CHAPTER 1

INTRODUCTION TO COASTAL ENGINEERING

I. OVERVIEW OF COASTAL ENGINEERING AND THE SPM

The Shore Protection Manual (SPM) assembles in a single source the current state-of-the-art of coastal engineering to provide appropriate guidance for application of techniques and methodology to the solution of coastal design problems. As the state-of-the-art advances, the manual is periodically revised. This is the fourth edition of the SPM and the seventh major revision of this material since its predecessor report "Shore Protection, Planning and Design" (TR-4) was originally published (U.S. Army, Corps of Engineers, 1954).

Coastal engineering, a specialized branch of the engineering profession, is a composite of the many physical science and engineering disciplines having application in the coastal area. Coastal engineering addresses both the natural and man-induced changes in the coastal zone, the structural and non-structural protection against these changes, and the desirable and adverse impacts of possible solutions to problem areas on the coast. Although the SPM focuses primarily on shore protection, i.e., coastal works designed to stabilize the shores against erosion due principally to water wave action, most of the material is also applicable to the design of harbor works and navigation channel improvements.

Because the nature and complexity of most coastal problems vary widely with location, the proper solution of any specific problem requires a systematic and thorough study. The first requisite for such a study is a clear definition of the problem, the causes, and the objectives to be met by the solution. Ordinarily, there will be more than one method of achieving the immediate objectives. Therefore, the immediate and long-term effects of each method should be studied, not only within the problem area but also in adjacent shore areas. All physical and environmental effects, advantageous and detrimental, should be considered in comparing the overall cost, including annual maintenance, and benefits to determine the justification of protection methods.

The SPM provides sufficient introductory material and engineering methodology to allow a person with an engineering background to obtain an understanding of coastal phenomena and to solve related engineering problems. The manual includes detailed summaries of applicable methods, techniques, and useful data pertinent to the solution of coastal engineering problems.

Chapter 1 presents a basic introduction to the subject. Chapter 2, "Mechanics of Wave Motion," reviews wave theories, wave refraction and diffraction, wave reflection, and breaking waves. Chapter 3, "Wave and Water Level Predictions," discusses wave forecasting and the water level fluctuations caused by tides, storm surges, and tsunamis. Chapter 4, "Littoral Processes," examines the characteristics and sources of littoral material, nearshore currents, littoral transport, and sand budget techniques. Chapter 5, "Planning Analyses," treats the functional planning of shore protection measures. Chapter 6, "Structural Features," illustrates the structural design of various coastal or protective structures. Chapter 7, "Structural Design--Physical Factors," considers the effects of environmental forces on the design of protective works. Chapter 8, "Engineering Analysis--Case Study," presents a series of calculations for the preliminary design of a hypothetical structure. Each chapter includes a listing of bibliographic sources.

The SPM concludes with four supporting appendixes. Appendix A is a glossary of coastal engineering terms used. Appendix B lists and defines the symbols used. Appendix C is a collection of miscellaneous tables and plates that supplement the material in the chapters, and Appendix D is the subject index.

II. THE COASTAL AREA

In any discussion on engineering, an agreement on the meaning of terms is necessary before effective communication can occur. Since the varied meanings of coastal engineering terms used over the years have complicated dialogue, the glossary in Appendix A has been assembled to establish a common vocabulary for the SPM. Figure 1-1 provides a visual definition of the terms discussed in this chapter.

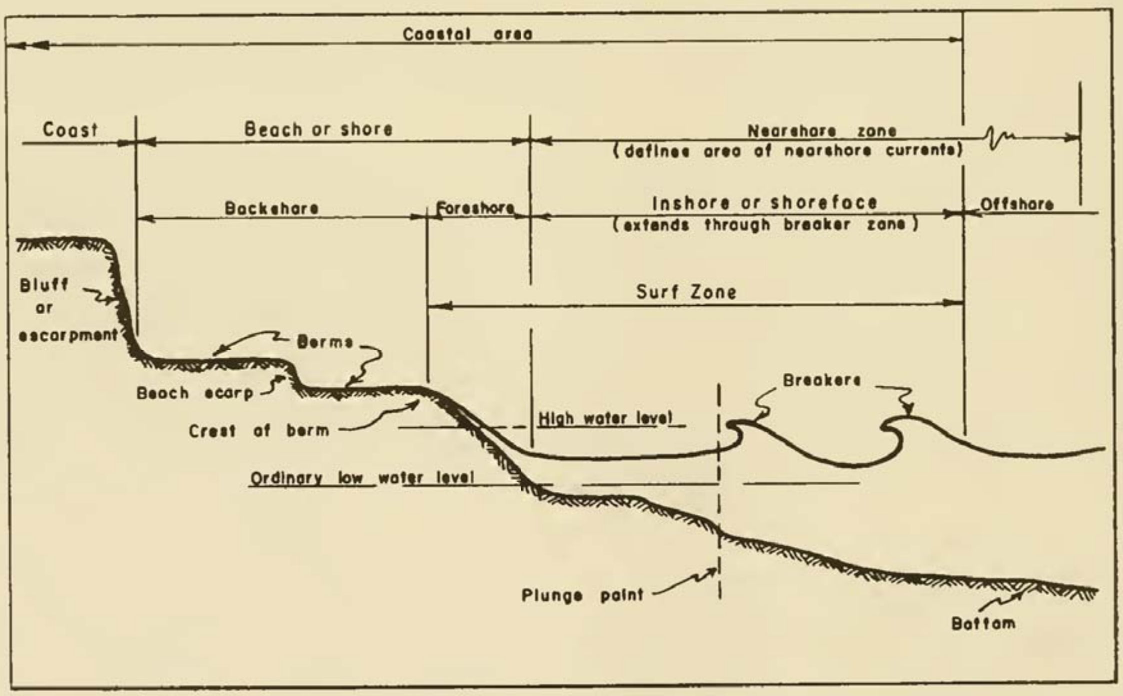

Figure 1-1. Visual definition of terms describing a typical beach profile.

Any overview of the coastal area quickly reveals a wide variability of coastal landforms. The "Report on the National Shoreline Study" (U.S. Army, Corps of Engineers, 1971) indicates that of the total 135,550 kilometers (84,240 miles) of U.S. shoreline, 55,550 kilometers (34,520 miles) (41 percent) is exposed shoreline and 80,000 kilometers (49,720 miles) (59 percent) is sheltered shoreline (i.e., in bays, estuaries, and lagoons). About 33,000 kilometers (20,500 miles) of the shoreline (or 24 percent of the total) is eroding. Of the total length of shoreline, exclusive of Alaska (59,450 kilometers or 36,940 miles), about 19,550 kilometers (12,150 miles) (33 percent) has beaches; the remaining 39,900 kilometers (24,790 miles) is rocky or otherwise lacks the typical beach characteristics described in Figure 1-1. Likewise the coast along shorelines varies. In New England, it is frequently rocky promontories while the south Atlantic and gulf coasts are generally low, dotted with backbays, wide estuaries, and marshes. Southern California with a history of a rising landmass has coastal cliffs of conglomerate material, some of which were at one time beaches. The coast of the north Pacific and Alaska is dominated by the basaltic deposits of postvolcanic activity, weathered by the action of water. Even on a more local scale, beaches and coasts can vary widely reflecting their differences in geologic history and recent wave and current action.

