CHAPTER 22

LITTORAL PROCESSES AND THE DEVELOPMENT OF SHORELINES

by

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ABSTRACT

Basic principles bearing on the nature of beaches and processes that act to modify them are considered in the light of present coastal development demands. A working hypothesis is developed that applies the principle of the conservation of mass to the mechanics of granular-fluid media. This hypothesis appears to have general application to sand transport processes in the littoral zone. Additional research must be done to provide basic information in some critical areas before application can be made with assurance.

INTRODUCTION

There are increasing demands on the shorelines of the world for recreation, shipping, industry, and marine resources of various kinds. Unfortunately, our understanding of the coastal environment has not yet advanced to the point where today's problems can be handled adequately. Therefore, it is imperative that we develop the means to preserve the beaches and harbors that we now have and that we develop practical techniques for creating new beaches and shoreline facilities. Protective structures for new harbor entrances interrupt the longshore transport of sand, often requiring expensive maintenance of the harbor and frequently causing deleterious effects on the adjacent coastal environment. The interception of sand supply at the source by flood control dams, and its loss to the beaches by deposition in deep water, present serious long-term problems to beach maintenance. We are in the curious position of developing and improving beach frontage without criteria for predicting changes in the beach or evaluating the likelihood of the beaches' existence in 10 or 20 years.

The support of the Coastal Engineering Research Center, U. S. Army Corps of Engineers, and the Office of Naval Research has made this work possible.

Contribution from the Scripps Institution of Oceanography, University of California, San Diego.

Before considering problems of coastal design and use management, the effects of waves and wave-induced currents on the transportation and distribution of sediments in the nearshore zone are summarized. This kind of information, augmented by additional research, must become an important part of the basis for discussions on coastal problems.

The major emphasis is directed towards those planning criteria that depend upon or are likely to be influenced by waves, currents, and the transportation of sediments. From this standpoint, the possible types of coastal structures and their design, successful operation, and maintenance can be considered broadly in terms of: a) general principles pertaining to littoral processes, b) the types of beach and adjacent bathymetry, c) exposure to waves, and d) the budget of littoral sediments.

NEARSHORE PROCESSES

However complex in detail, there are certain fundamental principles that have general application to the littoral zone. Although the kinds and amounts of sediment transported vary from place to place along the coast, the transport mechanisms appear to be general in their applications. Energy is transmitted to the coast by waves where it is dissipated in various ways, including reflection, generation of longshore currents, and the transportation of sediment.

Recently, a working model for beach mechanics, that appears to explain many of the known facts, has been formulated and partially tested (Inman and Bagnold, 1963; Inman and Bowen, 1963). Although more experimentation is necessary before this model can be accepted with confidence, it serves here as a working hypothesis in an approach to the understanding of littoral processes.

The model is based on the principle of the conservation of energy applied to the mechanics of granular-fluid media. If a stream of water transports sand, the stream can be considered as a transporting machine. The immersed weight of the transported sand is the machine's load, and it is of interest to consider the power required to transport this load. The immersed weight of solids of absolute volume v traveling over unit area of a sand bed is $(\rho_s-\rho)gv$ where ρ_s and ρ are the density of the solid and fluid respectively and g is the acceleration of gravity. If the solids are transported with velocity U, then the dynamic transport rate, i.e., the immersed weight transported across unit width of bed in unit time becomes

$$i = (\rho_s-\rho)gvU \, . \, . \, . \, . \, . \, . \, . \, . \, . \, (MT^{-3})^{1/} \qquad (1)$$

1/ The dimensions of equations are indicated by the symbols M, L, and T which represent mass, length, and time respectively. In British absolute units M is in pounds mass (lb). In British gravitational units force (MLT^{-2}) is in pounds force (lb_f).

where vU is the volume of solids transported in unit time across unit width of bed.

