoto, 1972. A method of numerical analysis of wave propagation: application to wave diffraction and refraction. Proc. 13th Int. Conf. Coastal Eng., pp. 503-522. American Society of Civil Engineers, New York.

Jeffreys, E.R., and M.H. Patel, 1982. Dynamic analysis models of tension leg platforms. J. Energy Resources Tech., v. 104.

Jelesnianski, C.P., 1972. SPLASH: special program to list amplitudes of surges from hurricanes. 1. Landfall storms. NOAA Tech. Memo. NWS, TDL-46. U.S. Department of Commerce, Washington, D.C.

Jelesnianski, C.P., and J. Chen, 1981. SLOSH: sea, lake and overland surges from hurricanes. Techniques Development Laboratory, National Weather Service, National Oceanographic and Atmospheric Administration, Silver Spring, Maryland.

Jumars, P.A., and A.R.M. Nowell, 1984. Effects of benthos on sediment transport: problems with functional grouping. Cont. Shelf Res., v. 3, pp. 115-130.

Kamphuis, J.W., 1975. Friction factor under oscillatory waves. Proc. Am. Soc. Civil Eng., J. Waterway, Port, Coastal, and Ocean Div., v. 101, pp. 135-144.

Kim, K.Y, R.O. Reid, and R.E. Whitaker, 1987. On an open radiational boundary condition for weakly dispersive tsunami waves. J. Comp. Phys.

Kinsman, B., 1965. Wind, Waves, Their Generation and Propagation on the Ocean Surface. The Johns Hopkins University. Prentice-Hall, Inc., Englewood Cliffs, New Jersey.

Kirby, J.T., and R.A. Dalrymple, 1984. A parabolic equation for the combined refraction-diffraction of stokes waves by mildly varying topography. J. Fluid Mech., v. 136.

Kirby, J.T., and R.A. Dalrymple, 1984. Verification of a parabolic equation for propagation of weakly-nonlinear waves. Coastal Eng., v. 8.

Komar, P.D., 1974. Oscillatory ripple marks and the evaluation of ancient wave conditions and environments. J. Sed. Petrol., v. 44, pp. 169-180.

Komar, P.D., and D.L. Inman, 1971. Longshore sand transport on beaches. J. Geophys. Res., v. 75, pp. 5914-5927.

Komar, P.D., and M.C. Miller, 1973. The threshold of sediment movement under oscillatory waves. J. Sed. Petrol., v. 43, pp. 1101-1110.

Komar, P.D., and M.C. Miller, 1975. Reply: on the comparison between the threshold of sediment motion under waves and uni-directional currents with a discussion of the fractional evaluation of the threshold. J. Sed. Petrol.

Kraus, N.C., ed., 1987. Proc. Conf. Coastal Sediments '87, New Orleans, p. 2177. American Society of Civil Engineers, New York.

Kraus, N.C., and Harikai, 1983. Numerical model of shoreline change at Oarai Beach. Coastal Eng., v. 7, pp. 1-28.

Kraus, N.C., K.J. Gingerich, and J.D. Rosati, 1988. Toward an improved empirical formula for longshore sand transport. Proc. Int. Conf. 21st Coastal Eng. American Society of Civil Engineers, New York.

Larson, M., H. Hanson, and N.C. Kraus, 1987. Analytical models of the one-line model of shoreline change. Tech. Rep. 72 CERC-87-15. U.S. Army Waterways Experiment Station, Coastal Engineering Research Center, 72 pp. + appendices.

Leendertse, J.J., 1984. Verification of a model of the eastern scheldt. Rand Report R-3108-NETH. The Rand Corporation, Santa Monica, California. 127 pp.

Leendertse, J.J., and S.K. Liu, 1975. A three-dimensional model for estuaries and coastal seas. II: Aspects of computation. Rand Report R-1764-OWRT. The Rand Corporation, Santa Monica, California.

Lhermitte, R.M., 1981. Observations of water flow with high resolution doppler snow . Geophys. Res. Letter, v. 8, no. 2.

Liu, P.L.-F., and T.K. Tsay, 1983. On weak reflection of water waves. J. Fluid Mech., v. 131, pp. 59-71.

Liu, S.K., and J.J. Leendertse, 1987. Modeling the Alaskan continental shelf waters. Rand Report R-3567-NOAA/RC. The Rand Corporation, Santa Monica, California. 136 pp.

