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A Primer of Basic Concepts of Lakeshore Processes

by

David B. Duane, D. Lee Harris, Richard O. Bruno,
and Edward B. Hands

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Water waves and currents vary among other things, with geography, water level (stage of tide), season, and offshore slope. The net effect of wave and current forces impinging upon a shoreline, ocean or lake is to change the morphology of the coastline as a result of erosion, transport, and deposition of sediment. In general, the model of sediment transport can be thought of as movement of a sand grain from some source such as a headland, to a barrier beach, to a dune, into an inlet or to an offshore sink. Knowledge of the

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processes of erosion, transportation, and deposition of sediment implicit in this model is of value to the engineer and the geologist as well as the shoreline property owner. Concepts of generation of water motions and directions of flow, characteristics of the flow, water levels and their periodicity, bed form generation and movement, and sediment entrainment and transport are fundamental to the understanding of lakeshore processes. Basic aspects of these concepts, in lay terms, are presented in this report.

PREFACE

This report is published to assist engineers in gaining a better understanding of the basic concepts of lakeshore processes. The work was carried out under the coastal construction research program of the U.S. Army Coastal Engineering Research Center.

During the past several years, the trend of continued rise in monthly average water levels of the Great Lakes has generated increased interest by shoreline property owners into those processes which change the configuration of the coastline and result, at times, in property loss. In part, as a response to the increased interest by the general public, this report was prepared by a Task Group under the overall direction of Mr. George M. Watts, Chief, Engineering Development Division. The Task Group included: Dr. David B. Duane (Group Leader), Dr. D. Lee Harris, Mr. Richard O. Bruno, and Mr. Edward B. Hands.

It is hoped this report will provide the basis for a better understanding by the general public of the processes which affect the Great Lakes shorelines. The literature cited and additional references in the bibliography will direct the interested reader to more detailed and technically complex discussions on specific aspects of the concepts presented in this report.

Comments on this publication are invited.

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JAMES L. TRAYERS
Colonel, Corps of Engineers
Commander and Director

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A PRIMER OF BASIC CONCEPTS OF LAKESHORE PROCESSES

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David B. Duane, D. Lee Harris, Richard O. Bruno,

and Edward B. Hands

I. INTRODUCTION

Waves and currents vary with, among other things, geography, water level (stage of tide), season, and offshore slopes. The net effect of wave and current forces impinging upon a shoreline is to change the morphology of that coastline. Because these waves and currents act to modify the present configuration of the coastline, they can collectively be referred to as *geologic agents*. Knowledge of the evolution of landforms (the response of the land to these forces), and the rate and manner of the modification of landforms are factors considered in coastal engineering practice.

In general, the model of sediment transport can be thought of as movement of a sand grain from some source such as a headland, to a barrier beach, to a dune, into an inlet or to an offshore sink. This process of sediment transport has been active since the beginning of geologic time and the record of such processes is preserved in the stratigraphic column. This natural process becomes of concern to man when it interferes with or affects what man wants to do. There is no complaint of coastal erosion until structures are threatened with destruction. There is no complaint of beach erosion until the sand beach a family enjoys is disappearing. There is no harbor siltation problem until boats can not enter the harbor.

Knowledge of the processes of erosion, transportation, and deposition of sediment in the coastal zone is of value to the engineer and the geologist. However, the time scale of interest in these processes differs; the scale used by the coastal engineer is short (real time to a few decades) while that of the marine geologist is longer (a few hundred to a billion years). In both disciplines however, the knowledge satisfies an economic need, as well as an intellectual need. Problems, analytical techniques, and ranges of precision differ because of the differences in time scale.

Design of engineering works in the coastal zone considers not only the materials to be employed and the forces which they must withstand, but also considers the modifications the works will introduce in the natural processes operating on the coast and nearshore zone. The basic concepts involve interactions of the atmosphere, hydrosphere, and lithosphere such as: generation of water motion and directions of flow; characteristics of the flow; water levels and their periodicity; bed form generation and movement; and sediment entrainment and transport. A brief discussion of these various concepts follows.

II. GENERATION OF WATER MOTION AND DIRECTION OF FLOW

1. General.

The motion of water in a lake is the result of many complex processes involving the interaction of the hydrosphere, atmosphere, and lithosphere. Present knowledge of water motion is a result of both theoretical and empirical investigations. Essential results of the physical theory along with a discussion of currents are described here in a qualitative manner.