If the total power supplied by the stream per unit area of its bed is ω, then a portion $K\omega$ of this power is expended in transporting the sediment, and the transport rate is given by

$$i = K\omega \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; (MT^{-3}) \qquad (2)$$

The dimensionless factor K is related to the efficiency of the transporting mechanism and can be expected to differ for differing modes of transport.2/

In the steady flow case, as in a stream or flume, ω is equal to the shear stress τ, multiplied by some mean flow velocity $\bar{u}$. Under wave action sediment movement is caused by the back-and-forth motion of the waves, and the power ω is proportional to τu_m where u_m is the horizontal component of the orbital velocity of the waves. If the orbital velocity is sinusoidal, as much sand moves backwards as forwards; and there is no net transport even though power ω is expended. Since the sediment is already supported by the wave stress, $\tau = \omega / u_m$, no additional stress is required to move it. Thus if a current $\bar{u}$, in any direction θ, is superimposed on the wave-induced back-and-forth movement of sediment, a net transport of sediment will occur in the direction θ,

$$i_\theta = K \frac{\bar{u}}{u_m} \omega \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; (MT^{-3}) \qquad (3)$$

where the factor K absorbs the numerical approximation resulting from equating ω to τu_m.

Thus the waves supply the power to keep the sediment in motion, and the current determines the magnitude and direction of the transport. This concept will be applied to the equilibrium profile of sand slopes and to the longshore transport of sediments. Equation (3) was derived by Bagnold (1963) and partially verified by experiments in a wave channel by Inman and Bowen (1963).

ENERGY PROFILE OF EQUILIBRIUM

The back-and-forth motion of waves in shallow water produces stresses on the bottom that place sand in motion. The interaction of the wave stresses with the bottom also induces a net boundary current $\bar{u}$ flowing in the direction of wave travel (Longuet-Higgins, 1953). The most rapidly moving layer of water is near the bed, and for waves traveling over a horizontal bed, the interaction of wave stresses and the boundary current produces a net transport of sand in the direction of wave travel as

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2/ Bagnold (1963, p. 513) shows that the efficiency $\mathcal{E}$ for bedload transportation is $K\tan\phi$, where $\tan\phi$ is the coefficient of internal friction for granular shear and ranges from 0.3 to 0.75. If the bed slopes down-stream at an angle β, the efficiency is $\mathcal{E} = K(\tan\phi - \tan\beta)$.

predicted by equation (3).[3] Thus, the wave-induced transport of sand acts to contain sand against the shore.

The action of waves on an inclined bed of sand eventually produces a profile that is in equilibrium with the energy dissipation associated with the oscillatory motion of the waves over the sand bottom. If an artificial slope exceeds the natural equilibrium slope, an offshore transport of sand will result from the gravity component of the sand load, until the slope reaches a new equilibrium. Conversely, if an artificial slope is less than the natural equilibrium slope, a shoreward transport of sand will result and the beach slope will steepen. Thus, the equilibrium slope is attained when the up-slope and down-slope transports are equal. Equating the up and down slope transports gives the following relation for the equilibrium slope:[4]

$$\tan\beta = \tan\phi \, \frac{1-c}{1+c} \tag{4}$$

where β is the slope of the bed, $\tan\phi$ is the coefficient of internal friction for granular shear, and c is a coefficient depending upon the ratio of the boundary currents to the orbital velocity of the waves.[4]

Since the equilibrium slope steepens with increasing energy dissipation and with increasing speed of the boundary current $\bar{u}$, it is usually gentle in deeper water where wave dissipation is slight and currents are low, and steeper near the surf zone where both dissipation of energy and the currents are greatest. This dependance of slope on wave stress and boundary currents causes the slight steepening of slope found just outside of the surf zone in many beach profiles (Figure 1).

Evaluation of the coefficients of equation (4) should provide limits on permissible nearshore bottom slopes that can be expected to be stable under given conditions of wave attack. Understanding of permissible bottom slopes would provide useful criteria for deciding feasibility of artificially extending an existing shoreline in a seaward direction.

NEARSHORE CIRCULATION

The water transported onto the beach by breaking waves produces a complex system of water currents nearshore. This nearshore circulation of water consists of an onshore transport by the breaking waves, a lateral transport inside the breaker zone by longshore currents, and a seaward

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[3] Measurements of sand transport rates and power losses in a wave channel gave values of K ranging between 0.1 and 0.3 (Inman and Bowen, 1963).