Longuet-Higgins, M.S., 1970. Longshore currents generated by obliquely incident sea waves. J. Geophys. Res., v. 75, pp. 6778-6801.

Longuet-Higgins, M.S., 1984. On the stability of steep gravity waves. Proc. R. Soc. London, Ser. A, v. 396, pp. 269-280.

Longuet-Higgins, M.S., 1985. Bifurcation in gravity waves. J. Fluid Mech., v. 151, pp. 457-475.

Longuet-Higgins, M.S., and R.W. Stewart, 1962. Radiation stresses and mass transport in gravity waves, with application to 'surf beat.' J. Fluid Mech., v. 13, pp. 481-504.

Lowe, R.L., 1987. Measuring sediment dynamics: continuous bedload sampling, Chapt. 58. In: R.J. Seymour, ed., Nearshore Sediment Transport. Plenum Press, New York.

Lynch, J.F., T.F. Gross, C. Libicki, and K. Bedford, 1987. Deepwater sediment concentration profiling in Hebbel using a one megahertz acoustic backscatter system. Proc. Conf. Coastal Sediments '87, New Orleans, pp. 818-833. American Society of Civil Engineers, New York.

Mader, C.L., 1984. A landslide source for the 1975 Hawaii tsunami. Int. J. Tsunami Soc., v. 2, pp. 71-78.

Madsen, O.S., and W.D. Grant, 1975. The threshold of sediment movement under oscillatory waves: a discussion. J. Sed. Petrol., v. 45, pp. 360-361.

Madsen, O.S., and W.D. Grant, 1976. Sediment transport in the coastal environment. Report No. 209, p. 105. Ralph M. Parsons laboratory for water resources, Mass. Institute of Technology, Cambridge.

Mason, C., W.A. Birkemeier, and P.A. Howd, 1987. Overview of DUCK85 nearshore processes experiment. Proc. Conf. Coastal Sediments '87, New Orleans, pp. 818-833. American Society of Civil Engineers, New York .

McCullough, J.R., 1978. Near-surface ocean current sensors: problems and performance. Proc. Working Conf. Current Measurements. Tech. Rep. DEL-SG-3-78, pp. 9-34. College of Marine Studies, University of Delaware, Newark.

McWilliams, J.C., W.B. Owens, and B.L. Hua, 1986. An objective analysis of the POLYMODE local dynamics experiment. Part I. General formalism and statistical model selection. J. Phys. Oceanogr., v. 16, pp. 483-504.

Mellor, G.L., and T. Yamada, 1974. A hierarchy of turbulence closure models for planetary boundary layers. J. Atmos. Sci., v. 31, pp. 1791-1806.

Meyer-Peter, E., and R. Muller, 1948. Formulas for bedload transport. Int. Assoc. Hydraulic Structures Res., pp. 39-64.

Miller, M.C., and P.D. Komar, 1980. A field investigation of the relationship between oscillation ripple spacing and the near bottom water orbital motions. J. Sed. Petrol., v. 50, pp. 183-191.

Mitsuyasu, H., 1969. On the growth of the spectrum of wind-generated waves. 2. Rep. Res. Inst. Appl. Mech., Kyushu University. v. 17. pp. 235-243.

Nath, J.H., and R.G. Dean, eds., 1984. National Hazards and Research Needs in Coastal and Ocean Engineering. National Science Foundation, Washington, D.C.

National Research Council (NRC), 1977. Building Research Advisory Board. Panel on Methodology for Calculating Wave Action Effects Associated with Storm Surges. Prepared by the Engineering Program on the Prevention and Mitigation of Flood Losses, Commission on Socio-Technical Systems, Washington, D.C.

National Research Council, 1982. Measuring ocean waves. Proceedings of a Symposium and Workshop on Wave-Measurement Technology. National Academy Press, Washington, D.C.

National Research Council, 1983. Evaluation of FEMA Model for Estimating Potential Coastal Flooding from Hurricanes and Its Application to Lee County, Florida. Committee on Coastal Flooding from Hurricanes. Advisory Board on the Built Environment. CETS. Washington, D.C.

National Research Council, 1987. Responding to Changes in Sea Level, Engineering Applications. Committee on Engineering Implications of Changes in Relative Mean Sea Level. National Academy Press, Washington, D.C.

National Research Council, 1987. Responding to Changes in Sea Level, Engineering Applications. Committee on Engineering Implications of Changes in Relative Mean Sea Level. National Academy Press, Washington, D.C.