Most of the energy expended by moving water in the earth's lakes and oceans originates from extraterrestrial sources, imparted either directly or indirectly to the water. Examples of direct application of extraterrestrial forces to the earth's waters include: solar and lunar gravitational attraction (which produces tides), the uneven heating of the water by solar radiation (creating density differences that in turn generate density currents), and meteorological phenomena (atmospheric pressure differences and winds). Meteorological forces, in turn, act directly on lakes and oceans to produce currents, waves, and storm surge or wind setup. Meteorological forces are by far the most efficient natural mechanisms for generating currents, waves, and storm surge; in most cases their effects greatly overshadow the direct effects of solar heating and solar and lunar gravitational attraction.

Water motion in the form of either waves or currents, entrains and transports sedimentary materials that comprise lake and ocean bottoms and shorelines. Bathymetric and shoreline configuration of lake and ocean basins reflect a response to the fluid forces exerted on them. The bottom and shoreline respond in proportion to their ability to withstand the fluid forces; loose, unconsolidated materials such as sand, respond quickly to changes in flow conditions, while consolidated materials such as granite rock respond slowly. A wide range of intermediate degrees of erodibility exist depending on the characteristics of the bottom and shoreline sediments.

To understand erosion, transport, and deposition processes in the ocean or lake environment, it is first necessary to understand the phenomena that generate waves and currents and their relative importance at various locations in the lake or ocean. This brief summarization describes the generation of waves and currents; their direction and characteristics; the influence of water levels on the effectiveness of waves and currents in eroding shorelines; the effect of waves and currents in entraining and transporting sediments; and the effect of manmade structures in modifying the flow and thereby modifying natural conditions.

Two basic physical principles govern the flow of all fluids: conservation of *mass* and conservation of *momentum*. In addition, information on the physical state of the fluid is required (i.e., is the fluid a gas or liquid, and how will the fluid density respond to changes in pressure and temperature). The first principle states that mass is neither *created* nor *destroyed* by any process. It is often termed the *continuity condition*. The second principle is a form of Newton's second law which states that the acceleration a body (in this case, an infinitesimally small element of fluid) experiences is *proportional* to the net sum of all forces acting on the body and is in the *direction* of the net force. Implicit in this statement is the principle that once a body is in motion, it can only be brought to rest by imposing a force in the direction opposite to the direction of motion in order to "decelerate" the body. Consequently, a volume of fluid set in motion will tend to remain in motion even after the force causing the flow is no longer acting. The opposing force which normally acts to decelerate a fluid is *friction*. Decelerating a fluid may take days or weeks after the driving forces have ceased.

Conservation of energy is a consequence following directly from these principles and the relationship between density, pressure, and temperature.

The principles can be expressed mathematically by (a) a continuity equation, (b) equations of motion termed the *Navier-Stokes* equations, and (c) an equation of state. All knowledge of lake circulations, currents, and waves follows directly from these equations and the physical laws they represent.

It is important to recognize the scale of a particular phenomenon under study since it will determine which aspects of the flow will be considered the mean flow and which aspects will be considered turbulence. Generally, it is easier to understand the aspects of a particular physical process when only one scale of motion is considered at a time, e.g., in many problems, the largest scale under investigation represents current motion while smaller-scale motions, such as waves, appear as irregularities in the mean flow. The small-scale phenomena are usually identified as turbulence when they appear to be disorganized and to be constantly changing their appearance. It is not uncommon to find that a particular flow phenomenon is regarded as the mean flow at one scale and turbulence at another scale. The definition depends on the flow scale of primary interest.

As indicated, fluid motions once established continue for some time after their generating mechanism has ceased to operate. An analogy between the water motion in a lake, e.g., Lake Michigan, and the motion of a wheel is apropos: stroking the top rim of a wheel toward the right will produce a downward motion on the right, a motion toward the left at the bottom and an upward motion to the left of the wheel. The motion of the entire system may continue for some time after one stops stroking the wheel. If the fluid in one part of Lake Michigan is forced to move from west to east, a return flow from east to west must occur in some other part of the basin. This may be associated with flow in a vertical plane or may involve flow in a horizontal plane. The fluid motion will continue after the generation force has ceased (as a wheel will continue to spin for some time after the addition of energy ceased) until the energy imparted to the system is dissapated by friction, mostly with the solid earth. Persistence of the motions is a function of scale — motions on a scale of inches may die off in a period of minutes, and those on a length scale measured in feet may die off within an hour, but motions whose scale is measured in miles may persist for days after their generating cause has been terminated.