[4] This relation is derived from energy considerations by Inman and Bagnold (1963, pp. 530-533). Reference to footnote 2 shows that c is approximately equal to the cube of the ratio of the maximum offshore component of orbital velocity to the maximum onshore compoent, $(u_{m-off}/u_{m-on})^3$.

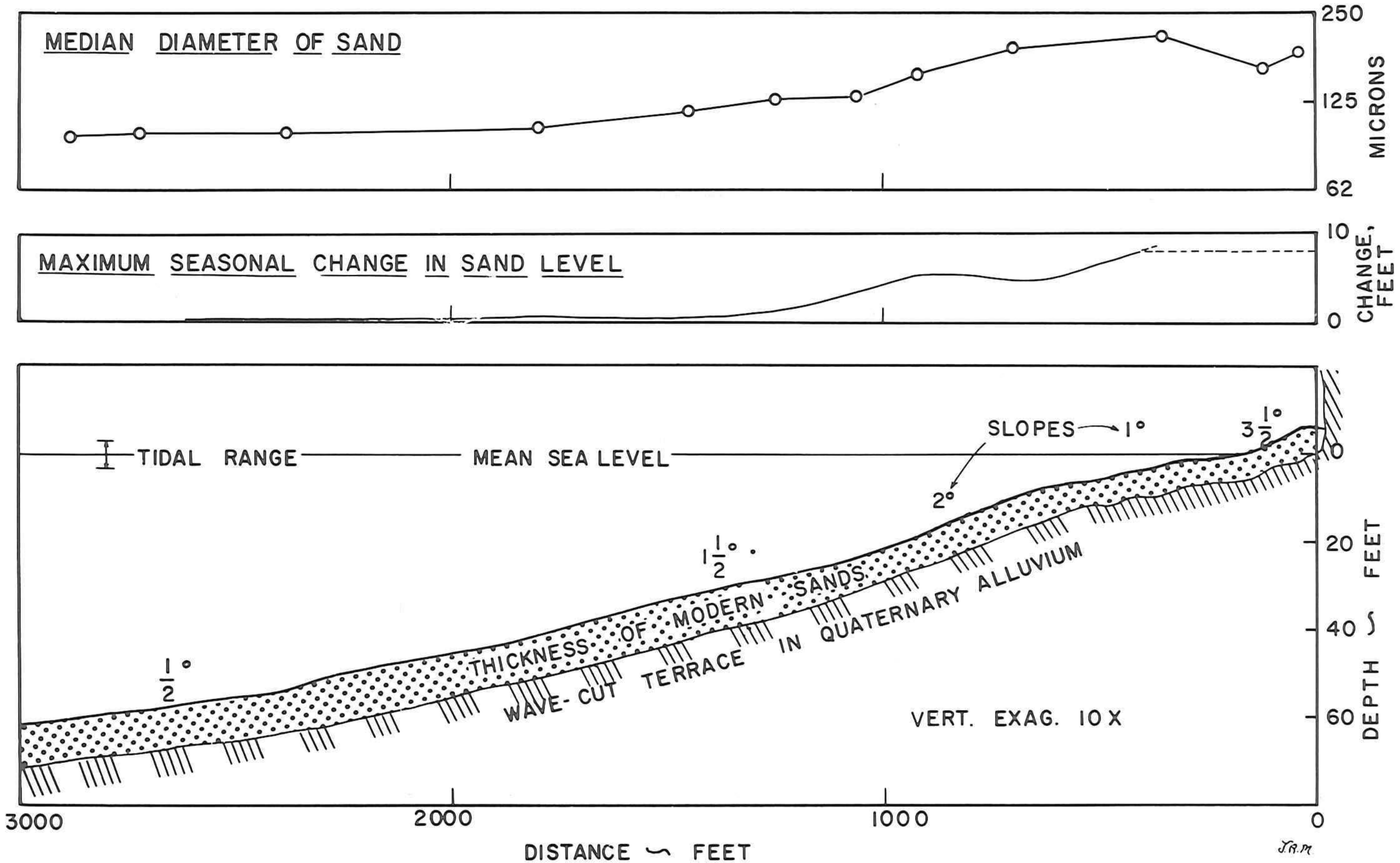

Figure 1. Equilibrium energy profile of a fine sand beach at La Jolla, California, showing the median sand size, the maximum seasonal change in the level of the sand associated with winter and summer waves, and the thickness of the modern littoral sand over the wave-cut terrace (after Inman and Bagnold, 1963).