Where the land meets the ocean at a sandy beach, the shore has natural defenses against attack by waves, currents, and storms. The first of these defenses is the sloping nearshore bottom that causes waves to break offshore, dissipating their energy over the surf zone. The process of breaking often creates an offshore bar in front of the beach that helps to trip following waves. The broken waves re-form to break again, and may do this several times before finally rushing up the beach foreshore. At the top of wave uprush a ridge of sand is formed. Beyond this ridge, or crest of the berm, lies the flat beach berm that is reached only by higher storm waves.

During the early days of the United States, natural beach processes molded the shore as in ages past. As the country developed, shore activity was confined principally to harbor areas, and development along the shore progressed slowly as small, isolated fishing villages. As the national economy grew and transportation improved, more people began to use the beaches. Gradually, extensive housing and commercial, industrial, recreational, and resort developments replaced the fishing villages as the predominant coastal manmade features. Examples of this development are Atlantic City, Miami Beach, Honolulu, and Imperial Beach south of San Diego.

Numerous factors control the growth of development at beach areas, but undoubtedly the beach environment is the development's basic asset. The desire of visitors, residents, and industries to find accommodations as close to the ocean as possible has resulted in man's encroachment on the sea. In their eagerness to be as close as possible to the water, developers and property owners often forget that land in the coastal area comes and goes, and that land which nature provides at one time may later be reclaimed by the sea. Once the seaward limit of a development is established, this boundary between land and sea is perceived as fixed and must be held if large investments are to be preserved. Whether the problem is one of natural erosion processes working on the coastal land that threatens man's presence there, or erosion induced by man's encroachment on the sea, the results are similar. Erosion generally leads to either great monetary losses due to storm damage or even larger expenditures for shore protection to prevent the loss.

Another problem in the coastal area is the need for inland waterborne commerce on rivers and bays which must pass through the coastal area to reach deep water. Inlets which once migrated to suit the water and wave forces acting on them are now being pinned in place by jetties, creating accretion and erosion problems on their flanks.

Coastal engineering is the discipline which deals with these problems. To do this, the coastal engineer must not only design a solution but also have knowledge of the natural processes at work, the wind and water forces driving them, and the probable impact of the solution on the existing coastal system and environment. Coastal engineering is a very site-specific discipline, and solutions successful at one point may not work at another.

To achieve the objectives of coastal engineering, practitioners must utilize several disciplines. From field investigations and a knowledge of physics, they develop an understanding of the coastal processes at the project site. Then using models, both physical and numerical, they study the possible solutions and their impacts. However, no factor is more important for the engineer than past experience. Monitoring of constructed projects provides tremendous assistance towards planning the next.

The coastal engineer's work is divided into three phases: understanding the nearshore physical system and the shoreline's response to it; designing coastal works to meet project objectives within the bounds of acceptable coastal impact; and overseeing the construction of coastal works and monitoring their performance to ensure that projects function as planned.

III. THE BEACH AND NEARSHORE SYSTEM

The beach and nearshore zone of a coast is the region where the forces of the sea react against the land. The physical system within this region is composed primarily of the motion of the sea, which supplies energy to the system, and the shore, which absorbs this energy. Because the shoreline is the intersection of the air, land, and water, the physical interactions which occur in this region are unique, very complex, and difficult to fully understand. As a consequence, a large part of the understanding of the beach and nearshore physical system is simply descriptive in nature.

1. The Sea.

Water covers 71 percent of the Earth, and thus a large part of the Sun's radiant energy that is not reflected back into space is absorbed by the water of the oceans. This absorbed energy warms the water, which in turn warms the air above the oceans, and forms air currents caused by differences in air temperature. These air currents blow across the water, returning some energy to the water by generating *wind waves*. The waves then travel across the oceans until they reach land where their remaining energy is expended on the shore. The power in the waves as they arrive in the nearshore zone can vary from 1.39 megawatts per kilometer (3,000 horsepower per mile) of beach on a relatively calm day (0.6-meter or 2-foot waves) to 25 times this amount or more during a storm.

The motions of the sea which contribute to the beach and nearshore physical system include waves, tides, currents, storm surges, and tsunamis. Wind waves are by far the largest contribution of energy from the sea to the beach and nearshore physical system. As winds blow over the water, waves are generated in a variety of sizes from ripples to large ocean waves as high as 30 meters (100 feet) (see Fig. 1-2).

Figure 1-2. Large waves breaking over a breakwater.

Wind waves, which are also known as oscillatory waves, are usually defined by their height, length, and period (see Fig. 1-3). Wave height is the vertical distance from the top of the crest to the bottom of the trough. Wavelength is the horizontal distance between successive crests. Wave period is the time between successive crests passing a given point. As waves propagate in deep water, only the waveform and part of the energy move forward; the water particles move in a nearly circular path.

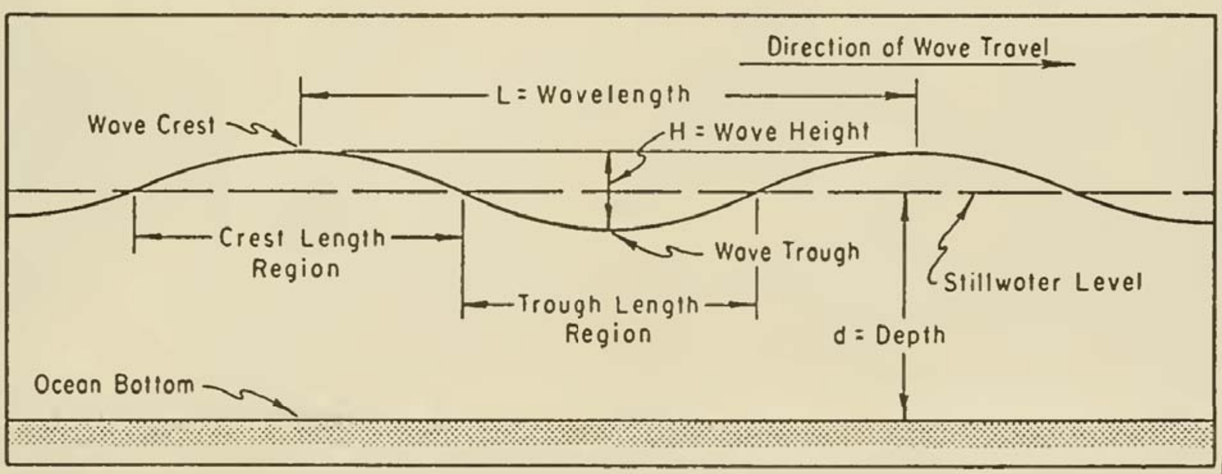

Figure 1-3. Wave characteristics.

The height, length, and period of wind waves at a site in the open ocean are determined by the *fetch* (the distance the wind blows over the sea in generating the waves), the windspeed, the duration (the length of time the wind blows), the *decay distance* (the distance the wave travels after leaving the generating area), and the water depth. Generally, increases in fetch, windspeed, or duration result in larger wind waves. The water depth, if shallow enough, will also affect the size of waves generated. The wind simultaneously generates waves of many heights, lengths, and periods as it blows over the sea.

If winds of a local storm blow toward the shore, the waves will reach the beach in nearly the same waveform in which they are generated. Under these conditions, the waves are steep; i.e., the wavelength is 10 to 20 times the wave height. Such waves are called *seas*. If waves are generated by a distant storm, they may travel through hundreds or even thousands of miles of calm wind areas before reaching the shore. Under these conditions, waves *decay*--short, steep waves are transformed into relatively long, low waves which reach the shore. Such waves, which have lengths from 30 to more than 500 times the wave height, are called *swell*.