Currents are modified by the basin shape and the density stratification of the water. In most freshwater lakes, the major factor controlling water density is water temperature. For freshwater, maximum density occurs at a temperature near 39°F (4°C). When the temperature is warmer than 39°F, it is common that the temperature increases upward through the water column and there is little mixing between water layers of different temperatures. For most purposes, it can be assumed that water cannot flow through the boundaries of the basin. Also, water tends to flow along surfaces of constant density and when flow exists in one direction a compensating flow in the opposite direction must occur somewhere within the basin. Thus near basin boundaries, the current direction is necessarily very nearly parallel to the boundaries, regardless of the direction of the generating force. Near the bottom, flow may be forced parallel to the boundaries of underwater valleys because flow in other directions would tend to upset the density stratification of the water. When surface water is forced to flow away from a shore, continuity of the water mass is maintained by the upwelling of cold water. This process is the primary cause for the cold surface current near the west coasts of both the American and African Continents.

2. Examples of Wind-Generated Currents.

An example which shows that wind generates currents in directions other than the wind direction can be visualized by considering a long narrow basin filled with water of constant density. If a uniform steady wind blows across the basin in a direction which makes an acute angle with the sides of the basin, friction between air and water will tend to generate a current in the direction of the wind. However, this current will be constrained by the sides of the basin and thus the actual surface current will be parallel to the boundaries of the basin in the general direction of the wind. A return flow at some greater depth will be generated in order to maintain continuity for the mass of water in the basin. Therefore, the wind generates two currents in opposite directions, neither of which is parallel to the wind direction.

The example described provides a qualitative understanding of the seiches in Lake Erie. Winds blowing from a generally west-southwesterly direction lead to low water levels in the western part of the lake and high water levels in the eastern part of the lake. Based on more detailed analyses, it is possible to obtain quantitatively accurate predictions of the flow. Studies pertaining to Lake Erie have been made by Henry (1903), Keulegan (1953), Harris (1954), Platzman (1963), Irish and Platzman (1962), Harris and Angelo (1963), and Richardson and Pore (1969).

If a steady uniform wind blows from south to north across a rectangular lake with a bottom that slopes downward uniformly from east to west, the energy transmitted from the air to the water will be nearly proportional to the surface area of the lake. This energy must be distributed over a much thicker water column at the western side of the lake. Thus, water velocities generated on the east side will be higher than those generated on the west side. As a result, water will be accumulated at the north-eastern corner of the basin more rapidly than elsewhere. A return flow will be generated in an east to west direction at the northern boundary of the lake, from north to south at the western boundary and from west to east at the southern boundary. It is possible that a shallow current from south to north would be generated throughout the lake. However, on the western side of the lake the mean flow will be from north to south since the return flow required by continuity can be more readily developed in deeper water where the velocity of generated currents are much lower in magnitude. It is because of the physical boundaries and Coriolis force (discussed below) that a wind may generate currents in all possible directions in different parts of a basin at the same time.

3. Modification of Currents by the Rotation of the Earth.

Newton's laws of motion pertain to a reference frame fixed in space. A reference frame that is fixed with respect to a point on the earth's surface rotates about the earth's axis with a velocity equal to the velocity of the earth's surface. In the Northern Hemisphere, an apparent force (an apparent force since it arises only because a rotating reference frame is used) deflects moving bodies to the right with respect to a rotating reference frame that is fixed on the earth's surface. In the Southern Hemisphere, the deflection is to the left. This apparent force is zero at the equator and is a maximum at the poles. Since Gaspard Gustave De Coriolis (1835) first explained this phenomenon, the force is termed the *Coriolis force. It must be considered to explain observed circulation patterns in large lakes and oceans*. This explains the large number of clockwise rotating currents in the oceans of the Northern Hemisphere and the corresponding counterclockwise rotating currents of the Southern Hemisphere.