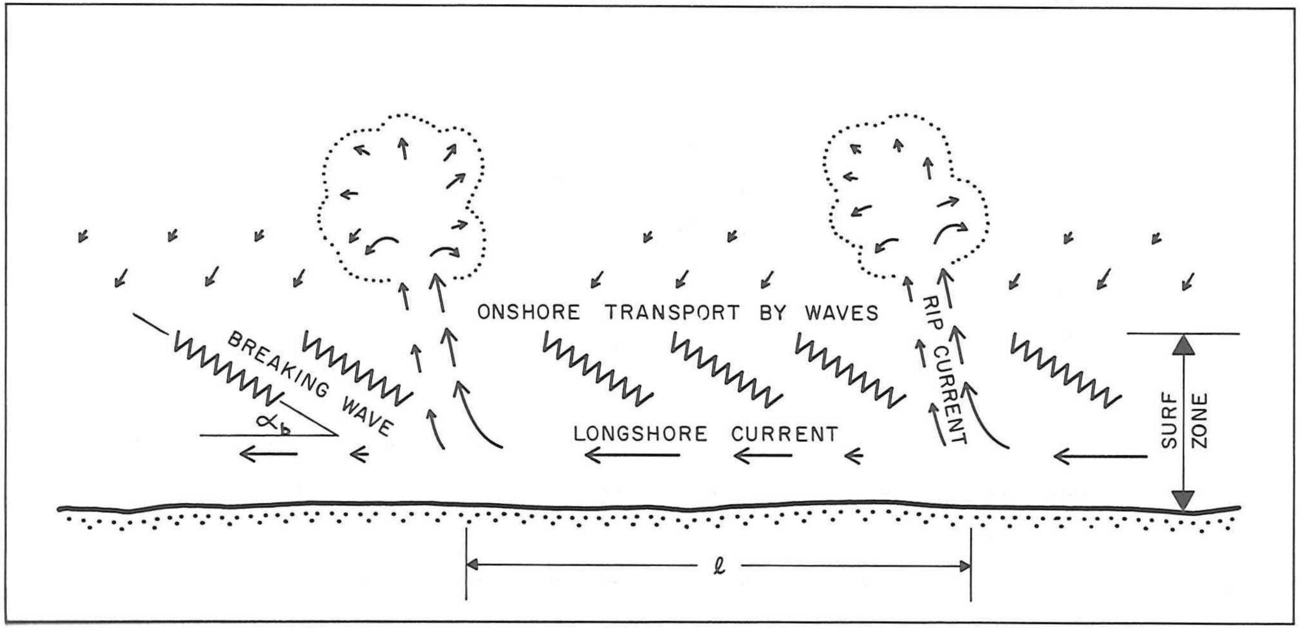

Figure 2. Schematic diagram of the nearshore circulation system.

return of the flow through the surf zone by rip currents (Figure 2). The seaward motion in the rip currents extends beyond the breaker zone for a distance about equal to the width of the surf zone. For example, rip currents generated by waves that break 1000 feet offshore can be expected to carry sand in suspension for a distance of about 2000 feet offshore.