Tides are created by the gravitational force of the Moon and, to a lesser extent, the Sun. These forces of attraction, and the fact that the Sun, Moon, and Earth are always in motion relative to each other, cause waters of ocean basins to be set in motion. These tidal motions of water masses are a form of very long period wave motion, resulting in a rise and fall of the water surface at a point. There are normally two tides per day, but some localities have only one per day. Tides constantly change the level at which waves attack the beach.

The range of tides varies tremendously with geographic location. Some areas, such as Eastport, Maine, experience an average tidal range of about 5.5 meters (18 feet) while other locations, such as Mobile, Alabama, experience variations of about 0.6 meter. Even more dramatic is the difference between mean tidal ranges at Anchorage (7.9 meters or 26 feet) and Kodiak Island (2.1 meters or 7 feet), Alaska. These sites are only 415 kilometers (224 nautical miles) apart.

Currents and *surges* sometimes play an important role in the nearshore physical system. When water in one area becomes higher than water in another area, water from the higher elevation flows toward the lower level, creating a current. Significant currents generated by tides occur at inlets to lagoons and bays or at entrances to harbors. Tidal currents in these constricted places flow in when the tide is rising (floodtide) and flow out as the tide falls (ebbtide). Exceptions can occur at times of high river discharge or strong winds. Currents can be caused by differences in water elevation due to (a) wind, (b) waves breaking on a beach, and (c) river discharge. The river discharge to the sea introduces currents into the nearshore zone.

Wind creates currents as it blows over the water surface, producing a stress on surface water particles and starting the movement of the particles in the direction in which the wind is blowing. Thus, a surface current is created. When the surface current reaches a barrier, such as the coast, water tends to pile up against the land. Strong winds create *wind setup* or *storm surges* in this way. The height of storm surge depends on wind speed and direction, fetch, atmospheric pressure, offshore bathymetry, and nearshore slope. In violent storms, storm surge may raise the water level at the shore as much as 6 meters (20 feet). In the United States, larger surges occur on the gulf coast because of the shallower and broader shelf off that coast compared to the shelf off both the Atlantic and Pacific coasts. Storm surges may also be increased by a funneling effect in converging shorelines within estuaries.

When waves approach the beach at an angle, they create a current in shallow water parallel to the shore, known as the *longshore current*. This current, under certain conditions, may turn and flow seaward in what is known as a *rip current*.

Tsunamis are waves created by earthquakes or other tectonic disturbances on the ocean bottom. These long-period waves can travel across entire oceans at speeds exceeding 800 kilometers (500 miles) per hour. Tsunamis can cause extensive damage at times, but fortunately major tsunamis do not occur frequently.

2. The Beach and Nearshore Zone.

The shoreline, the intersection of the land and the sea, is where tides, winds, and waves attack the land; and it is where the land responds to this attack by a variety of "give and take" measures which effectively dissipate the sea's energy. The shores of the United States include practically all known landforms of many clastic materials from various stages of geologic evolution. The areas most directly affected by the forces of the sea are the *beach* and the *nearshore zone* regions that experience the full impact of the sea's energy. Hence, they are the most dynamic areas in the coastal zone.

Beach sediments on most beaches range from fine sands to cobbles. The size and character of sediments and the slope of the beach are related to the forces to which the beach is exposed and the type of material available on the coast. Much of the beach material originates many miles inland where weathering of the mountains produces small rock fragments that are supplied to the beach by streams and rivers. When these fragments reach the shore as sand, they are moved alongshore by waves and currents. This longshore transport is a constant process, and great volumes may be transported. Beach material is also derived from erosion of the coastal formations caused by waves and currents and, in some cases, by onshore movement of sediment from deeper water. In some regions, a sizable fraction of the beach material is composed of marine shell fragments, coral reef fragments, or volcanic materials. Clay and silt do not usually exist on ocean beaches because the waves create such turbulence in the water along the shore that these fine particles are kept in suspension. The particles settle and deposit on the bottom only after moving away from the beaches into the quieter water of lagoons and estuaries or the deeper water offshore.

Beach characteristics are usually described in terms of average size of the sand particles that make up the beach, range and distribution of sizes of the sand particles, sand composition, elevation and width of berm, slope or steepness of the foreshore, the existence (or lack) of a bar, and the general slope of the inshore zone fronting the beach. Generally, the larger the sand particles the steeper the beach slope. Beaches with gently sloping foreshores and inshore zones usually have a preponderance of the finer sizes of sand. Daytona Beach, Florida, is a good example of a gently sloping beach composed of fine sand.

Barrier islands are an important part of the physical system in some areas (see Fig. 1-4). These are long narrow islands or spits lying parallel to the mainland. Most of the coast on the U.S. Atlantic south of Long Island and along the gulf is composed of barrier islands. During severe storms these barrier islands provide protection for the mainland by absorbing the brunt of the wave attack. However, many barrier islands are so highly developed that the protection of their beaches has become an important consideration (see Fig. 1-5).

Figure 1-4. Undeveloped barrier island on the gulf coast of Alabama after Hurricane Frederic.

Lagoons are shallow bodies of water separating the barrier beach from the mainland. They are usually connected to the sea by narrow channels through which tidal currents flow. Lagoons provide a habitat for a wide variety of wildlife, and many lagoons serve as safe harbors and navigable waterways.

An *inlet* is the narrow opening between the lagoon and the ocean. Inlets occur at fairly regular intervals along a barrier island chain, and they often, when improved, provide a navigation passage to the sea. When barrier beach dunes are breached by storm wave attack, the result may be the cutting of a new inlet. An inlet can permit beach material removed by storms to enter a lagoon and be deposited there. It may also allow some bottom material from a lagoon to be carried oceanward by tidal currents and then be transported along the shore by wave action. Over time, changing conditions may cause some inlets to close and new inlets to open.

Figure 1-5. Developed barrier island, Atlantic City, New Jersey.

IV. DYNAMIC BEACH RESPONSE TO THE SEA

The beach constantly adjusts its profile to provide the most efficient means of dissipating incoming wave energy. This adjustment is the beach's natural dynamic response to the sea. Although an equilibrium is sometimes reached between the beach and the sea, the "peace" is short-lived and the "battle" soon begins anew.

There are two general types of dynamic beach response to wave motion: response to normal conditions and response to storm conditions. Normal conditions prevail most of the time, and the wave energy is easily dissipated by the beach's natural defense mechanisms. However, when storm conditions generate waves containing increased amounts of energy, the coast must respond with extraordinary measures, such as sacrificing large sections of beach and dune. In time the beach may recover, but often not without a permanent loss.

1. Normal Beach Response.

As a wave moves toward shore, it encounters the first beach defense in the form of the sloping nearshore bottom. When the wave reaches a water depth equal to about 1.3 times the wave height, the wave collapses or breaks. Thus a wave 0.9 meter (3 feet) high will break in a depth of about 1.2 meters (4 feet). Breakers are classified as four types--plunging, spilling, surging, or collapsing. The form of breakers is controlled by wave steepness and nearshore bottom slope. Breaking results in a dissipation of wave energy by the generation of turbulence in the water and by the transport of sediment lifted off the bottom and tossed around by the turbulent water. Broken waves often re-form to break again, losing additional energy. Finally, the water travels forward as a foaming, turbulent mass and expends most of its remaining energy in a rush up the beach slope. If there is an increase in the incoming wave energy, the beach adjusts its profile to facilitate the dissipation of the additional energy. This is most frequently done by the seaward transport of beach material to an area where the bottom water velocities are sufficiently reduced to cause sediment deposition. Eventually enough material is deposited to form an offshore bar which causes the waves to break farther seaward, widening the surf zone over which the remaining energy must be dissipated. Tides compound the dynamic beach response by constantly changing the elevation at which the water intersects the shore and by providing tidal currents. Thus, the beach is always adjusting to changes in both wave energy and water level.