In ignoring Coriolis effect and the interaction between fluid layers, one might be led to believe that in the middle of the ocean, where lateral boundaries and the bottom do not have any significant effect on the flow, wind-generated currents would be parallel with the wind. However, this is not the case. Wind-generated currents are almost always deflected to the right of the wind direction in the Northern Hemisphere and to the left of the wind direction in the Southern Hemisphere. Ekman (1905), observed that friction between two fluid layers could be described as a diffusion of motion from one fluid layer to another. A finite time is required for this diffusion process to take place. By considering the diffusion of momentum through the fluid column along with the Coriolis force, Ekman found that the angle between the mean wind direction and the mean current direction should be 45° at the surface and that current direction should rotate in a clockwise direction with increased depth. Observations have shown that current direction does rotate in the direction indicated. This rotation to the right with increasing depth is known as the *Ekman Spiral*, and must be taken into account to understand the relation between surface winds and wind-generated currents in the sea. Shulman and Bryson (1961) have shown that this rotation of the surface current to the right of the wind can be observed on Lake Mendota in Madison, Wisconsin. Defant (1961) summarized many generalizations of the Ekman theory aimed primarily at obtaining better descriptions of the diffusion process. Defant also summarized many papers reporting empirical evaluations of the theory.

When the time-dependent response of the sea to a steady wind is considered, it is found that water travels in a circular path making one complete revolution in a time period equal to one-half a pendulum day. The length of a half-pendulum day depends upon the angle of latitude, and represents the period of rotation of the plane of rotation of a Foucault pendulum. The radius of the circular path described by the water motion is termed the *radius of the inertia circle*. It also depends on the angle of latitude. These inertial motions in the sea were first explained by Gustafson and Otterstedt (1932). Webster (1968) summarized most of the observations of inertial period-motion in the deep sea from the time of Gustafson to 1968. The importance of inertial motion has been demonstrated in Lake Michigan where 54 current meter stations were established by the Great Lakes-Illinois Rivers Basin Project of the Public Health Service in 1962. Holleyman (1966) gives a map of station locations and an inventory of the data collected. Verber (1965, 1966) gives several examples of data collected on this network which shows the importance of inertial circle motion.

4. Wind-Generated Surface Waves.

In addition to currents, surface waves are also generated by wind. If other things are equal, wave height and period will increase with windspeed, with path length of the wind over the water, and with duration of the wind. For low windspeeds, either path length or wind duration can limit the growth of waves. When water depths exceed about one-half of the wave length, the water motion due to waves consists of approximately circular orbits in a vertical plane with the water moving in the direction of wave propagation under a wave crest and in the opposite direction under a wave trough. The speed of the water motion under a wave crest is slightly greater than the speed under a trough. Because of this, a net water motion in the direction of wave travel is present; this motion is referred to as the *mass transport*. Its speed is proportional to the square of the wave height. The existence of this wave-generated current and a partial explanation was published by Stokes (1847), and significant extensions to the theory have been given by Longuet-Higgins (1953, 1958), Longuet-Higgins and Stewart (1962, 1963, and 1964), Collins (1964), and Hunt (1962). Mass transport is of little consequence in the open sea where there is ample room for return flow. However, it can be significant in shallow water near a beach.

The speed of wave propagation is primarily a function of wave period in deep water (where the wave speed in feet per second is approximately 5 times the wave period in seconds: $C = 5.12T$). As waves move into water depths shallower than one-half of the wavelength, the propagation speed decreases with decreasing depth. The period of an individual wave remains constant as the wave approaches the beach. Therefore, the reduction in speed leads to a reduction in wavelength; the energy per unit length of wave crest remains reasonably constant for a given wave. As the wavelength is reduced in shallow water, the energy density is increased and the wave height increases. This process is known as *shoaling*.

