CHAPTER 15

LITTORAL PROCESSES ON SANDY COASTS

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THE GEOLOGICAL ASPECT OF SHORE PROCESSES

Seacoast littoral transport may be defined as the movement of sediment along the coastal region by currents primarily induced by waves and tides. It is a phase of the geomorphic process by which sediments forming the earth's surface seek an environment conducive to permanent deposition.

In his classic work on the subject of shore processes and shoreline development, Johnson (1919) reviewed with great thoroughness the work of earlier and contemporary students of that subject and introduced his concept of littoral transport. Johnson (1919) reached the conclusion that marine forces attacking a shore would produce over a limited period of time a "profile of equilibrium," at which stage the degree of slope at every point on the littoral berm would correspond exactly with the ability of wave energy developed at that point to dispose of the debris there in transit. The equilibrium profile would vary in detail within limits fixed by the variability of wave energy and the resistance of the sediments to transport. On the basis of ultimate development, he visualized diminution of the rate of delivery of sediments to the littoral zone by reason of flattening of the land mass, and further reduction of littoral material by marine abrasion and consequent removal from the littoral zone, resulting in dominance of the marine forces to the extent that they are capable of reducing broad land areas to a plane of marine denudation.

At the conclusion of his discussion of the forces responsible for littoral transport, Johnson stated that it is much easier to describe the complexities of these forces and the mistakes which are frequently made in interpreting them than it is to present a solution in a given case which is not open to criticism. To this expression of the problem the author heartily subscribes. Johnson (1919) further stated his opinion that "the time will come when our present limited knowledge of both wave and current action will be enormously extended by means of improved mechanical appliances, permitting actual observation of sediment movement at considerable depths and exhaustive studies of limited coastal areas under varying conditions." His predictions have been borne out to a limited extent but much work remains to be done before the mechanics of littoral transport can be stated conclusively. The work of Johnson (1919) remains the outstanding contribution of this century to the fundamental principles of shore processes.

The comprehensive work of Twenhofel (1939) on sedimentation treats only briefly the subject of littoral transport, but he discusses a concept of importance to the study of littoral processes which can be summarized briefly in his terms "base level of erosion", "base level of deposition" and "profile of equilibrium." He defines the marine base level of erosion as the lowest level to which marine agencies can cut a bottom. The base level of deposition is the highest level to which a sedimentary deposit can be built. His concept provides that the base level of deposition due to marine agencies coincides with the base level of erosion, resulting in a single surface that would be the base level of deposition over places that are filled and the base level of erosion over eroded surfaces. When, during an intermediate stage of development, erosion and deposition become so nearly the same that the surface is being neither raised nor lowered, it is defined as a profile of equilibrium. A profile of equilibrium is thus transitory, and may exist temporarily far above the base levels of erosion and deposition while rates of supply and loss remain equal but in the stage of final development it would attain those levels. He does not attempt to evaluate the forces or

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factors governing these phenomena. Following his concept, a sandy coast which is being acted upon by littoral forces (waves and tides) is in a position above the base level of erosion and deposition and is therefore temporary in a geologic sense.

A third comprehensive treatment of littoral processes has been presented by Shepard (1948). In addition to presenting extensive data on his examinations of submarine canyons and the materials which form the continental shelves, Shepard (1948) takes issue with the concept that the continental shelves are formed as wave cut or wave built terraces. He contends that the presence of rock and coarse sediments in abundance on the outer shelves, and lack of evidence that the surface sediments do not progressively decrease in size with increase in the distance from shore, are not consistent with the earlier theories as to origin of the shelves. He suggests that they may be of complex origin, and proposes as contributing factors sea level changes during the glacial period, the influence of glacial deposits in glaciated areas, and tectonic changes due to extensive faulting in many coastal regions.

It does not appear to the author that the evidence of Shepard (1948) is intended to discredit completely the earlier theories that wave action is the primary force in shaping the shelves, but rather to explain the factors which also influence them, even though in terms of geological development these latter factors may serve only to interrupt temporarily, by what Johnson (1919) terms an accident in the cycle, the development of the so-called base level of erosion and deposition, or ultimate profile of equilibrium.

The preceding resumé of the geological aspects of littoral processes has been presented in very abbreviated manner as an introduction to the problems of the engineer who is called upon to analyze and design works for the improvement or protection of the shore, or to predict the effect of proposed coastal works upon the natural shore processes. It has often been demonstrated that failure to analyze properly the littoral characteristics of a site may reduce the effectiveness of the improvement for its intended purpose or require maintenance expenditure far in excess of that anticipated. It may also result in unforeseen costly damage to adjacent shores.

Johnson (1919) cites the remarkable disagreement which has existed among investigators in different localities concerning the precise mechanics of littoral transport. He ascribes this condition as due at least in part to the difference in dominant factors prevailing at different localities which makes doubtful the existence of a single hypothesis which would fit all cases precisely. The engineer nevertheless must establish a basis for analyzing specific problems, and where facts are not reasonably obtainable he must substitute opinion. The author has been for many years a student of coastal processes, and has progressively developed a concept of the fundamental mechanics of seacoast littoral transport which, although lacking in quantitative application, has been a useful guide in the analysis of specific problems. This concept does not purport to be either a final or a complete summary of the subject. It has been changed many times over the years and is therefore quite likely to undergo some change in the future. The features involving considerable doubt will be readily apparent. In the following discussion the author will attempt to stress the gaps in present knowledge, with a view to emphasizing the necessity for further investigation.

THE MECHANICS OF LITTORAL TRANSPORT

The transport of sediment by flowing water has long been a subject of broad interest to the engineering profession. The accelerated program in recent years for the control of floods, reclamation, and soil conservation has brought about extensive research in the United States with a view to solving the problems of sediment transport in our streams, rivers and watersheds. While these studies have added to our knowledge of the subject there remains much to be learned about the true mechanics of sediment transport on the surface of the land.