Natural protective dunes are formed by winds blowing onshore over the foreshore and berm, transporting sand landward from the beach (see Figs. 1-6 and 1-7). Grass and sometimes bushes and trees grow on the dunes, and the dunes become a natural levee against sea attack. Dunes provide a reservoir of beach sand which in turn provides the final natural protection line against wave attack.

2. Beach Response to Storms.

The subtle changes in the beach which occur during normal conditions are nearly imperceptible to the untrained observer, but the beach's defense mechanisms become obvious when storms attack. Storms do not occur often, but their effects are often devastating in terms of shoreline erosion.

During storms, strong winds generate high, steep waves. In addition, these winds often create a storm surge which raises the water level and exposes to wave attack higher parts of the beach not ordinarily vulnerable to waves. The storm surge allows the large waves to pass over the offshore bar formation without breaking. When the waves finally break, the remaining width of the surf zone is not sufficient to dissipate the increased energy contained in the storm waves. The remaining energy is spent in erosion of the beach, berm, and sometimes dunes which are now exposed to wave attack by virtue of the storm surge. The eroded material is carried offshore in large quantities where it is deposited on the nearshore bottom to form an offshore bar. This bar eventually grows large enough to break the incoming waves farther offshore, forcing the waves to spend their energy in the surf zone. This process is illustrated in Figure 1-8.

Beach berms are built naturally by waves to about the highest elevation reached by normal storm waves. When storm waves erode the berm and carry the sand offshore, the protective value of the berm is reduced and large waves can overtop the beach. The width of the berm at the time of a storm is thus an important factor in the amount of upland damage a storm can inflict.

In severe storms, such as hurricanes, the higher water levels resulting from storm surges allow waves to erode parts of a dune. It is not unusual for 18- to 30-meter-wide (60- to 100- foot) dunes to disappear in a few hours. Storm surges are especially damaging if they occur concurrently with high astronomical tides.

1976

Figure 1-6. Sand dunes on Padre Island, Texas.

1977

Figure 1-7. Sand dunes at Nauset Spit, Cape Cod, Massachusetts.

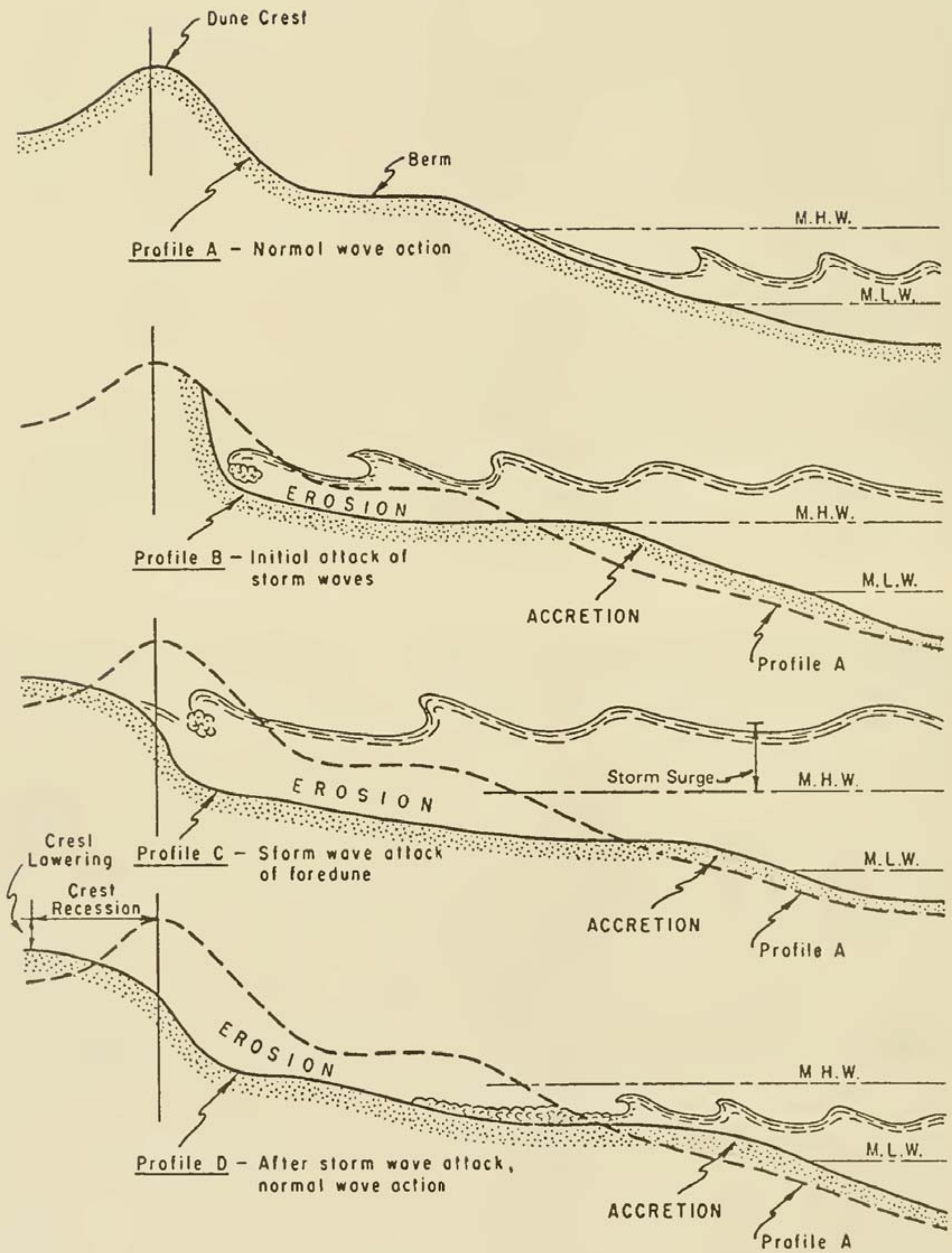

Figure 1-8. Schematic diagram of storm wave attack on beach and dune.

In essence, the dynamic response of a beach under storm attack is a sacrifice of some beach, and often dune, to provide material for an offshore bar. This bar protects the shoreline from further erosion. After a storm or storm season, natural defenses may again be re-formed by normal wave and wind action.

Besides causing erosion of the shoreline, storm surges can damage shore structures that are inadequately protected and located close to the water by either direct wave attack or undermining of the structure.

At locations where there is a low section of protective dunes, or when the storm conditions are particularly severe, the storm surge and wave action may succeed in completely overtopping the dunes causing extensive coastal flooding. When this occurs, beach and dune sediments are swept landward by the water, and in the case of barrier islands, are deposited as *overwash fans* on the backshore or in the lagoon. This process results in a loss of sand from the dynamic beach system. Often, storm overwash and storm flooding return flow will erode enough sand to cut a new tidal inlet through the barrier island. Depending on various factors, the new inlet may become a permanent feature of the coastline.