5. Longshore Current Generation.

If water depth varies along a wave crest (usually the case when a wave approaches the shoreline at an angle) that part of the wave in deeper water will travel faster. The result of this process, known as *refraction*, is that the wave front will aline itself so that it is nearly parallel to the bottom contours. If bottom contours are parallel to the shore, refraction will cause a decrease in wave energy density and a decrease in wave height. The combination of refraction and shoaling can lead to either a decrease or increase of wave height near a shore. In a shoal area, with deeper water on both sides, wave crests will be bent to cause a convergence of energy over the shoal. The net result of shoaling and refraction will increase the wave height in the shallow region and decrease the wave height in the deeper water between shoal areas. As waves move closer to shore, the effect of shoaling in increasing wave height usually overrides any effect of refraction in decreasing wave height. Therefore, waves eventually reach a point where the fluid motion under the crests becomes unstable, and then the waves break. During breaking, a part of the wave energy is dissipated, and if the waves break at an angle with the shoreline, a part of the wave energy generates a current parallel with the shoreline. This is termed a *longshore current*. The speed of the current is determined by both the direction and height of the waves. Thus, both direction and speed of the longshore currents are highly variable. Quantitative mathematical and empirical discussions of the generation of longshore currents by waves are given by Bowen (1969) and Longuet-Higgins (1970). In the Great Lakes, waves are generally small between storms and longshore currents will be small. During storms when waves near shore may be 10 to 12 feet in height, the magnitude of the longshore current becomes significant. Theory and empirical data both indicate that wave-induced longshore currents provide the primary motive forces in the swash and surf zones where maximum sand transport occurs. In comparison, currents generated in the deeper parts of a lake are relatively insignificant.

6. Water Motions Generated by Sharp Changes in Atmospheric Pressure.

Sharp changes in atmospheric pressure associated with squall lines occasionally produce long wave disturbances which can be regarded as currents for some purposes. These are particularly well documented for Lake Michigan. These disturbances are called *long waves* because their wavelengths extend for several miles. The waves can produce severe damage in marinas and have at times been responsible for loss of life. They have been studied by Donn and Ewing (1956), Ewing, Press and Donn (1954), Harris (1957), Platzman (1958, 1965), Hughes (1965), and Irish (1965). Their effect on sediment transport has not been documented.

7. Lake Tides.

Water motion generated in the Great Lakes by tides and by subsurface flow are infinitesimal when compared to the causes discussed previously.

8. Effects of Water Stratification.

If pronounced horizontal gradients in water density exist in a basin, currents may be generated as denser water seeks to flow under lighter water. Currents of this type are significant in the ocean and are sometimes significant in estuaries where freshwater flows over saltwater. Such currents are rarely significant in the Great Lakes.

From late spring to late autumn the water in the Great Lakes is stratified with warm water near the surface and cold water at greater depths. Internal waves can form on the discontinuity between warm and cold water. The presence of internal waves greatly complicates the description of water motion in a lake.

III. CHARACTERISTICS OF FLOW

Turbulence Near the Lake Bottom.

The water motion near the bottom of a lake is the net result of all currents and waves present. At the bottom (or a short distance below the bottom if made up of sedimentary material), the water velocity perpendicular and along the bottom must be zero. The shearing forces generated between adjacent fluid layers in this region lead to the generation of small scale irregular motions known as *turbulence*. Collins (1963) discusses the inception of turbulence under gravity waves, and concludes that for waves with a period of 6 seconds in water about 20 feet deep, the flow will be turbulent for wave heights of about 1 foot. Lower waves may produce turbulence in lesser depths. The turbulence intensity is directly proportional to the square of the total speed of the water particles a short distance above the lakebed. Turbulent motions die off rapidly when velocity shear decreases. It is not uncommon to observe pulses of sedimentary material picked up into the fluid column as a wave crest passes and to find much of the material returned to the seabed before the next wave crest passes.

During the period when sedimentary material is pulled upward by turbulent motion it may also be transported in the direction of any persistent or transient currents. Individual sand particles may be picked up and deposited several times each minute as they are transported either along a beach or in a seaward or landward direction.

When currents flow past breakwaters, bulkheads, or piling, shear exists between the flow and the immobile solid boundary. Turbulence generated in this way can cause scour near pilings and breakwaters. The turbulence however, never persists very far from the boundary which brought it into existence.

The construction of a breakwater or groin that interferes with the flow of water parallel to a beach decreases the velocity on both sides of the obstruction and slightly increases velocities near the end of the obstruction. Decreasing the water velocities decreases bottom shear and turbulence. Sedimentary material carried in the neighborhood of the obstruction may come to rest, and unless sufficient turbulence exists, will remain at rest. Observed accretion along updrift sides of groins is a result of this process.