Undersea sediment transport is similar in fundamental process to that which occurs on the upland. The sediments which form the ocean bed have the same variable characteristics of density, size, shape and position as the remainder of the earth's surface. The fluid characteristics of the sea vary only slightly from those of our fresh water streams and rivers. The flow characteristics are the same in the sea as in water flowing over the land with respect to sediment transport capability. The principal difference in the problem of the two regions lies in the extremely complex flow pattern in the littoral zone as compared with that in a confined waterway. Einstein (1948) has concisely and effectively defined the relationship of the problem in the two regions.

Along the sea coasts of the continents, measurements have been made of rates of erosion or accretion at specific localities, usually where barriers, which intercept material in the process of littoral transport, have been erected. The evidence developed from such measurements, supplemented by consideration of the littoral forces involved, forms the basis for the author's concept of littoral transport. An attempt will be made to state this briefly. The views expressed are not original, but an effort has been made to express them in logical sequence to aid the coastal engineer in his analysis of specific problems.

Littoral transport. The movement of water over the bed of the sea exerts a tractive force upon the surface particles on the bottom. When the force exerted exceeds the resistance of the particle to movement, transport takes place. The characteristics of transport are thus dependent principally upon the velocity and direction of water movement; upon the size, density, shape, and position of the surface particle; and upon the slope of the bed. The author chooses to identify that portion of the coastal slope over which littoral material is transported by currents primarily induced by waves and tides as the littoral berm.

In a confined channel with unidirectional flow, it has been possible, in a limited degree, to establish relationships of the variables stated above. Because of the range of variability of turbulent flow and material characteristics, a rigorous solution applicable to all conditions encountered in nature has not been practicable. The variability of flow characteristics in the littoral zone of a seacoast is probably the most complex of all waterways in which sediment transport is of interest. The waters in this region are in motion by reason of currents caused by wind, tide, atmospheric pressure, density, temperature, and waves. To reduce all the components to a resultant seems at present to be an insurmountable task.

Wave induced currents. The currents considered to be most important to material transport on an open seacoast are those induced by waves. Ordinarily, only wave currents cause bottom velocity sufficient to set bed material in motion. For practical purposes, the limiting depth for a measurable wave-induced current is half the wave length. Movement of bed material observed in depths exceeding 400 ft. has been attributed to wave action, but excluding extraordinary occurrences, the limiting depth of such movement is probably of the order of 200 ft. The wave current is oscillatory, moving in the direction of wave travel during passage of the crest and in the opposite direction during passage of the trough. In deep water, the current path is orbital in a vertical plane. In shallow water, it is elliptical at the surface and approximately horizontal at the bottom. The orbital movement is irrotational, resulting in mass transport of relatively small magnitude in the direction of wave travel. In deep water, the theoretical wave form is such that a horizontal component of the orbital velocity is the same in each direction. To a degree governed by the height-length ratio of the waves and the coastal slope, the crest steepens as the wave moves up the slope, and if measured at still water level, becomes shorter than the trough. This has the important effect of unbalancing the oscillatory current, the greater velocity being in the direction of wave travel. The current, in a space of 1/2 the wave period, is obliged to accelerate from the rest to maximum velocity and decelerate to rest. Maximum velocity attained is about 1.6 times the average velocity. Because deformation of the wave is coincident with its ability to exert force upon the bottom, the velocity differential favoring onshore transport is believed to prevail over the surface of the littoral berm.

Bed material movement. The combined effect of mass transport and velocity differential give the wave currents greater competence to move material in the direction of wave travel. Offsetting this onshore component are gravity (to move onshore, the material must move up the slope), return flow due to mass transport, and the currents produced by wave reflection. If the bottom is regular, the shore straight for appreciable length, and aligned normal to the direction of wave travel, the return flow and wave reflection may produce a current which flows seaward along the bottom in the surf zone, commonly observed as "undertow." If irregularities in the bed develop, the return flow may be localized in swift streams flowing offshore, commonly called "rip tides" but more accurately named rip currents. If the wave direction is not normal to the shore, the reflected currents may be visualized as following an orbital or elliptical path in a horizontal plane, with an alongshore component favoring the direction of wave travel in the shoreward half of the orbit or ellipse, and opposing it in the seaward half. When the waves approach from two or more directions coincidentally, the return flow may again occur in the form of rip currents, probably more numerous, less conspicuous, and with less individual power and duration than in the case cited above. Thus throughout the waters overlying the littoral berm, there exists a pattern of forces vectoral in character and infinite in number, with equilibrium at any point very unlikely.

Material sorting and slope. Considering only the effect of the velocity differential in the oscillating (unbroken) wave current upon material sorting we find that greater competence of the shoreward component should cause persistent shoreward movement of the more resistant particles. Theoretically, for a given depth, slope and wave, there is a characteristic bed material which would be shifted back and forth but would not depart from its oscillitory orbit, which could be classified as equilibrium material. For convenience in discussion let us assume that density, position and shape characteristics of the bed material remain constant and that resistance to movement is governed by size of the particles. Assuming a fixed slope and wave, the equilibrium particle size would increase as the depth decreases, because the current competence in a shoreward direction likewise increases as the depth decreases. For a fixed depth and wave, the equilibrium particle size would increase as the slope steepens, because gravity increases in influence as the slope steepens, therefore the same particle would advance to a higher position on a flat slope than on a steeper one. For a fixed depth and slope, the equilibrium particle size would increase as the bottom velocities decrease, that is, as the period or height of the wave decreases, for weaker currents cannot push the larger particles as far uphill. The significance of this hypothesis lies in the reasoning that all particles larger or smaller than the equilibrium size are in transit shoreward or seaward, respectively. Further reasoning follows that if the limits of variability of slope, depth and wave characteristics are known, they can be translated to terms of bands paralleling the shore, with limits fixed by depth, within which material of specified characteristics remains. Because of the nature of the variables, these bands must necessarily overlap. For example, if we consider the 10-ft. depth curve on a typical California shore, at which depth the slope is about 1:40, we find that the depth curve moves seaward and shoreward over a range of more than 300 ft. due solely to the effect of tide. At greater depths, the slope is ordinarily flatter, and the band widens. The variability of bottom current characteristics produced by waves introduces a much broader band. Slope variability is obviously a combination of cause and effect, since the slope is constantly in a state of adjustment while the transporting forces and the material characteristics are seeking equilibrium. A storm wave episode concurrently with a falling spring tide may shift a large volume of beach sand offshore to considerable depth. Continuance of the same storm through the interval of a rising spring tide may bring the same material to shallower depths, where subsequent weaker waves may return it to the shore. A complete correlation of beach and offshore surveys with wave and tidal data, over a suitable range to confirm or adjust this hypothesis, still remains to be accomplished.