3. Beach and Dune Recovery from Storm Attack.

Following a storm there is a return to more normal conditions which are dominated by low, long swells. These waves transport sand from the offshore bar, built during the storm, and place the material on the beach. Winds then transport the sand onto the dunes where it is trapped by the vegetation. In this manner the beach begins to recover from the storm attack. The rebuilding process takes much longer than the short span of erosion which took place. Therefore, a series of violent local storms over a short period of time can result in severe erosion of the shore because the natural protection does not have time to rebuild between storms. Sometimes full recovery of the beach never occurs because sand is deposited too far offshore during the storm to be returned to the beach by the less steep, normal waves which move material shoreward. This is particularly true in the Great Lakes and in bays and estuaries where waves are fetch-limited and do not develop into long swell waves.

Alternate erosion and accretion may be seasonal on some beaches; the winter storm waves erode the beach, and the summer swell (waves) rebuilds it. Beaches also appear to follow long-term cyclic patterns, where they may erode for several years and then accrete for several years.

4. Littoral Transport.

Another dynamic feature of the beach and nearshore physical system is *littoral transport*, defined as the movement of sediments in the nearshore zone by waves and currents. Littoral transport is divided into two general classes: transport parallel to the shore (longshore transport) and transport perpendicular to the shore (onshore-offshore transport). The material that is transported is called *littoral drift*.

Onshore-offshore transport is determined primarily by wave steepness, sediment size, and beach slope. In general, high steep waves move material offshore, and low waves of long period (low steepness waves) move material onshore. The onshore-offshore process associated with storm waves is illustrated in Figure 1-8.

Longshore transport results from the stirring up of sediment by the breaking wave and the movement of this sediment by both the component of the wave energy in an alongshore direction and the longshore current generated by the breaking wave. The direction of longshore transport is directly related to the direction of wave approach and the angle of the wave (crest) to the shore. Thus, due to the variability of wave approach, longshore transport direction can vary from season to season, day to day, or hour to hour. Reversals of transport direction are quite common for most U.S. coasts. Direction may vary at random, but in most areas the net effect is seasonal.

The rate of longshore transport is dependent on the angle of wave approach, duration, and wave energy. Thus, high storm waves will generally move more material per unit time than that moved by low waves. However, if low waves exist longer than high waves, the low waves may be more significant in moving sand than the high waves.

Because reversals in transport direction occur, and because different types of waves transport material at different rates, two components of the longshore transport rate become important. The first is the net rate, the net amount of material passing a particular point in the predominant direction during an average year. The second component is the gross rate, the total of all material moving past a given point in a year regardless of direction. Most shores consistently have a net annual longshore transport in one direction. Determining the direction and average net and gross annual amount of longshore transport is important in developing shore protection plans. In inland seas, such as the Great Lakes, a longshore transport rate in one direction can normally be expected to be no more than about 115,000 cubic meters (150,000 cubic yards) per year. For open ocean coasts, the net rate of transport may vary from 75,000 to more than 1.5 million cubic meters (100,000 to 2 million cubic yards) per year. The rate depends on the local shore conditions and shore alinement, as well as the energy and direction of wave approach.

5. Effect of Inlets on Barrier Beaches.

Inlets may have significant effects on adjacent shores by interrupting the longshore transport and trapping onshore-offshore moving sand. During ebbtide, sand transported to the inlet by waves is carried seaward a short distance and deposited on an outer bar. When this bar becomes large enough, the waves begin to break on it, moving the sand over the bar back toward the beach. During floodtide, when water flows through the inlet into the lagoon, sand in the inlet is carried a short distance into the lagoon and deposited. This process creates shoals in the landward end of the inlet known as *middleground shoals* or *inner bars*. Later, ebb flows may return some of the material in these shoals to the ocean, but some is always lost from the littoral system and thus from the downdrift beaches. In this way, tidal inlets store sand and reduce the supply of sand to adjacent shores. Estimates of the amount of material deposited in the middleground shoals range from 100,000 to 160,000 cubic meters (130,000 to 210,000 cubic yards) per year for inlets on the east coast of Florida (Walton and Adams, 1976), but quantities elsewhere vary widely according to local conditions.

6. Beach Stability.

Although a beach may be temporarily eroded by storm waves and later partly or wholly restored by swells, and erosion and accretion patterns may occur seasonally, the long-range condition of the beach--whether eroding, stable, or accreting--depends on the rates of supply and loss of littoral material. The shore accretes or progrades when the rate of supply exceeds the rate of loss. The shore is considered stable (even though subject to storm and seasonal changes) when the long-term rates of supply and loss are equal. Thus, conservation of sand is an important aspect of shore protection.

V. CAUSES OF SHORELINE EROSION

Before embarking upon any method of coastal protection, it is important to identify and understand both the short- and long-term causes of coastal erosion. Failure to do this may result in the design and placement of shore protection measures which actually accelerate the process that the protection measure was intended to alleviate. Although the most serious incidents of coastal erosion occur during storms, there are many other causes, both natural and man-induced, which need to be examined.

Natural causes of erosion are those which occur as a result of the response of the beach to the effects of nature. Man-induced erosion occurs when human endeavors impact on the natural system. Much of the man-induced erosion is caused by a lack of understanding and can be successfully alleviated by good coastal zone management. However, in some cases coastal erosion can be due to construction projects that are of economic importance to man. When the need for such projects is compelling, the coastal engineer must understand the effects that the work will have on the natural system and then strive to greatly reduce or eliminate these effects through designs which work in harmony with nature.

Natural and man-induced causes of erosion, as discussed below, are given in Table 1-1.

1. Natural Causes.

a. Sea Level Rise. A long-term rise in sea level relative to the land exists in many areas of the world. This rise results in a slow, long-term recession of the shoreline, partly due to direct flooding and partly as a result of profile adjustment to the higher water level.

b. Variability in Sediment Supply to the Littoral Zone. Changes in the world's weather pattern that cause droughts can result in a reduction in the occurrence of floods on rivers supplying sediment to the coastal zone.

c. Storm Waves. Steep waves from a coastal storm cause sand to be transported offshore with temporary storage in a bar or shoal. Later partial recovery of the beach may be made through natural transport of this material onshore by longer period, flatter waves. But, in most cases, some material is permanently lost into the greater offshore depths.

d. Wave and Surge Overwash. Overwash is a phenomenon which occurs during periods of storm surge and severe wave action. Waves and overflowing water erode the beach and transport and deposit this material shoreward of the beach, or as an overwash fan on the bay side of low-lying barrier islands.

e. Deflation. The removal of loose material from a beach by wind action can be a significant cause of erosion. In many parts of the world, major natural dune fields exist well behind the active beach zone. These dunes can represent a large volume of beach sediment.

f. Longshore Sediment Transport. Sand is transported alongshore by waves breaking at an angle to the shore. If the sediment carrying capacity of the longshore current generated by these waves exceeds the quantity of sediment naturally supplied to the beach, erosion of the beach results.

g. Sorting of Beach Sediment. Sorting of beach sediment by wave action results in the selective redistribution of sediment particles (sand, shell, and shingle) along a beach profile according to size or hydraulic properties. This mechanism is particularly important in designing beach nourishment projects because the selective loss of finer material to the offshore region and the retention of the coarse material in the surf zone require the placement of additional fill in order to balance this loss. Best results are usually achieved when the fill material is similar in grain-size distribution to the native beach material.