IV. WATER LEVELS AND PERIODICITY

Records of lake level elevations on the Great Lakes go back to 1836. The Lake Survey Center operates many water level gages throughout the Great Lakes. Some are maintained year round, others only during the ice-free part of the year. For the purpose of determining monthly and annual averages, one gage has been selected at the master gage site for each of the Great Lakes: Superior, Michigan, Huron, Erie, and Ontario. The latest monthly averages along with historic records, and a 6-month forecast, are published regularly by the National Oceanic and Atmospheric Administration, Lake Survey Center, Detroit, Michigan. Over the last 113 years, various gages have been employed and several different reference datums adopted and discarded. Surveys were run in 1877, 1903, and 1955 to determine elevations above sea level. The latest determination established the International Great Lakes Datum (IGLD, 1955) based on a uniform, vertical control network tied to the first-order leveling of the United States and Canada. Elevations, actually dynamic heights, are referred to sea level as measured at Father Point, Quebec over the 11-year period before 1957 (Coordinating Committee, Great Lakes Basic Hydraulic and Hydrologic Data, 1961). Levels recorded with respect to earlier datums (e.g., U. S. Lake Survey, 1903 and 1935) were recalculated to bring them into adjustment with IGLD.

Long-term changes in lake levels result from both tilting of the basin due to differential uplift or downwarping of the earth's crust, and more importantly in modern times, from actual changes in the water volume of the basin. Isostatic rebound has been a major cause of crustal movement in the Great Lakes area, i.e., the crust has slowly recovered from the load of Pleistocene glaciers. The effect in this area is a relative tilt upward toward the northwest. MacLean (1963) summarizes several earlier papers which gave estimates for the Great Lakes region as 0.1 to 1 foot per 100 miles per 100 years. Long-term lake level fluctuations are usually thought of as volumetric changes, predominantly climatic in origin, which can be summarized as follows:

$$S = (P-E) + (I-O)$$

where

S = change in storage volume

P = precipitation in drainage area

E = evaporation

I = inflow

O = outflow

These processes have been discussed by Day (1926), Bajorunas (1963), Brunk (1961, 1963), DeCooke (1968), Richards and Irbe (1969), and Rowe (1969).

Using the discharge values, basin areas, and precipitation volumes given by DeCooke (1968), it can be seen that all of the above processes are of the same order of significance in determining Lake Michigan-Huron levels. For example, the rate of inflow to Lake Michigan-Huron from Lake Superior, via the St. Marys River is about 40 percent of the rate of outflow from Lake Michigan-Huron to Lake Erie, via the St. Clair River. The remaining 60 percent is supplied by precipitation within the Michigan-Huron basin. By using an annual rainfall rate of 31 inches per year, the total precipitation falling in the basin is roughly 3 times that required to account for the balance of the volume of water in the lake. Therefore, evaporation must be roughly two-thirds of precipitation and removes more water from the basin than does outflow. Furthermore, since evaporation is greater on sunny, dry, windy days, and during the growing season, the timing of precipitation as well as its total annual contribution becomes a major factor in determining lake levels. Timing of ice formation on the Great Lakes is an additional factor affecting evaporation and inflow-outflow rates. Deviations in any of these processes from their average, balanced rates lead to changes in water storage volumes and therefore in long-term lake levels.

V. GENERATION AND MOVEMENT OF BED FORMS

Fluid motion, including wave oscillations and steady currents, interacting with a bed of loose sediment results in a variety of features that have been classified under the term bed forms. Different flow conditions (tranquil, rapid, steady, and reversing) produce different and often diagnostic bed forms. Their presence reveals certain characteristics of the flow that formed them. Interpretations must be made cautiously, however, as the bed forms need not reflect present conditions because they may persist long after the fluid motion that formed them has ceased. Bed forms are common in sedimentary rocks, and are used as a means of interpreting the environment in which the rocks were originally formed. A single bed form may not characterize general flow conditions. In the nearshore zone a variety of flows are superimposed. Depending on the situation, the flows may be ranked as to their effect in transporting sediment. Each flow, in interaction with the bed, may have produced a distinctive bed form. For example, uprush and backwash produce a planar swash zone, but the waves producing the swash may also ripple the bottom seaward of the plunge point; these same waves drive longshore currents that may form lunate ripples atop the first bar, transverse to the first-mentioned ripples (Clifton, Hunter, and Phillips, 1971). Simultaneously, adjacent flows may be strongly influenced by stream discharge and, farther offshore, by wind drift or density currents. The total flow system is thus composed of many vector fields each associated with a distinct bed form. Therefore, to specify the system even with regard to transport direction, much less flow conditions, a thorough statistical analysis of bed forms is required.