At the seaward limit of the littoral berm, wave directions are only slightly influenced by the bottom, and may be at a very sharp angle with the bottom contours. As the waves progress up the slope, their directions are changed by refraction, the trend of change always being toward an alignment normal to the contours. Thus those forces affecting material transport which result from mass transport and current velocity differential although weaker as the depth increases, tend to have a greater alongshore component in the deeper area of the littoral berm than in the shallow area. In the concept of orbital or elliptical currents developed by return flow, an opposing current tends to counteract the alongshore wave current component in the deeper region. Little or no knowledge exists of the nature of resultant transport in the deeper portion of the littoral berm.

Surf zone. In the shoreward portion of the littoral berm, the concept of orbital or elliptical return flow tends to augment the alongshore component produced by the wave angle. The resultant flow pattern has the appearance of a current paralleling the shore, commonly called the littoral current. In this portion of the berm, known as the surf zone, the wave characteristics previously discussed change abruptly. Upon reaching a depth 1 to 1-1/2 times the wave height, depending upon bottom slope and reflected currents, the waves reach a state of critical steepness (crest orbital velocity greater than velocity of wave advance) and break. The manner of breaking varies widely between ranges characterized as the "spilling" type and the "plunging" type. A high degree of turbulence exists in the vicinity of the breaking point. A surface current moving shoreward develops, passing over the remnant of the reflected current from preceding waves flowing seaward along the bottom. The wave may re-form and break again a number of times before reaching the shore, depending upon slope and wave period. Within the surf zone, bed material is brought into suspension, in quantity depending upon the degree of turbulence, and both bed load and suspended load transport are in progress. A littoral current, if present, importantly affects net material transport in this region. The material brought into suspension by the breaking wave is carried landward by the surface current until it settles into the reflected bottom currents, whence it is carried seaward again. Net transport landward or seaward is again dependent upon material characteristics, depth, wave characteristics, and beach slope, the latter being constantly in adjustment toward equilibrium. The angles of incidence and reflection govern the path of material particles, although the path is not necessarily angular, thus there is an alongshore component of material transport within the surf zone favorable to the direction of wave travel even though the so-called littoral current in unidirectional pattern should be nonexistent.

Offshore bars. The concept of greater competence of the onshore phase of the oscillatory wave current admits that under favorable conditions of wave, depth, and material characteristics, net transport shoreward may occur in the area seaward of the surf zone. At some point on the slope of the berm, onshore transport will be checked by the effect of gravity and reflected currents. At this point, conditions are favorable to an accumulation of material, known as an offshore bar. The position at which the bar will form is dependent upon depth, slope, material and wave characteristics. When depth change is rapid, as during spring tides, or when wave characteristics are non-uniform, the position favorable to bar building shifts rapidly shoreward or seaward, and a measurable bar is unlikely to develop. Once started, a bar may govern the breaking point of waves for the range of depth change for the lower range of tides. At certain localities on the Pacific coast, it is not uncommon for a substantial bar to form during the period of neap tides, and to merge with the shore during ensuing spring tides, advancing the high water shore line as much as 100 ft. in the space of a few days. Subsequent slope adjustment, over a longer period, restores the shore to normalcy. Less conspicuous bar development and disintegration is considered to be normal to littoral processes. At the more mature stages of its development, the larger type offshore bar may have a pronounced effect upon drift phenomena, principally by creating a semi-confined channel paralleling the shore within which swiftly moving currents flow, altering the normal path of the return flow currents previously discussed.

Summary of the problem. The preceding hypothesis conceives radically different processes of littoral transport in those portions of the littoral berm which lie respectively seaward and shoreward of the breaking point of waves. A feature distinctly common to both regions is that the dominant forces involved are those produced by wave action. Another common feature is the importance of the character of bed material upon the manner of transport. In the surf zone, the transport takes place both in suspension and along the bed. In the offshore zone, the forces involved appear capable of producing only bed load transport. Relative values of net alongshore transport in the two zones is unknown. It has been generally believed that the surf zone is by far the most important in this respect. Mounting evidence of major volumetric changes in offshore areas has led the author to suspect that the littoral processes in the deeper zone may be of equal or greater magnitude than those occurring in the surf zone. Research now in progress under guidance of the Beach Erosion Board is expected to develop much additional data on this subject. The importance of littoral transport in the offshore zone will be discussed below.

ANALYSIS OF LITTORAL CHARACTERISTICS

In the opinion of the author, knowledge of the littoral characteristics of the area in which engineering works are being considered is of vital importance to the coastal engineer. Any coastal structure which extends into the sea will both affect, and be affected by, the littoral processes. Failure to understand and evaluate these effects properly is likely to materially alter the economic value of the completed work. Likewise, projects which would change the natural depth, such as dredging to deepen an inlet, will be governed to a considerable extent with respect to maintenance cost by the rate and mode of littoral drift at that point.

There is no clear-cut path leading to a solution of all such problems. Positive quantitative analysis is still not possible at any location, but deductions from pertinent factual data can produce approximations which will increase in accuracy as experience is gained. The basic factors involved are the magnitude and direction of the littoral forces and the source and disposition of littoral material. If these are properly understood, an approximation of the direction and rate of littoral drift can be made.