Table 1-1. Causes of coastal erosion.

Natural	Man-induced
a. Sea level rise	a. Land subsidence from removal of subsurface resources
b. Variability in sediment supply to the littoral zone	b. Interruption of material in transport
c. Storm waves	c. Reduction of sediment supply to the littoral zone
d. Wave and surge overwash	d. Concentration of wave energy on beaches
e. Deflation	e. Increase water level variation
f. Longshore sediment transport	f. Change natural coastal protection
g. Sorting of beach sediment	g. Removal of material from the beach

2. Man-Induced Causes.

a. Land Subsidence from Removal of Subsurface Resources. The removal of natural resources, such as gas, oil, coal, and groundwater underlying the coastal zone, may cause subsidence of the beach. This has the same effect as a sea level rise.

b. Interruption of Material in Transport. This factor is probably the most important cause of man-induced erosion. Improvement of inlets by both channel dredging and channel control and by harbor structures impounds littoral material (see Fig. 1-9). Often, the material is permanently lost from the downcoast beach regime either by the deposition of dredged material outside of the active littoral zone or the building of bars, shoals, and wider updrift beaches. This can be mitigated by sand-bypassing systems. Construction of protective works at the source of littoral material, such as an eroding cliff or bluff, can also result in disruption of supply. Realinement of the shoreline by the use of such structures as groins also interrupts the transport of littoral material. These structures may not only reduce the rate of a longshore transport but also may reduce littoral material reaching downcoast beaches by entrapment.

c. Reduction of Sediment Supply to the Littoral Zone. In some areas the transport of sediment to the coast by rivers form the major source of material to the littoral zone. Dams constructed on these rivers not only form sediment traps but also reduce peak floodflows, thereby reducing the sediment supply to the coast which results in coastal erosion.

d. Concentration of Wave Energy on Beaches. The building of coastal structures (such as a vertical wall) either in the active beach zone or on the backshore can increase the amount of wave energy being dissipated by the beach material fronting the structure, resulting in an increase in the rate of erosion.

e. Increase Water Level Variation. The deepening and widening of navigation inlets may adversely affect the tidal range within a harbor or bay, and may permit larger waves to enter the harbor area and adjacent beaches. An increase in tidal range will expose more of the harbor or bay beach face to the erosive effects of waves and cause a change in the beach profile.

f. Change Natural Coastal Protection. The dredging of nearshore bars and shoals can change the pattern of energy dissipation on a beach face. If the change increases the wave energy acting on a given section of beach, erosion will likely result at that section. Onshore, the leveling of dunes, destruction of beach vegetation, paving of large backshore areas, and construction of boat channels on the backside of a narrow barrier island can further increase the overwash erosion and island breaching potential.

g. Removal of Material from the Beach. Excavation of beach material is undertaken in many parts of the world. This material is sometimes mined for the minerals it contains; in other places it is used for construction purposes (landfills, construction aggregate). For whatever purpose, it is a direct loss of available supply of material for littoral transport.

VI. COASTAL PROTECTION METHODS AND NAVIGATION WORKS

The sloping beach and beach berm are the outer line of defense in absorbing most wave energy; dunes are the last zone of defense in absorbing the energy of storm waves that overtop the berm. Although dunes erode during severe storms, they are often substantial enough to afford complete protection to the

circa 1974

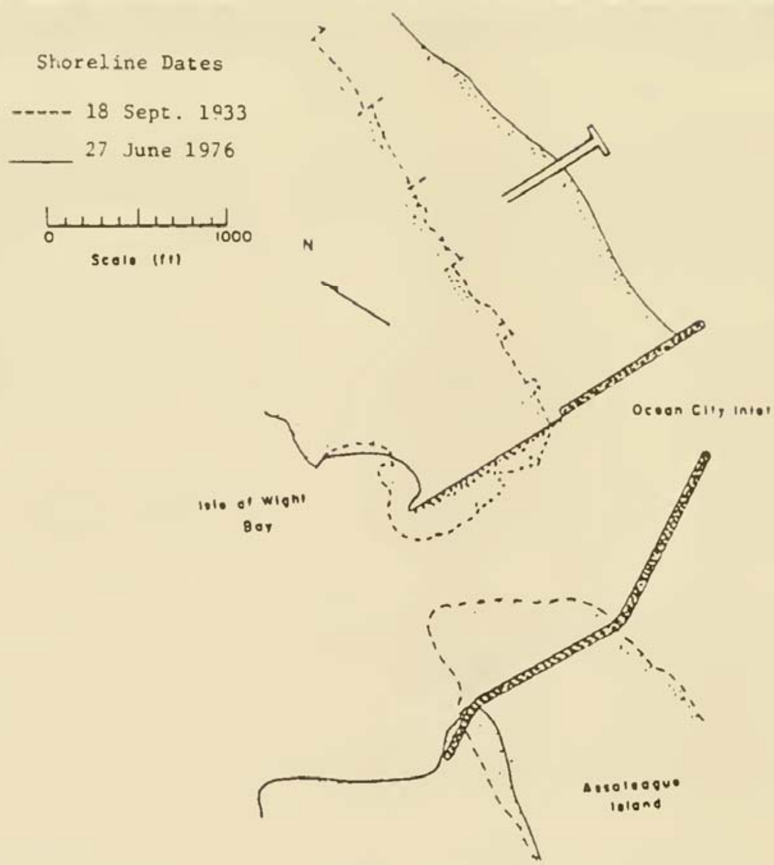

Figure 1-9. Littoral barrier, Ocean City Inlet, Maryland (after Dean and Perlin, 1977).

land behind them. Even when breached by severe storm waves, dunes may gradually rebuild naturally (over a period of several years) to provide protection during future storms.

Continuing encroachment on the sea with manmade development has often taken place without proper regard for the protection provided by dunes. Large dune areas have been leveled to make way for real estate developments, or have been lowered to permit easy access to and view of the beach area. Where there is inadequate dune or similar protection, storm waves may attack beach-front structures (see Fig. 1-10), and wave overwashes may flood and damage backshore property. Even when coastal flooding does not occur, high storm surges and associated waves can undermine and damage structures placed too close to the beach (Fig. 1-11).

When the natural protection system fails during large storms, the first solutions frequently chosen are quasi-natural methods such as beach nourishment or artificial sand-dune building. Such solutions retain the beach as a very effective wave energy dissipater and the dune as a flexible last line of defense. However, even these methods provide only a temporary solution to chronic long-term erosion caused by the diminishing supply of sediment in the littoral system and by the slow sea level rise.

The method of placing beach fill to ensure sand supply at the required replenishment rate is important. Where stabilization of an eroding beach is the problem, suitable beach material may be stockpiled at the updrift sector of the problem area. The establishment and periodic replenishment of such a stockpile is termed artificial beach nourishment. To restore an eroded beach and stabilize it at the restored position, fill is placed directly along the eroded sector, and then the beach is artificially nourished by the stockpiling method.

When conditions are suitable for artificial nourishment, long reaches of shore may be protected by this method at a relatively low cost per linear meter of protected shore. An equally important advantage is that artificial nourishment directly remedies the basic cause of most erosion problems--a deficiency in natural sand supply--and benefits rather than damages the adjacent shore. An added consideration is that a widened beach has value as a recreation feature. One of the most recent beach restoration projects began in 1977 along 17 kilometers (10.5 miles) of beach in Dade County, Florida (including Miami Beach). This project is shown in Figure 1-12.