National Research Council, 1987. Sedimentation Control to Reduce Maintenance Dredging of Navigational Facilities in Estuaries, Report and Symposium Proceedings, pp. 342. Marine Board. National Academy Press, Washington, D.C.

National Research Council of Canada, 1986. Canadian Coastal Sediment Study. Final report of steering committee: A.J. Bowen, D.M. Chartrand, T.E. Daniel, C.W. Glodowski, D.J.W. Piper, J.S. Readshaw, J. Thibault, and T.H. willis, ed. Hydraulics Laboratory Technical Report No. TR-HY-013. Division of Mechanical Engineering, Ottawa, Ontario, Canada, 96 pp.

Niedzwecki, J.M., and E.W. Sandt, 1986. Non-linear wave load effects on the stochastic behavior of fixed offshore platforms. 18th Annual Offshore Technology Conference. OTC, Report 5139.

Nielsen, P., 1984. Field measurements of time-averaged suspended sediment concentrations under waves. Coastal Eng., v. 8, pp. 51-72.

Nishimura, H., and T. Sunamura, 1987. Numerical simulation of beach profile changes. Proc. 20th Int. Conf. Coastal Eng., pp. 1444-1455. American Society of Civil Engineers, New York.

Noda, E.K., 1974. Wave-induced nearshore circulation. J. Geophys. Res., v. 79, pp. 4097-4106.

Nowell, A.R.M., P.A. Jumars, and J.E. Eckman, 1981. Effects of biological activity on the entrainment of marine sediments . In: C.A. Nittrouer, ed., Developments in Sedimentology, v. 32, pp. 133-153. Elsevier, Amsterdam.

Office of Chief of Engineers, 1986. Manual-Engineering and Design: Storm Surge Analysis and Design Water Level Determinations. Engineer Manual No. 1110-2-1412. U.S. Army Corps of Engineers, Washington, D.C.

Pelnard-Considere, R., 1956. Essai de theorie de l'evolution des formes de vivage en plages de sable et de galets. IVeme Journees de l'Hydraulique, Les Energies de la Mer, Rapport no. 1, pp. 289-298.

Perlin, M., and R.G. Dean, 1983. A numerical model to simulate transport in the vicinity of coastal structures. Report MR-83-10, Waterways Experiment Station Coastal Engineering Research Center, Vicksburg, Mississippi.

Pinkel, R., and J.A. Smith, 1987. Open ocean surface wave measurement using Doppler sonar. J. Geophys. Res., v. 92, pp. 12, 967-973.

Reid, R.O., and R.E. Whitaker, 1976. Wind-driven flow of water influenced by a canopy. J. Waterways, Harbors, and Coastal Eng. Div. Proc. Am. Soc. Civil Eng., pp. 63-77.

Rubin, D.M., and D.S. McCulloch, 1979. The movement and equilibration of bedforms in central San Francisco Bay. In: T.J. Conamos, ed., San Francisco Bay, the Urbanized Estuary. Pacific Division, American Association for the Advancement of Science , 58th Annual Meeting, San Francisco, California, pp. 97-113.

Salkield, A.P., G.P. LeGood, and R.L. Soulsby, 1981. An impact sensor for measuring suspended sand concentration. Proc. Conf. Electronics for Ocean Tech., pp. 37-47. IERE, London.

Sallenger, A.J., B.E. Jaffe, and T.L. Kelley, 1986. Sonar for measurement of bottom changes in the high energy surf zone. Abstract in Fall Meeting, December, 8-10, 1986, San Francisco, California. American Geophysical Union, Washington, D.C.

Schuman, R.A., and D.K. Rea, 1981. Determination of beach sand parameters using remotely sensed aircraft reflectance data. Remote Sensing Environ., v. 11, p. 295.

Schwerdt, R.W., F.P. Ho, and R.R. Watkins, 1979. Meteorological criteria for standard project hurricane and probable maximum hurricane windfields, gulf and east coasts of the United States. NOAA Tech. Rep. NWS 23. U.S. Department of Commerce, Washington, D.C.

Schwiderski, E.W., 1980. On charting global tides. Rev. Geophys. Space Phys., v. 18(1), pp. 243-266.

Sea Wave Modeling Project Group (SWAMP), 1985. Ocean Wave Modeling, p. 256. Plenum Press, New York.

Seymour, R.J., 1987. An assessment of NSTS. Proc. Conf. Coastal Sediments '87, New Orleans, pp. 642-651. American Society of Civil Engineers, New York.