One of the simplest methods of classifying bed forms considers only their wavelength: ripples have wavelengths less than 2 feet; megaripples between 2 and 20 feet; and sand waves greater than 20 feet (Coastal Research Group, 1969). Within this classification, each type of bed form is further subdivided into a number of subtypes according to crest linearity and continuity. The size that a bed form actually assumes, within these defining limits, is often a function of shear velocity, grain size, overall slope and roughness of the bed, and flow depth. A change in any of these fundamental variables initiates maximum rates of morphologic change, after which the rate of change of the bed form (or alternatively the bottom) decreases unless or until flow conditions again change. When the rate of change becomes negligible, the bed form (or bottom) is said to be in equilibrium with the flow. Bed forms in equilibrium can continue to migrate; the migration, if not balanced by some other mechanism, changes the shape of the bottom. Therefore the mechanism of migrating bed forms, e.g., ripples moving ashore, can function as a method for adjusting a bottom that is not in equilibrium with flow conditions (perhaps due to a change in lake level).

Linear shoals with wavelengths of hundreds of feet are common features on the Atlantic Inner Continental Shelf from Long Island to southern Florida (Duane, et al, 1972). These linear shoals are distinct from tidal sand waves such as those described in the North Sea (Stride, 1972), Georgia (Oertel and Howard, 1972), and Virginia (Ludwick, 1972).

A dominant feature of the surf zone along many of the Great Lakes shelves is a bed form distinct from those mentioned, and is properly referred to as a *longshore bar*. Longshore bars can occur singly, but are often found in a parallel sequence that follows shoreline trends almost continuously for many miles. The spacing between bars in a parallel sequence approximates a geometric series, beginning with about 100 feet between inner bars and progressing up to a spacing of several hundred feet between the outermost bars. Longshore bars form along tidal and tideless coasts wherever there is a sufficient supply of sand-sized material in the nearshore zone and a bottom slope of the proper steepness. Within a range of bottom steepness from 0.002 to 0.02, the number of bars that can form increases as slope decreases (Bascom, 1953; Zenkovitch, 1967).

In contrast to other types of bed forms, the formation of longshore bars is a direct response of the bottom to shoaling waves. Currents in the littoral zone modify bar geometry but are not necessary for bar formation. Local deepening of bar troughs by longshore currents (Knaps, 1959) and reduction of bar crest heights by rip currents (Shepard, 1950) occur. Bars can build in the absence of longshore currents. This is amply proven by the generation of bars in wave tanks solely under the influence of wave action (Keulegan, 1948; McKee and Sterrett, 1961). In the laboratory, wave-generated currents cannot develop the natural circulation systems established in nature but these experimentally produced bars have the same shape and geometry as prototype longshore bars. Hence, it can be concluded that bars are a direct result of shoaling wave action.

On some coasts, longshore bars appear only seasonally. They are built up in winter by relatively steep storm waves and destroyed in the summer by a net shoreward transport under swell which tends to move the sand onto the upper beach. On other coasts, notably those with restricted fetch (Great Lakes; Baltic, Black, and Mediterranean Seas), bars persist throughout the year (Davis, 1964; Bajorunas and Duane, 1967; Berg and Duane, 1968; Otto, 1911-12; and King, 1959).

According to theory and experiments in wave tanks (Keulegan, 1948), bars have a fixed and definite relationship to the stillwater level. A change in water surface elevation induces a like change in bar elevation. The reaction of bars in the vicinity of east central Lake Michigan (Pentwater Harbor) to rising lake levels supports this relationship — bars moved inward and upward in such a manner as to preserve a fixed depth beneath the slowly changing lake surface (Saylor and Hands, 1970).

Coastal engineers are interested in longshore bars since they control the position of breaking waves and remove much of the wave energy before it reaches the shore (Munk, 1949). In some instances bars represent temporary storage bodies for sand that are eventually returned to the upper beach by natural processes (Bascom, 1960, 1964; Coastal Research Group, 1969; Inman, 1953; and Shepard, 1950). Bars control the position of the ice-foot formations which help to protect shorelines from winter storms (Bajorunas and Duane, 1967; Marsh, et al, 1973). At harbor entrances, bars must often be dredged periodically to maintain navigable depths in entrance channels.

The longshore bar pattern is a useful parameter for delimiting the effects of coastal structures. Where the bar pattern is locally altered to be significantly different from the pattern in adjoining or similar areas, it is either because one of the fundamental variables in bar formation (sand supply or wave exposure) is locally modified or some destructive process is locally active. This effect can be seen on offshore bars in the Great Lakes and has also been observed along the Gulf Coast.