There have been numerous studies relating longshore current velocity to the wave and beach characterisitics (e.g. Putnam, Munk, and Traylor, 1949; Inman and Quinn, 1952; Bruun, 1963; Galvin and Eagleson, 1965). However, none of these have considered the effect of rip currents on the budget of water in the surf zone. If the longshore current is confined to the surf zone, the discharge of water into the surf zone would cause the longshore current to continue to increase indefinitely with distance along the beach if it were not for the existence of outward flowing rip currents. These considerations of the conservation of mass in the surf zone led Inman and Bagnold (1963) to formulate the following theoretical expression for the mean velocity of longshore current

$$\bar{u}_\ell = k \frac{\ell}{T} \tan\beta \sin\alpha_b \cos\alpha_b \; . \; . \; . \; . \; . \; . \; (LT^{-1}) \qquad (5)$$

where ℓ is the separation distance between rip currents, T the wave period, α_b the breaker angle, and β is the slope of the beach face. k is a factor depending upon the type of breaking wave and theoretically would have a constant value of 2.0 for solitary waves. Unfortunately, there are few studies where the rip spacing ℓ has been evaluated. The few field and laboratory measurements available indicate that on the average, ℓ is two to four times greater than the width of the surf zone. These observations indicate that the above relatively simple expression is in reasonably good agreement with measured values of the longshore current.

The position of rip currents along a beach and the spacing between rip currents have significant implications in recreational planning and beach maintenance. Since the longshore current feeds the rip currents, the velocity of longshore currents tends to be least just down coast of rip currents. The positions of rip currents are migratory along very straight beaches with parallel offshore bottom contours. However, their position tends to become stabilized by slight irregularities in bottom topography; and their approximate position can be predicted along some beaches. To be effective, the design and spacing of groins requires a knowledge of the spacing between rip currents (Figure 5).

LONGSHORE TRANSPORTATION OF SEDIMENTS

Since the waves supply the energy to set the sand in motion, any net current will produce a transport of sand in the direction of the current (equation 3). Thus, in effect, the wave stresses "de-weight" the sediment load, placing it in a condition where any current, no matter how weak, is competent to move the load in the direction of the current. Therefore, the transport of sand should be proportional to the product of the amount of wave energy dissipated and the velocity of the current.