Seymour, R.J., ed., 1989. Nearshore Sediment Transport. Plenum, New York.

Seymour, R.J., A.L. Higgins, and D.P. Bothman, 1979. Tracked vehicle for continuous nearshore profiles, Proc. 16th Conf. on Coastal Eng., Hamburg, West Germany, pp. 1542-1554. American Society of Civil Engineers, New York.

Sheng, Y.P., 1983. Mathematical modeling of three-dimensional coastal currents and sediment dispersion: model development and application. Tech. Report CERC-83-2. U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi. 288 pp.

Sheng, Y.P., 1982. Hydraulic applications of a second-order closure model of turbulent transport. In: P. Smith, ed., Applying Research to Hydraulic Practice, pp. 106-119. American Society of Civil Engineers, New York.

Smith, J.D., 1977. Modeling of sediment transport on continental shelves. The Sea, v. 6, pp. 539-577. Interscience, New York.

Sobey, R.J., 1986. Wind-Wave Prediction. Annu. Rev. Fluid Mech., v. 18, pp. 149-172.

Soulsby, R.L., 1988. The structure of suspended sediment transport formulae for uni-directional and wave-plus-current flows. IAHR Symposium on Mathematical Modelling of Sediment Transport in the Coastal Zone, pp. 68-78.

Southard, J.B., 1971. Representation of bed configurations in depth-velocity size diagrams. J. Sed. Petrol., v. 41, pp. 903-915.

Sunamura, T., and K. Horikawa, 1974. Two-dimensional beach transformation due to waves. Proc. 14th Int. Conf. Coastal Eng., pp. 920-938. American Society of Civil Engineers, New York.

Svendsen, I.A., H.A. Schaffer, and J.B. Hansen, 1987. The interaction between the undertow and the boundary layer flow on a beach. J. Geophys. Res., 92, pp. 11845-11856.

Swart, D.H., 1974. Offshore sediment transport and equilibrium beach profiles. Publication No. 131. Delft Hydraulics Laboratory, Delft, The Netherlands.

Swart, D.H., 1977. Predictive equations regarding coastal transport. Proc. 15th Int. Conf. Coastal Eng., pp. 1113-1132. American Society of Civil Engineers, New York.

Symonds, G., and A.J. Bowen, 1984. Interactions of nearshore bars with incoming wave groups. J. Geophys. Res., v. 87, pp. 9499-9508.

Symonds, G., D.A. Huntley, and A.J. Bowen, 1982. Two-dimensional surf beat: Long wave generation by time-varying breakpoint. J. Geophys. Res., v. 87, pp. 492-498.

Tanaka, M., 1985. The stability of steep gravity waves, part 2. J. Fluid Mech., v. 156, pp. 281-289.

Tetra Tech., Inc., 1981. Coastal Flooding Storm Surge Model. Part 1, Methodology; Part 2, User's Guide; Part 3, Codes. Federal Emergency Management Agency, Washington, D.C.

Thomas, I.L., 1980. Suspended sediment dynamics from repetitive LANDSAT data. Int. J. Remote Sensing, v. 1, p. 285.

Thornton, E.B., 1970. Variation of longshore current across the surf zone. Proc. 12th Int. Conf. Coastal Eng., pp. 291-308. American Society of Civil Engineers, New York.

Thornton, E.B., and R.T. Guza, 1986. Surf zone longshore currents and random waves: field data and models. J. Phys. Oceanogr., v. 16, pp. 1165-1178.

Tsay, T.K., and P.L.-F. Liu, 1982. Numerical solution of water-wave refraction and diffraction problems in the parabolic approximation. J. Geophys. Res., v. 87(C10), pp. 7932-7940.

U.S. Army Corps of Engineers. 1982. Field Experience with Floating Breakwaters on the Eastern United States. Report MR 82-4. Coastal Engineering Research Center, Vicksburg, Mississippi.

U.S. Army Corps of Engineers, 1984. Shore Protection Manual, Vols. 1 and 2. U.S. Government Printing Office, Washington, D.C.

U.S. Army Corps of Engineers, 1989. Impact of the January 1988 Storm. Quarterly Bulletin of the Coast of California Storm and Tidal Waves Study. U.S. Army Corps of Engineers Los Angeles District, Coastal Resources Branch, Los Angeles, California.