The direction and magnitude of littoral forces. Pursuant to the general concept of littoral processes recited herein, the currents induced by waves are considered to be the dominant transporting force. Thus it would appear that the initial step in the problem is a statistical determination of wave characteristics. The data required are direction, height and period of all waves reaching the seaward limit of the littoral berm for a sufficient length of time to encompass a reasonable meteorological cycle for the tributary wave generating zone. Such a compilation, covering a 3-year period, was derived for the Los Angeles District, Corps of Engineers, from synoptic weather maps by Scripps Institution of Oceanography (1947) for five points in deep water off the coast of California. Limits of accuracy of the methods employed are not yet established, but when applied to localities where the rate and direction of drift has been established by measurement, reasonable agreement is apparent. Recording wave gages have been operated at several localities in the United States in recent years, but statistical data from that source covering a suitable period is still lacking.

Wave measurements derived by observation (recording wave gages) would be expected to produce the most accurate obtainable statistics of the height and period, which can be reduced theoretically to terms of energy, work, or power as described by R. L. Wiegel and J. W. Johnson in Chapter 2. Unfortunately no satisfactory means has yet been devised for measuring and recording wave direction, therefore the directional component of the transport capacity cannot now be determined by means of wave gages. This method of deriving statistical wave data has additional disadvantages in that observations at a single site are applicable to a very limited area, and the length of time required to establish an adequate cycle for statistical purposes is often prohibitive for the problem at hand. Mechanical advancement and the passage of time will doubtless overcome these disadvantages and statistics based upon direct observation will ultimately become available.

Sea and swell charts for the open oceans published by the U.S. Navy, Hydrographic Office, (see Chapter 9) provide statistical wave data based on observations by ships at sea and will often be the only immediate source of such data. Accuracy of the charts for any specific area is dependent upon the number of observations reported and the care exercised in making the observations. Wave statistics from this source will normally be available, and should be determined and evaluated regardless of data obtained from other sources. Wave statistics may also be obtained by "hindcasting" wave characteristics from synoptic weather charts, mentioned earlier as a method employed for the coast of California (Scripps Institution of Oceanography, 1947). This method is advantageous in that a substantial period of time may be covered with reasonable expenditure of effort, and the results can be assembled readily in any form desired. Its accuracy is dependent upon the limitations of theory and empirical values, upon the skill and experience of those making the "hindcasts," and upon the accuracy of synoptic weather charts employed (see Chapter 8).

Wave statistics determined by either of the latter two methods establish the wave characteristics in deep water. To determine changes in wave direction, length and height over any point on the littoral berm, wave refraction studies, and diffraction studies where applicable, are made. The transformation of waves in shallow water has been explained in detail by M. A. Mason in Chapter 3 and methods of determining the effects of refraction and diffraction are described by J. W. Dunham in Chapter 4. By means of wave statistics and refraction and/or diffraction studies, it is thus possible to determine an approximation of the vectors and the resultant of wave energy, power, or work, at any point on the littoral berm.

This method of analysis has been employed at several localities on the California coast where predominant direction of littoral drift has been previously established by observing the effects of barriers, and excellent agreement is apparent as regards direction. A satisfactory basis for application of the resultant wave factor in terms of sediment transport capacity has not been established. In the Scripps Institution of Oceanography report (1947) it was suggested that wave work might be a useful parameter for the transporting force, and work factors were computed for that purpose by wave periods and directions. Experimenting with this parameter during wave studies in Santa Monica and San Pedro Bays engineers of the Los Angeles District (1950) computed values of what has been termed the "littoral drift factor" from the following formula:

$$Q = k\, w\, e \sin\alpha_b \cos\alpha_b$$

Q = littoral drift factor = total amount of material moved in littoral drift past a given point on the shore by waves of a given period and direction

w = total work performed by all waves of a given period and direction in deep water just offshore during a typical year

e = wave energy coefficient at the breaker line for waves of a given period or direction, defined as the ratio of the unit width energy at the shore to the unit width energy in deep water

α_b = angle between the wave at the breaker line and the shore

k = a constant determined by observational data and units of measure, probably varying with beach slopes and grain sizes.

Taking a summation of the values thus derived for all wave directions and periods reaching the selected point, and assuming k = unity, the Los Angeles District found some correlation in trend between computed values of the resultant Q and the measured rates of littoral drift at the various points selected. The results did not justify adoption of any empirical values for the constant in the experimental formula. It is the opinion of the author that variability in sediment characteristics governed largely by the variability in rates of supply to the littoral zone, will in most cases prohibit a mathematical relationship involving littoral forces and material characteristics which in itself can be relied upon for determining the rate of littoral drift. Also, the depth at which α_b should be measured remains in doubt. The resultant of the wave work vectors in deep water is believed to afford a means of determining the predominant direction of littoral transport, and together with a consideration of material supply, may indicate whether the rate of littoral drift is large or small.

Sources and disposition of littoral material. The littoral berm adjoining a shore segment of specific length may receive material from several sources. Sediments eroded from the upland may be delivered directly to it by tributary streams, the shore itself may be eroded by waves and the eroded material transferred to the littoral berm, or material from adjoining littoral berms may be transported to it by littoral forces. The littoral berm cannot be fed by material moving onshore from greater depths, since by definition its outer limit is the greatest depth at which sediments can be moved by littoral forces. The deeper region of the littoral berm may in certain cases be an important source of beach material, particularly in regions formerly glaciated.

Assume the case of a shore segment in which the shore and adjoining littoral berm is composed of rock strong enough to resist temporarily erosion by littoral forces. If material is fed to this shore segment from the updrift littoral berm at a rate less than the transporting capacity of the littoral forces, it will move across the rock segment leaving no residue. Individual particles will seek a path in a depth environment compatible with their characteristic size, shape and density.