Where beaches and dunes protect shore developments, additional protective works may not be required. However, when natural forces do create erosion, storm waves may overtop the beach and damage backshore structures. Manmade structures must then be constructed to provide protection. In general, measures designed to stabilize the shore fall into two classes: (1) structures to prevent waves from reaching a harbor area (e.g., breakwaters, seawalls, bulkheads, revetments) and (2) manmade structures, such as groins and jetties, used to retard the longshore transport of littoral drift. These may be used in conjunction with seawalls or beach fills or both.

Separate protection for short reaches of eroding shores (e.g., individual shore-front lots) within a larger zone of eroding shore, is a difficult and costly approach. Such protection often fails at flanks of these reaches as the adjacent unprotected shores continue to recede. Partial or inadequate protective measures may even accelerate erosion of adjacent shores. Coordinated action under a comprehensive plan that considers erosion processes over the full length of the regional shore compartment is much more effective and economical.

Onshore structures, termed *bulkheads*, *seawalls*, and *revetments*, provide protection, based on their use and design, for the upper beach which fronts backshore development or erodible bluffs. Shore-front owners have resorted to this shore armoring by wave-resistant walls of various types when justified by the economic or esthetic value of what is protected.

Figure 1-10. Damage after the 1962 storm, Rehoboth Beach, Delaware.

Bulkheads and seawalls are similar in design with slightly differing purposes. Bulkheads are primarily soil-retaining structures which are designed to also resist wave attack. Conversely, seawalls are principally structures designed to resist wave attack but also may retain some soil to assist in resisting wave forces. The land behind seawalls is usually a recent fill area. Bulkheads and seawalls may be built of many materials including steel, timber, or concrete piling, gabions, or rubble-mound structures.

Figure 1-11. Undermining of structures by storm waves, Potham Beach, Maine.

For ocean-exposed locations vertical bulkheads alone do not provide a long-term solution because of foreshore erosion and flanking. Unless combined with other types of protection, the bulkhead must be enlarged into a massive seawall capable of withstanding the direct onslaught of the waves. Seawalls may have vertical, curved, stepped, or sloping faces. Although seawalls protect the upland, they often create a local problem. Downward forces of water, produced by waves striking the wall, can rapidly remove sand from in front of the wall. A stone apron is often necessary to prevent excessive scouring and undermining.

A revetment armors the existing slope face of a dune or embankment. It is usually composed of one or more layers of quarrystone or precast concrete armor units, with a filter layer overlaying a graded in situ soil slope. Revetments are of little benefit if placed at the toe of a marginally stable slope since they are usually only a protective armor and not a retaining structure. Because the sloping face of the quarrystone revetment is a good energy dissipater, revetments have a less adverse effect on the beach in front of them than a smooth-faced vertical bulkhead.

Before

After

Figure 1-12. Beach Restoration, Dade County, Florida.

Breakwaters are wave energy barriers designed to protect any landform or water area behind them from the direct assault of waves. However, because of the higher cost of these offshore structures over onshore structures (e.g., seawalls), breakwaters have been mainly used for harbor protection and navigational purposes. In recent years shore-parallel, detached, segmented breakwaters have been used for shore protection structures.

Breakwaters have both beneficial and detrimental effects on the shore. All breakwaters reduce or eliminate wave action in their lee (shadow). However, whether they are offshore, detached, or shore-connected structures, the reduction or elimination of wave action also reduces the longshore transport in the shadow. For offshore breakwaters this leads to a sand accretion in the lee of the breakwater in the form of a sandbar (called a tombolo) which grows from the shore toward the structure, as well as the associated downdrift beach erosion.

Shore-connected breakwaters provide protection to harbors from wave action and have the advantage of a shore arm to facilitate construction and maintenance of the structure. In recent years, shore-parallel breakwaters built of short detached groupings have provided adequate large storm protection without adversely affecting the longshore transport.

At a harbor breakwater, the longshore movement of sand generally can be restored by pumping sand from the side where sand accumulates through a pipeline to the eroded downdrift side. This type of operation has been in use for many years at such places as Santa Barbara, California, and Channel Islands Harbor, California.

Offshore breakwaters have also been used in conjunction with navigation structures to control channel silting. If the offshore breakwater is placed immediately updrift from a navigation opening, the structure impounds sand in its lee, prevents it from entering the navigation channel, and affords shelter for a floating dredge plant to pump out the impounded material across the channel to the downdrift beach. This method has been successfully used at Channel Islands Harbor near Port Hueneme, California.

While breakwaters have been built of everything from sunken ships to large fabric bags filled with concrete, the primary material in the United States is a rubble-mound section with armor stone encasing underlayers and core material. Some European and Japanese breakwaters use a submerged mound foundation in deeper water topped with a concrete superstructure, thereby reducing the width and overall quantity of fill material necessary for harbor protection.

Groins are barrier-type structures that extend from the backshore into the littoral zone. Groins are generally constructed in series, referred to as a groin field or system, along the entire length of beach to be protected. The basic purposes of a groin are to modify the longshore movement of sand and to either accumulate sand on the shore or retard sand losses. Trapping of sand by a groin is done at the expense of the adjacent downdrift shore unless the groin or groin system is artificially filled with sand to its entrapment capacity from other sources. To reduce the potential for damage to property downdrift of a groin, some limitation must be imposed on the amount of sand permitted to be impounded on the updrift side. Since more and more shores are being protected, and less and less sand is available as natural supply, it is now desirable, and frequently necessary, to place sand artificially to fill the area between the groins, thereby ensuring an uninterrupted passage of the sand to the downdrift beaches.

Groins that have been constructed in various configurations using timber, steel, concrete, or quarrystone are classified as high or low, long or short, permeable or impermeable, and fixed or adjustable, according to their design and construction. A high groin, extending through the surf zone for ordinary or moderate storm waves, initially entraps nearly all of the longshore moving sand within that intercepted area until the accumulated sand fills the entrapment area and the sand passes around the seaward end of the groin to the downdrift beach. Low groins (top profile no higher than that of desired beach dimensions or natural beach elevation) trap sand like high groins. However, some of the sand also passes over the top of the structure. Permeable groins permit some of the wave energy and movement of sand through the structure.

Jetties are structures used at inlets to stabilize the position of the navigation channel, to shield vessels from wave forces, and to control the movement of sand along the adjacent beaches so as to minimize the movement of sand into the channel. The sand transported into an inlet will interfere with navigation and will usually necessitate more frequent dredging to maintain the navigation depth. Because of the longshore transport reversals common at many sites, jetties are often required on both sides of the inlet to achieve complete channel protection. Jetties are built from a variety of materials, e.g., timber, steel, concrete, and quarrystone. Most of the larger structures are of rubble-mound construction with quarrystone armor and a core of less permeable material to prevent sand passing through. It is the impoundment of sand at the updrift jetty which creates the major impact. When fully developed, the fillet of impounded sand extends well updrift on the beach and outward toward the tip of the jetty.

Like the groin, the jetty's major adverse impact is the erosion of the downdrift beach. Before the installation of a jetty, nature supplies sand by intermittently transporting it across the inlet along the outer bar. The reduction or cessation of this sand transport due to the presence of a jetty leaves the downdrift beach with an inadequate natural supply of sand to replace that carried away by littoral currents.