U.S. Army Corps of Engineers, Coastal Engineering Research Center (CERC), 1984. Remote Sensing in Coastal Engineering. CERC Bull. (v) CERC-84-3. Vicksburg, Mississippi.

U.S. Department of the Interior, Bureau of Reclamation, 1957. Density measurement of saturated submersed sediment by gamma ray scattering. Div. of Eng. Labs., Chem. Eng. Lab. Rept. No. SI-11, March 25, 1957. Washington, D.C.

Van Dorn, W.G., 1984. Source tsunami characteristics deducible from tide records. J. Phys. Oceanogr., v. 13, pp. 353-363.

Vastano, A.C., and R.O. Reid, 1970. Tsunami response at Wake Island: comparison of hydraulic and numerical approaches. J. Mar. Res., v. 28, pp. 345-356.

Vastano, A.C., and R.O. Reid, 1985. Sea surface topography estimation with infrared satellite imagery. J. Atmos. Oceanic Technol., v. 2, pp. 393-400.

Vermulakonda, S.R., A. Swain, J.R. Houston, P.D. Farrar, L.W. Chou, and B.A. Ebersole, 1985. Coastal and inlet processes, numerical modeling system for Oregon Inlet, North Carolina. Report CERC 85-6, p. 93. Waterways Experiment Station, Coastal Engineering Research Center, Vicksburg, Mississippi.

Vesecky, J.F., R.H. Stewart, R.A. Shuchman, H.M. Assal, E.S. Kasischke, and J.D. Lydent, 1986. On the ability of synthetic aperture radar to measure ocean waves. In: D.M Phillips and K. Hasselman, eds., Wave Dynamics and Radio Probing of the Ocean Surface. Plenum Press, New York.

Vincent, C.L., and D.E. Lichy, 1982. Wave measurements in ARSLOE, Paper presented at the Conference of Directional Wave Spectra Applications. American Society of Civil Engineers, San Francisco, California.

Walsh, E.J., D.W. Hancock III, D.E. Hines, and J.E. Kenney, 1986. Remote sensing of directional wave spectra using the surface contour radar. In: D.M Phillips and K. Hasselman, eds., Wave Dynamics and Radio Probing of the Ocean Surface. Plenum Press, New York.

WAMDI Group, 1988. The WAM model—A third generation ocean wave prediction model. J. Phys. Oceanog., v. 18, pp. 1775-1810.

Wang, D.P., and C.N.K. Mooers, 1976. Coastal trapped waves in a continuously stratified ocean. J. Phys. Oceanogr., v. 6, pp. 853-863.

Wang, S., and E. Noble, 1982. Columbia River Entrance Channel Ship Motion Study. J. Waterways, Port, Coastal, and Ocean Eng., v. 108, WW3. New York: American Society of Civil Engineers.

Watanabe, A., 1982. Numerical models of nearshore currents and beach deformation. Coastal Engr. in Japan, v. 25, pp. 147-161.

Whalin, R.W., 1972. Wave refraction theory in a convergence zone. Proc. 13th Int. Conf. Coastal Eng., pp. 451-470. American Society of Civil Engineers, New York.

White, T.E., and D.L. Inman, 1987. Measuring longshore transport with tracers, Chapter 13. In: R.J. Seymour ed., Nearshore Sediment Transport. Plenum Press, New York.

Williams, A.J., III, and J.S. Tochko, 1977. An acoustic sensor of velocity for benthic boundary layer studies. In: J.C.J. Nihoul, ed., *Bottom Turbulence*, pp. 33-97. Elsevier, Amsterdam.

Wright, L.D., A.D. Short, and M.O. Green, 1985. Short-term changes in the morpho-dynamic states of beaches and surf zones: an empirical predictive model. Mar. Geol., v. 62, pp. 339-364.

Wu, C.-S., and P.L.-F. Liu, 1985. Finite element of modeling of nonlinear coastal currents. J. Waterways, Port, Coastal Ocean Eng., Proc. Am. Soc. Civil Eng., v. 111(2), pp. 417-432.

Wu, C.-S., E.B. Thornton, and R.T. Guza, 1985. Waves and longshore currents: Comparison of a numerical model with field data. J. Geophys. Res., v. 90, pp. 4951-4958.

Wu, Jin, 1985. Parameterization of wind-stress coefficients over water surfaces. J. Geophys. Res., v. 90, pp. 9069-9072.

Yalin, M.S., 1977. Mechanics of sediment transport, 2d ed. Pergamon Press, Oxford.