If the rate of material supply is increased to exceed the transport capacity, or if the littoral forces are sufficiently reduced, sediments will accumulate over the rock surface. As those deposits reduce the depth, the littoral berm will assume a profile governed by the littoral forces. Assuming that the material characteristics remain constant in gradation the profile of equilibrium would be reached when all of the rock is covered between maximum and minimum depth limits governed by environmental characteristics of the specific material supplied.

Continued excess supply after the profile of equilibrium is reached would advance the littoral berm seaward without appreciable change in profile, causing deposit of sediments in depths greater than the littoral forces were competent to accomplish at an earlier stage.

Broadening of the littoral berm would cause dispersion of the littoral forces. If the initial equilibrium profile did not tolerate sediments above sea level to form a visible beach, such a beach would ultimately form when littoral forces in the shore region became sufficiently weakened by dispersion. Once above the sea, the material would be exposed to landward transport by winds. When the rate of landward transport reached the rate of excess littoral supply the littoral berm would become stable.

In reverse order, if the supply of littoral material should be discontinued or reduced below the transport capacity of littoral forces, the littoral berm would recede and the rock ultimately would be laid bare. Material which was forced seaward to depths beyond the initial limit of the littoral berm would remain undisturbed, and in the absence of a lowering of the sea or an increase in the depth capacity of littoral forces, would not resume littoral transit.

The preceding analogy is presented to illustrate the author's concept of the manner in which sediments permanently leave the littoral zone and to illustrate the importance of material balance in maintaining stability of a shoreline.

The littoral berm is fed in part by sediments eroded from the uplands and delivered to the shore by streams. Sediments which are transported in suspension across and to depths beyond the littoral berm before deposition are disregarded because they are of no importance to littoral processes. The littoral berm is depleted by windborne landward transport of the coarser (but not the coarsest) materials and perhaps by permanent seaward deposit of the finer materials. Comparative rates of gains and losses to the littoral berm control the position of the shoreline.

Another source of supply to the littoral berm, more active in earlier geologic time than at present for shores of principal interest, is the glacial outwash. Course materials were delivered by this means to position of considerable depth in the coastal region, from whence, by littoral processes, they may be transported shoreward to the upper regions of the littoral berm. There is considerable evidence that beaches in some localities, particularly on the north and middle Atlantic coast of the United States, may receive nourishment from this source.

LITTORAL BARRIERS

The previously stated concept of littoral processes assumes that the angle between the shore (or littoral berm) and the resultant of the littoral forces is a factor affecting the rate of littoral transport. Thus any shore segment not in equilibrium with respect to rates of supply and loss will tend toward realignment in a direction normal to the resultant of littoral forces, receding if the material supply is deficient and advancing if the supply is excessive. An abrupt change in shore alignment, such as a prominent headland, may act as a littoral barrier, causing material to accumulate on the updrift side. Prominent examples of such natural littoral barriers on the California coast are Monterey Peninsula and the Palos Verdes headland. These mark the southern extremities of Monterey Bay and Santa Monica Bay, respectively. Conclusive evidence of predominant north to south littoral drift exists at both localities. The curving shore alignment in the bight of each bay marks the realignment trend concomitant with reduction in the southerly component of the littoral forces. Extensive dune deposits in the southerly region of each bay are repositories of excess littoral material.

Inlets to tidal bays or estuaries may act as limited littoral barriers. The typical migrating tidal inlet through a barrier beach is manifested by accretion on the updrift side encroaching upon the tidal channel, causing the currents to erode the downdrift shore. The eroded material enters the littoral stream and provides nourishment for the downdrift shore. Thus there is an exchange of the source of littoral material but with generally localized effect upon the littoral regimen.

Tidal inlets on the Atlantic coast are subject to ebb and flood tidal flow of about equal intensity, at estuaries where there is no appreciable fresh water discharge. In the process of inlet migration, a portion of the littoral material is carried into the bay by flood tide currents and deposited out of the range of ebb currents or littoral forces. Each natural migrating inlet thus tends to store littoral material and deficiency in material balance, if any, must be made up at the expense of the downdrift beach.

Diurnal inequality of tides in the Pacific Ocean cause substantially different flow characteristics at tidal inlets from those described above. The sequence of tides during the spring, or highest ranges, is lower low, lower high, higher low, higher high and lower low. Maximum velocities are reached in ebb flow. At an unimproved inlet, littoral material entering the inlet during flood tide is swept seaward by the ebb and deposited offshore in the form of a bar. The depth, profile and alignment of the bar are dependent upon the littoral forces, the character of the littoral material, and tidal characteristics of the inlet. Variability of these functions has prevented the establishment of inlet bar criteria of general applicability. Inlet bars are by no means restricted to Pacific coast waters, but their pattern and behavior appears more uniform in these waters than elsewhere.

For the channels at the throats of Pacific Coast estuaries, it has been determined that the area of cross section in square feet below mean sea level is approximately equal to the tidal prism in acre feet, measured between mean higher high water and mean lower low water (Robbins, 1933). If an inlet is stable rather than migratory, littoral material is being transported across it by natural forces, and the throat dimensions above are fixed by the scouring capacity of the ebb current.

It is generally believed that the bar is the principal path followed by littoral material crossing an inlet. The uniformly fine sands found on the crests of the larger bars (Robbins, 1933) leads the author to believe that the coarser material is transported across in the region of the throat of the inlet. Evidence to a firm conclusion to that effect is presently lacking. It can be stated with reasonable assurance, however, that a stable tidal inlet with a mature bar is not necessarily a littoral barrier.

MAN-MADE LITTORAL BARRIERS

There are three basic types of coastal works which function as littoral barriers. The most common is the jetty or groin which extends from the shore across a portion of the littoral berm, acting as a dam to entrap the littoral drift. The impounding capacity of such a structure is dependent upon three factors: its length, the slope of the littoral berm upon which it is built, and the equilibrium alignment of the shore in that region (normal to the resultant of littoral forces).