To minimize the downdrift erosion, some projects provide for dredging the sand impounded by the updrift jetty and pumping it through a pipeline (bypassing the inlet) to the downdrift eroding beach. This provides for nourishment of the downdrift beach and may also reduce shoaling of the entrance channel. If the sand impounded at the updrift jetty extends to the head or seaward end of the jetty, it will move around the jetty and into the channel causing a navigation hazard. Therefore, the updrift impounded sand should be bypassed to the downcoast beach, not only to reduce downdrift erosion but also to help maintain a safe navigation channel.

A more recent development for sand bypassing provides a low section or weir in the updrift jetty over which sand moves into a sheltered predredged, deposition basin. By dredging the basin periodically, channel shoaling is reduced or eliminated. The dredged material is normally pumped across the navigation channel (inlet) to provide nourishment for the downdrift shore. A *weir jetty* of this type at Murrells Inlet, South Carolina, is shown in Figure 1-13.

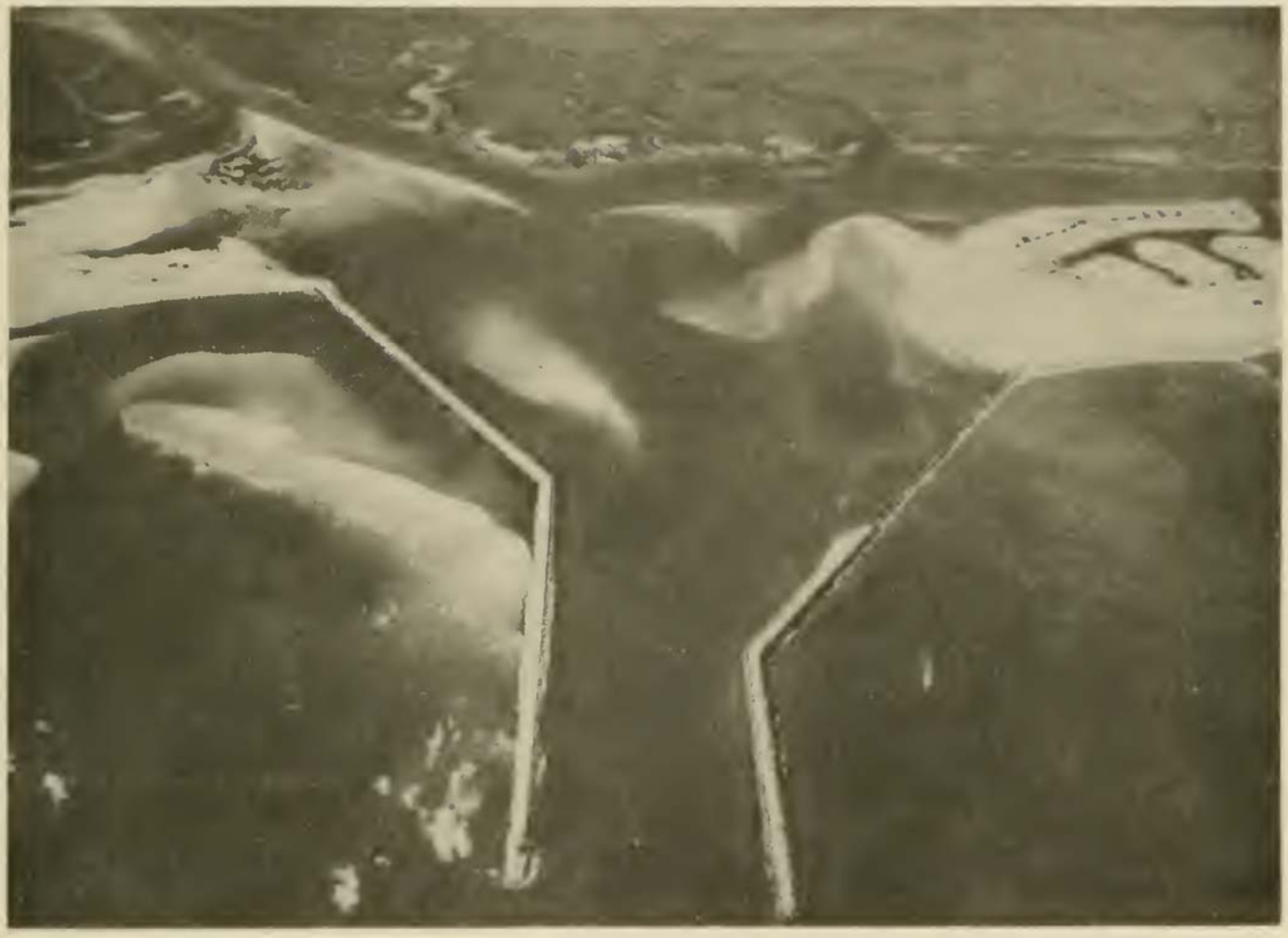

Figure 1-13. Weir jetty at Murrells Inlet, South Carolina, 1981.

VII. CONSERVATION OF SAND

Throughout this chapter the primary importance of an adequate sand supply has been clearly shown. Where sand is available in abundant quantities, protective measures are generally not required or greatly simplified. When dunes and broad, gently sloping beaches can no longer be provided, it is necessary to resort to alternative structures, causing the recreational attraction of the seashore to be lost or greatly diminished. Because sand is a diminishing resource in many coastal areas, its conservation is an important factor in the preservation of our coastal areas and must be included in long-range planning.

Sand was once available to the shores in adequate supply from streams and rivers and by natural erosion of coastal formations. Now development in the watershed areas and along previously eroding shores has progressed to a stage where large areas of the coast now receive little or no sand through natural geologic processes. Continued land development along both inland rivers and coastal areas has been accompanied by erosion control methods which have deprived the coastal areas of sediment formerly available through the natural erosion process. These methods reduce the amount of sand transported along the coast. It thus becomes apparent that sand must be conserved. This does not mean local hoarding of beach sand at the expense of adjoining areas, but rather the elimination of wasteful practices and the prevention of losses from the coastal zone whenever feasible.

Fortunately, nature provides extensive storage of beach sand in bays, lagoons, estuaries, and offshore areas that can be used as a source of beach and dune replenishment where the ecological balance will not be disrupted. Massive dune deposits are also available at some locations, though these must be used with caution to avoid exposing the area to flood hazard. The sources are not always located in the proper places for economic utilization nor are they considered permanent. When these sources are depleted, increasing costs must be faced for the preservation of the beaches. Offshore sand deposits will probably become the most important source in the future.

Mechanical bypassing of sand at structured coastal inlets is one means of conservation that will come into increasing practice. Mining of beach sand for commercial purposes, formerly a common procedure, is rapidly being reduced as coastal communities learn the need for regulating this practice. Modern hopper dredges equipped with a pump-out capability and split-hulled dredges are being used to facilitate nearshore discharge of sands from navigation channel maintenance dredging. On the California coast where large volumes of sand are lost into deep submarine canyons near the coast, facilities are being considered that will trap the sand before it reaches the submarine canyon and transport it mechanically to a point where it can resume advantageous longshore transport. Dune planting with appropriate grasses and shrubs reduces landward windborne losses and aids in dune preservation.

The protection of coastal areas is not a simple problem; neither is it insurmountable. It is a task and a responsibility that has increased tremendously in importance in the past 50 years, and is destined to become a necessity in future years. While the cost will mount as time passes, it will be possible through careful planning, adequate management, and sound engineering to do the job of protecting coastal areas properly and economically.

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