VI. SEDIMENT ENTRAINMENT AND ALONGSHORE TRANSPORT

1. General.

Sediment movement in the presence of fluid motion over a mobile bed is an extremely complex problem. Material can move completely within the fluid (suspension), at the fluid-bottom interface (bedload), or within the sediment (creep). Motion can be unidirectional, as in a river bed; bidirectional, by oscillating flow such as wave-induced motion; or random, as in well developed turbulent flow.

2. Bed Movement in Unidirectional Flow.

As the fluid flow velocity over a flat surface of loose grains is increased, a condition is eventually reached where a few grains first begin to move due to forces exerted on them by the flow. Since 1753 when Brahms investigated the problem, researchers have attempted to establish the conditions of incipient motion (Raudkivi, 1967). Shields (1936) first presented a graph of an entrainment function versus a particle's Reynolds number; he also indicated that the type of bed form which will develop is determined by flow velocity conditions and can be predicted from his graph.

3. Bed Movement in the Presence of Waves.

Waves traveling toward shallow water eventually reach a depth where the water motion near the bottom begins to agitate the sediment. At first, only low density material moves, e.g., seaweed and other organic matter. This material oscillates back and forth with the waves, often in ripple-like ridges parallel to the wave crests. For a given wave condition, as the depth decreases, the water velocity immediately above the sediment bed increases until it exerts enough shear to move sand particles. The sand then forms ripples with crests parallel to the wave crests. These offshore sand ripples are typically uniform and periodic, and the sand moves from one side of the ripple crest to the other with the passage of each wave.

As the water depth decreases to several times the wave height, the time variation of velocity changes from approximately sinusoidal motion to a high shoreward velocity associated with the brief passage of the wave crest and a lower seaward velocity associated with the longer time interval occupied by the passage of the trough. As the shoreward velocity associated with a passing wave crest slows down and begins to reverse direction over a ripple, a cloud of sand is lifted upward from the lee (landward) side of the ripple crest. The cloud of sand then drifts seaward with the ebbing flow under the trough.

The water stress on the bottom due to turbulence and wave-induced velocity gradients moves sediment in the surf zone with each passing breaker crest. Sediment motion is by both bedload and suspended load transport. The high velocities under breaking waves entrain sediments so that they can be easily transported along the shoreline by alongshore currents.

The length of time sediment particles remain entrained in the water column depends on their fall velocity, which is a function of sediment size, shape, composition (density), and characteristics of the fluid and flow. While in the water column, particles will respond to any currents present and will be displaced from their origin. Since waves generally approach the coast at some angle, a part of the wave energy is directed alongshore driving the longshore current. This current, coupled with the entrainment capacity of shoaling waves, is the major force moving sediments at the coast (Johnson and Eagleson, 1966; Kennedy and Locher, 1972).

VII. BEACH EROSION-EFFECT OF STRUCTURES

As discussed previously, waves and wave-generated currents entrain sediment and transport it alongshore. Waves, through mass transport, also move sediment onshore and offshore (Johnson and Eagleson, 1966). At any particular beach, erosion or accretion is the net effect of all forces acting upon that beach. A beach area erodes when the total amount of material leaving the area exceeds the total amount of material arriving, irrespective of the amount of material transported along the beach. Conversely, a beach will accrete if the total amount of material arriving exceeds the amount of material leaving, again irrespective of the amount of material in transport.

In the case of a beach or coastal sector containing a structure such as a jetty or groin, when waves from the open sea can approach the beach unimpeded, the turbulence generated by the waves will be nearly as great on the downstream side of the obstruction of flow as they would be in the absence of the obstruction. A longshore current will be developed in the downstream direction which can carry any sedimentary material picked up, but the supply of sand from the upstream direction will have been cut off. Thus a net erosion will occur, not because the turbulence intensity on the beaches has been increased, but because the supply of sand for that beach which would normally replace that lost to longshore currents has been interrupted.

Again, the concepts of beach erosion and the effects of structures are intimately related to all facets of the preceding discussions. Numerous examples of beach erosion and the effect of structures on beaches are discussed in many of the references cited and in the proceedings of the biannual coastal engineering conferences published by the American Society of Civil Engineers.

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