If such a structure is built on a shore which is stable with respect to material balance, accretion will occur in the form of a fillet on the updrift side with alignment tending toward equilibrium. Deficiency in material balance on the downdrift side will result in erosion, the alignment likewise tending toward equilibrium. The transport of sediments whose natural habitat is a depth greater than that at the seaward end of the structure would not be affected. Accretion of the coarser sediments on the updrift side results in a slope steeper than normal, whereby these coarser sediments may be transported at greater than normal depths. Depending upon limitations of the impounding capacity of the barrier, littoral material will be transported around its seaward end at an increasing rate until the impounding capacity is reached, whereupon material balance is re-established on each side of the barrier. Stability shore alignment may be permanently altered, resulting in an abrupt offset at the barrier.

If the barrier be sufficiently long or if it extends to great depth, it may alter the character of littoral forces on a localized segment of the downdrift shore. If the region be one subject to reversals in drift direction, accretion may occur on the downdrift as well as the updrift side but to a lesser degree. The erosion zone in this case will be situated beyond the shadow of the barrier on the downdrift shore. Many examples of this phenomenon exist, notably on the California coast, the Humboldt Bay jetties, Newport Harbor jetties, and Camp Pendleton Harbor jetties.

If the equilibrium shore alignment varies only slightly from the stability alignment, the impounding area of a littoral barrier will be elongated along the updrift shore and will be proportionately large with respect to the length or limiting depth of the barrier. Examples of such characteristics are the various littoral barriers in the bight of Santa Monica Bay and on the New Jersey coast, particularly the Cold Spring Inlet jetties at Cape May. Examples of the opposite case, (the equilibrium alignment varying substantially from the stability alignment), are evident along the south shore of Long Island and at Santa Barbara.

If the littoral berm is narrow by reason of precipitous slopes at its seaward margin, a relatively short barrier may have an excessively large impounding capacity. Advance of the littoral berm to re-establish stability characteristics may require an excessive volume of material on such abnormally steep slopes. This feature has not been fully explored, but barriers suspected of possessing this characteristic are Newport Harbor west jetty, Hueneme Harbor west jetty, and Moss Landing north jetty, all in California.

A second type of man-made littoral barrier is the offshore breakwater. This structure is designed to intercept waves and to create a protected area of calm water, usually to meet navigation requirements. Its effect upon littoral processes is the reduction or elimination of the principal component of the littoral forces (waves) within that portion of the littoral berm in its lee, with the result that littoral material accumulates in the protected area. The resulting shore advance acts similarly to a jetty or groin in causing updrift shore accretion beyond the region of direct effect of the structure itself, and corresponding erosion on the downdrift shore. An outstanding example of this type of littoral barrier is the Santa Monica Breakwater (Handin and Ludwick, 1950).

A third type of littoral barrier is the dredged channel across the littoral berm. Such a channel creates greater than normal depths, with the result that littoral material accumulates therein. Maintenance of the channel by dredging removes the littoral accumulations, thus preventing restoration by natural processes of normal littoral transport. If the littoral deposits be removed and redeposited on the downdrift littoral berm in such manner as to resume normal littoral travel, material balance may be maintained and detrimental shore effect would be unlikely. If the material is removed and deposited elsewhere, deficiency of supply to the downdrift shore, with consequent erosion, is probable. The factors affecting a solution of this problem, as well as that of other littoral barriers, are discussed below.

RESTORING NORMAL LITTORAL PROCESSES

Whenever a littoral barrier produces an undesired effect, as is usually the case, it becomes necessary to examine the means by which normal littoral processes may be restored. If the impounding capacity of the barrier is small and if preservation of a navigable channel is not involved, it is probable that the restoration of normal processes solely by the forces of nature will suffice. In other cases, consideration must be given to artificial means of by-passing littoral material across the barrier. Alternative means of preserving the downdrift shore by defensive works or by restoring material balance from a source other than littoral accumulation on the updrift side of the barrier must also be considered. Economic analysis of the benefits from each method in comparison with its cost will determine which should be employed.

Perhaps the most important feature of the problem is a proper understanding of the littoral regimen of the specific problem area. Variable conditions exist in different continental regions depending upon the stage of geologic development. Along the Pacific coast of the United States, it is the author's belief that the littoral zone is fed intermittently along the shore by material eroded from the upland. Principal replenishment occurs at the time of major floods, when large delta deposits are formed and serve to feed the littoral stream during the intervening periods between floods. The natural littoral barriers establish the limits of the littoral regimen for each independent shore segment. If a man-made barrier is created within such a shore segment with impounding capacity sufficiently large, its effect may ultimately extend along the entire downdrift shore to the next natural barrier. Defection in material balance will accelerate the depletion of each delta deposit in succession along the shore. The frequency and size of the deltas, as well as the frequency of floods, will govern the rate of progress along the shore of what may be termed the erosion wave resulting from defection in material balance.

Proper understanding of the limits of the littoral regime between natural barriers is thus of paramount importance in determining the ultimate as well as the immediate effect of intervening man-made littoral barriers, the justification for remedial measures, and the best method of accomplishing such measures. Defensive works have been employed extensively in the past, often without advance knowledge of the ultimate length of shore likely to require protection, and without consideration of the comparative cost of restoring natural littoral processes in lieu of defensive works.

By-passing littoral drift has not been successfully accomplished in enough cases to establish criteria which can be applied to any locality for analysis and determination of cost. Fundamental requirements for successful by-passing are that:

1. The limiting effective depth of the littoral barrier be known.
2. Material intercepted by the barrier be removed at the rate of accumulation (resulting in no net accumulation of material on the updrift side of the barrier).
3. The material be deposited on the downdrift littoral berm, in a location fully exposed to littoral forces, and in depths not exceeding the limiting effective depth of the barrier.

At Santa Barbara, California, (Los Angeles District, 1948a) a breakwater connected with the shore served as a littoral barrier for approximately 5 years. Thereafter the updrift shore became stable and all littoral material in transit shoreward of the limiting effective depth of the structure moved around it and deposited in the harbor. Because of the protection afforded by the breakwater, it has been a simple matter to dredge all of the accumulated material biennially with conventional pipe line dredging plant and deposit it on the downdrift shore. The method employed has been successful in maintaining the downdrift shore, although the rate of depletion of the downdrift disposal area (feeder beach) between replenishments has been somewhat less than the rate of accumulation in the harbor. This indicates that the feeder beach may be shorter than optimum length, with result that some material is placed in depths greater than its natural environment from whence it is moved less rapidly than normal. Further study of the Santa Barbara problem is in progress by the University of California, Berkeley, as part of a program of research sponsored by the Beach Erosion Board.

At South Lake Worth Inlet on the east coast of Florida, by-passing of littoral material, by means of land-based plant near the jetty end, has been in progress intermittently for several years (see Chapter 34). It is the opinion of the author that the impounding capacity of the jetties at South Lake Worth Inlet has been virtually exhausted, and that littoral material is passing the barrier by natural means in substantial quantity. The by-passing operation, by removing the accumulations of coarser material moving in the shallower zone, prevents extreme shoaling of the adjacent navigation channel and maintains the downdrift beach. The quantity by-passed, reported to be 50,000 to 70,000 cubic yards per year, is about one-third the rate of accumulation in early stages of the barrier's history.

Effectiveness of this installation indicates that in certain cases, natural processes may be restored and required depth of a navigation channel maintained by by-passing only that material which has a native depth environment less than the required depth of the navigation channel. Present knowledge of the depth environment characteristics of littoral material is inadequate to enable quantitative prediction of an operation of this character. Material balance requirements must for the present be determined experimentally.

Because of the uncertainty of the effectiveness and cost of by-passing material across jettied inlets by means of land-based plant, consideration has been given to constructing littoral traps on the updrift side of inlets by means of an offshore breakwater (Los Angeles District, 1948b). This method permits use of a conventional floating pipe line dredge for the by-passing operation and is considered to be positive in results attained. The method has not previously been employed in a case where it was designed for the specific purpose of by-passing littoral drift, but is similar in operation to Santa Monica Breakwater (Handin and Ludwick, 1950) where the first fully effective by-passing operation was accomplished in 1949, 15 years after the structure started to function as a littoral barrier. Observations to determine the rate of filling of the area dredged in lee of the breakwater are in progress.

ARTIFICIAL NOURISHMENT OF THE LITTORAL ZONE

It is often necessary to restore eroded shores, or widen existing beaches, by making beach fills. The concept of material environment characteristics in the varying depths of the littoral berm has an important bearing upon determining suitability of specific material for use in a beach fill, and upon the manner in which it should be placed.

The material sorting, or selective transport characteristic of the littoral processes requires that regardless of the composition of underlying material, the surface material will adjust itself to its depth environment. If uniformly fine material is placed on the foreshore of a beach normally composed of uniformly coarse material, the fill will rapidly be shifted offshore to its proper depth. If the gradation of the fill material covers a broad range, with a substantial proportion in the size range of the native material, the surface will readily acquire the characteristics of the native beach. Seasonal changes and recessions due to storms will expose the underlying materials periodically to littoral forces, and progressive loss of the finer particles to deeper regions will occur.

In somewhat the same manner, coarse materials deposited offshore may be prevented from moving shoreward by a selective surface coating of finer material which has attained its proper environment. By occasional exposure to littoral forces, the underlying coarse material may work its way shoreward. Experiments by the Beach Erosion Board at Long Branch, New Jersey (Hall and Herron, 1950), when analyzed on the basis of the reasoning above, provide some support for the hypothesis. Non-conformity of surface samples taken from the littoral berm may also be explained by this reasoning.

Selection of material for a beach fill must therefore be based upon an analysis of the probable ultimate distribution of the material along the littoral berm and the effect that such distribution will have upon the intended purpose of the fill. If one purpose is to create a flatter offshore slope, availability of a substantial portion of fine material would be desirable. If the purpose is to armor the foreshore slope, fine material would have no value. If the purpose is to widen a beach, material of any size will serve for the major portion provided the seaward face is built of sand corresponding generally to the native beach for a thickness adequate to accommodate expected fluctuations due to storm and seasonal changes.

Beach fills amounting to more than 50,000,000 cubic yards of material, creating more than 1,000 acres of additional sandy beach, have been made at various locations on the coast of Southern California over the past 15 years. The purposes have been varied, and for the larger part of the total quantity the object was simply to dispose of excess dredged material for which no other suitable disposal area was available. Little attention was paid to the character of the material, which was for the most part sand but included in several instances clay, gravel and boulders. The author has followed the progress of littoral forces acting upon these beach fills and in all cases they have rapidly assumed the characteristic appearance of the native beach except that slope characteristics have apparently been permanently altered in some instances. It can be stated in general that with one exception in the easterly portion of Newport Beach, all of the fills have been eminently satisfactory with no detrimental effect. In the exception cited the foreshore slope has remained much steeper than normal though there is evidence that it may be flattening gradually. The material deposited in that reach of shore contained a large proportion of very coarse sand.

Sampling and mechanical analysis of materials deposited to make beach fills mentioned above were unfortunately either omitted or were too limited to provide reliable data. Subsequent sampling of the beaches has been accomplished without regard to seasonal or storm wave effect and are of limited value for analytical purposes. The author hopes to obtain suitable data for a future paper on this subject.

SUMMARY AND CONCLUSIONS WITH RESPECT TO ECONOMIC ASPECTS OF LITTORAL PROCESSES

From the standpoint of geological processes, a sandy beach is an interim phase in the ultimate development of a coastline, principally because a sandy beach can survive only if it receives nourishment at the rate of depletion. Depending upon its stage of maturity, a particular coastal segment may be advancing, retreating or in a state of approximate equilibrium. Its precise status in any phase is dependent upon material balance, that is, the rate at which sediments are delivered to the littoral zone compared with the rate at which they are removed therefrom. The ultimate stage of development may be described as a state in which the littoral forces are incapable of transporting materials which form the littoral berm, and erosive forces acting upon the land mass are incapable of delivering sediments to or from the coastal shores.

The rate of changes wrought solely by natural geologic processes is ordinarily so slow as to be of minor importance to the engineer whose mission is to protect or improve a particular shore segment. Because the engineer's problem is fundamentally dependent upon the state of material balance, he must investigate that feature sufficiently to determine the extent to which material balance is influenced by natural processes and by works of man. In this investigation he may be aided by the geologist competent to analyze the geomorphology of the region, and by measurements of the effects of man-made works in accelerating or retarding the transport of sediments within the area tributary to the shore under consideration.

It is of the utmost importance that the engineer determine the limits of the littoral compartment for a shore segment under investigation. These limits will be fixed by the natural barriers to littoral transport on each side of the shore segment, and will often be at great distances from the particular problem area. Knowledge of the limits of the littoral compartment will enable determination of the natural sources of littoral nourishment, the region within which the magnitude and direction of littoral forces must be considered, and the zone of influence upon littoral processes of structures or other works existing or being considered.

The littoral forces consist primarily of the currents induced by wave action. The rise and fall of the sea surface in the form of tides, and the configuration of the surface of the littoral berm, greatly influence the distribution of littoral forces over the littoral berm. The sediments are selectively transported according to characteristics of size, density and shape. Wave induced currents possess greater competence in the direction of wave travel, thus the more resistant sediments tend to move shoreward. A specific sediment particle is shifted shoreward and seaward while seeking environment compatible with its character but will remain within depth limits fixed by the variability of tides and wave characteristics peculiar to the region.

More or less constant onshore and offshore movement of material is accompanied by lateral movement along the shore in a direction governed by the resultant of the littoral forces. Relative rates of alongshore movement of sediments at different depths is not known at this time, although it is generally believed that the coarse sediments native to the surf zone have a greater velocity of travel along the shore than the finer materials in the offshore portion of the littoral berm. Evidence is mounting that a substantial proportion of the net rate of littoral drift over the entire littoral berm may occur in depths seaward of the surf zone.

The effect of selective transport and the transport rate at varying depths are important to the engineer in his analysis of the effect of existing or proposed littoral barriers. He may determine the predominant direction of littoral drift with reasonable accuracy by analysis of the littoral forces and the shore characteristics within the littoral compartment. In the absence of measurements of rates of accumulation at existing littoral barriers, present knowledge does not provide a means of quantitative determination of the rate of littoral drift. Even though the rate of drift be determined by measurement at a specific barrier, evidence is lacking as to the transport in progress in depths greater than the limiting effective depth of the barrier. Until knowledge of the mechanics of littoral processes becomes available, the engineer is obliged to substitute opinion based upon all the pertinent facts he can obtain.

Examples of man-made littoral barriers are groins, jetties, breakwaters and dredged channels in the littoral berm. Each has an impounding capacity depending upon its limiting effective depth (and size in the case of a dredged channel). When the impounding capacity of such a barrier is reached, normal littoral drift past the structure will be resumed. Disregarding the effect of seasonal or cyclical changes in the natural rate of littoral drift, the rate of accumulation at a barrier will be highest in the earliest stages and will decelorate as the impounding capacity is approached. This fact must not be neglected in estimating the drift rate by measuring accumulations at existing barriers.

The effect of a littoral barrier is to alter the material balance on the downdrift littoral berm. Except for a limited local area depending upon the extent and nature of the barrier, the littoral forces will not be altered. The downdrift shore must therefore supply such deficiency in material balance as the barrier may create. The ordinary consequence is erosion of the downdrift shore. The engineer planning a littoral barrier must include in his analysis the effect upon the downdrift shore in terms of magnitude, rate, duration, and economic value. If the effect thus determined is in the nature of a consequential damage, an evaluation of the damage must be considered, in conjunction with the cost of constructing and maintaining the barrier, in determining economic justification of the project.

Remedial measures to offset or prevent consequential damage, resulting or expected to result from a littoral barrier, are feasible in many cases and should be considered and analyzed economically. Such measures may be divided basically as to type into two classes, defensive works and restoration of normal littoral processes.

If the barrier is located in the updrift region of a littoral compartment, and there is no nearby source of supply such as a river delta on the downdrift shore, defensive works will rarely be an economic solution. Such works protect only the immediate shore upon which they are constructed. Defensive works in the form of groins, designed to trap littoral drift, may protect a portion of the shore while causing accelerated erosion elsewhere. Defensive works employed to offset a deficiency in material balance in the case stated above retard but do not prevent erosion, and are not likely to be permanently effective. This is a case in which restoration of normal littoral processes by mechanically transporting material across the barrier is likely to be the most practicable solution.

If a relatively short length of shore is exposed to hazard by reason of a littoral barrier, as at the downdrift end of a littoral compartment, defensive works are more likely to be warranted. Maintenance by nourishment from sources other than littoral accumulations at the barrier may in some cases be employed economically with or without defensive works.

In the opinion of the author restoration of normal littoral processes at littoral barriers would solve most of the erosion problems now existing on the coastal shores of the United States. It is believed that this method of shore protection should be analyzed and evaluated economically wherever barriers have caused a deficiency in material balance.

Much knowledge must be gained before the mechanics of littoral processes can be stated with assurance. This situation presents a challenge to the coastal engineer who must constantly deal with littoral processes. It is believed that the present state of knowledge is adequate to avoid repetition of many errors made in the past. Investigations now in progress by the Beach Erosion Board promise to add to our knowledge of the subject. Littoral barriers have been designed which incorporate means for by-passing littoral material. It will be through the construction and operation of such works that our greatest advances in knowledge will be made.

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