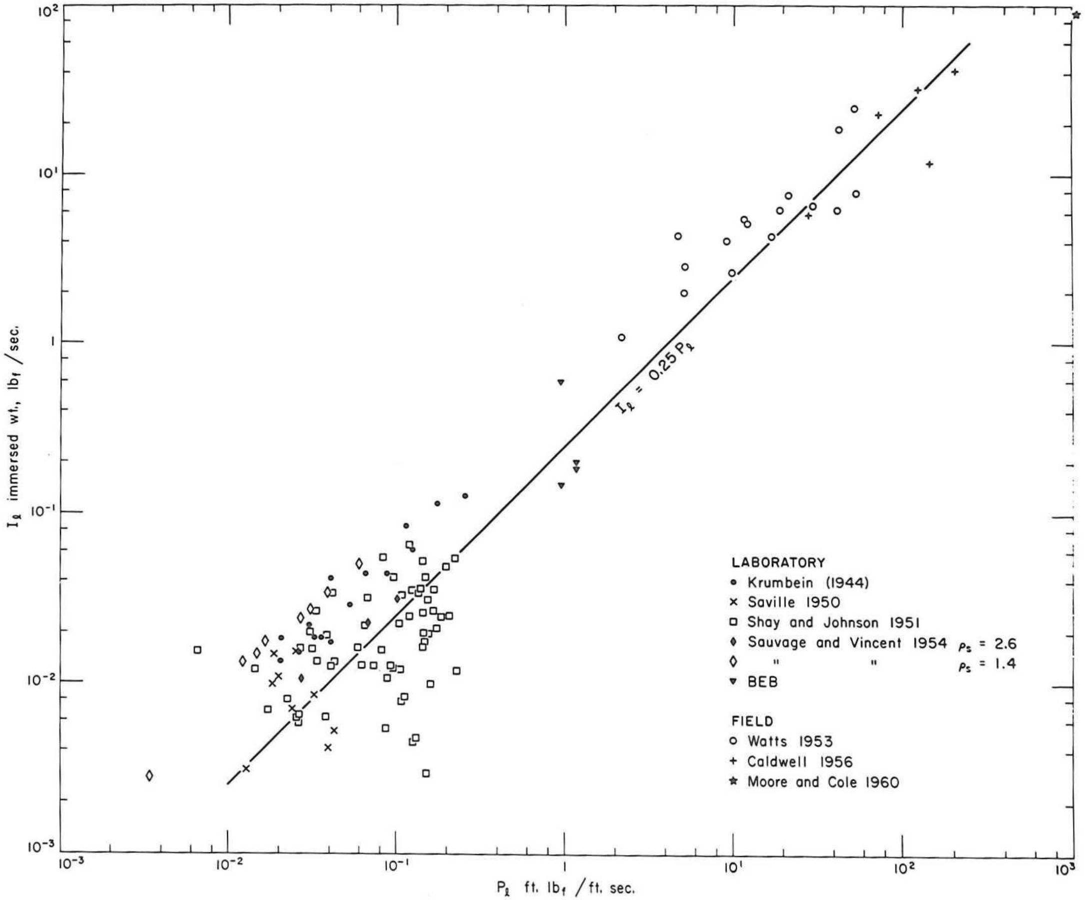

Figure 3. Relation between the dynamic longshore transport rate I_ℓ, and the longshore component of wave power per unit length of beach P_ℓ (calculations by D. F. McGeary).

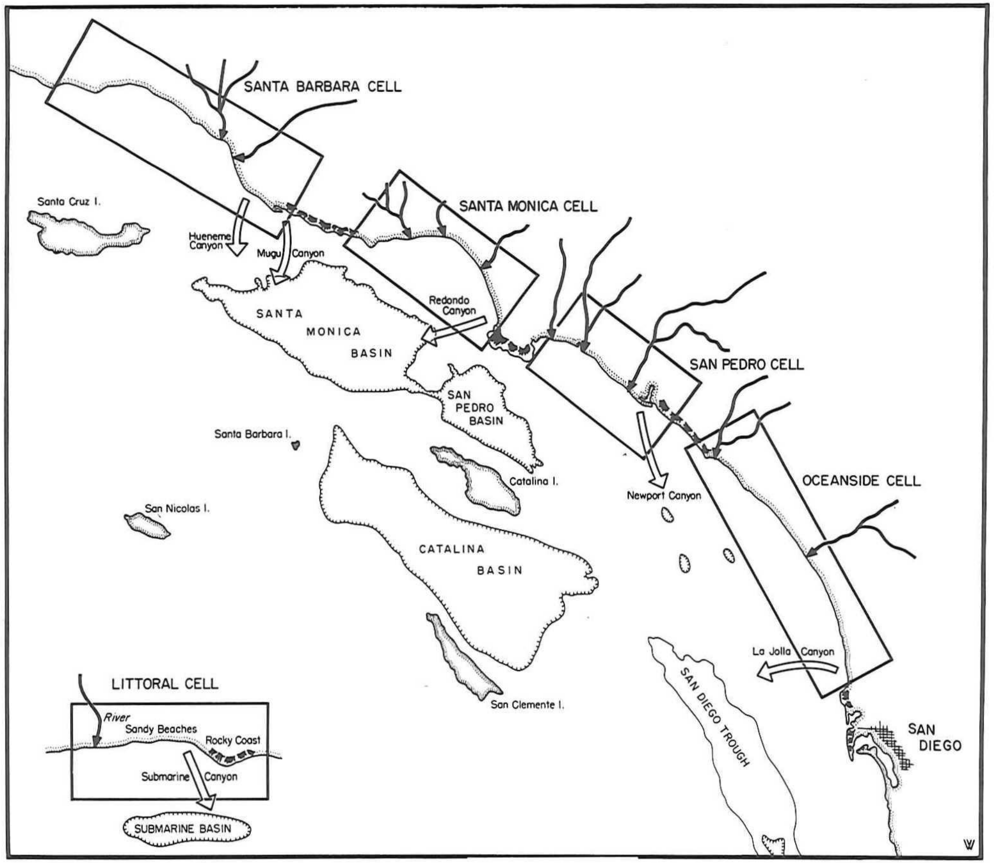

Figure 4. Schematic representation of littoral sedimentation cells along the southern California coast. Each cell contains a complete sedimentation cycle: Sand is brought to the coast by streams, carried along the coast by waves and currents, and lost into deep submarine basins through submarine canyons.

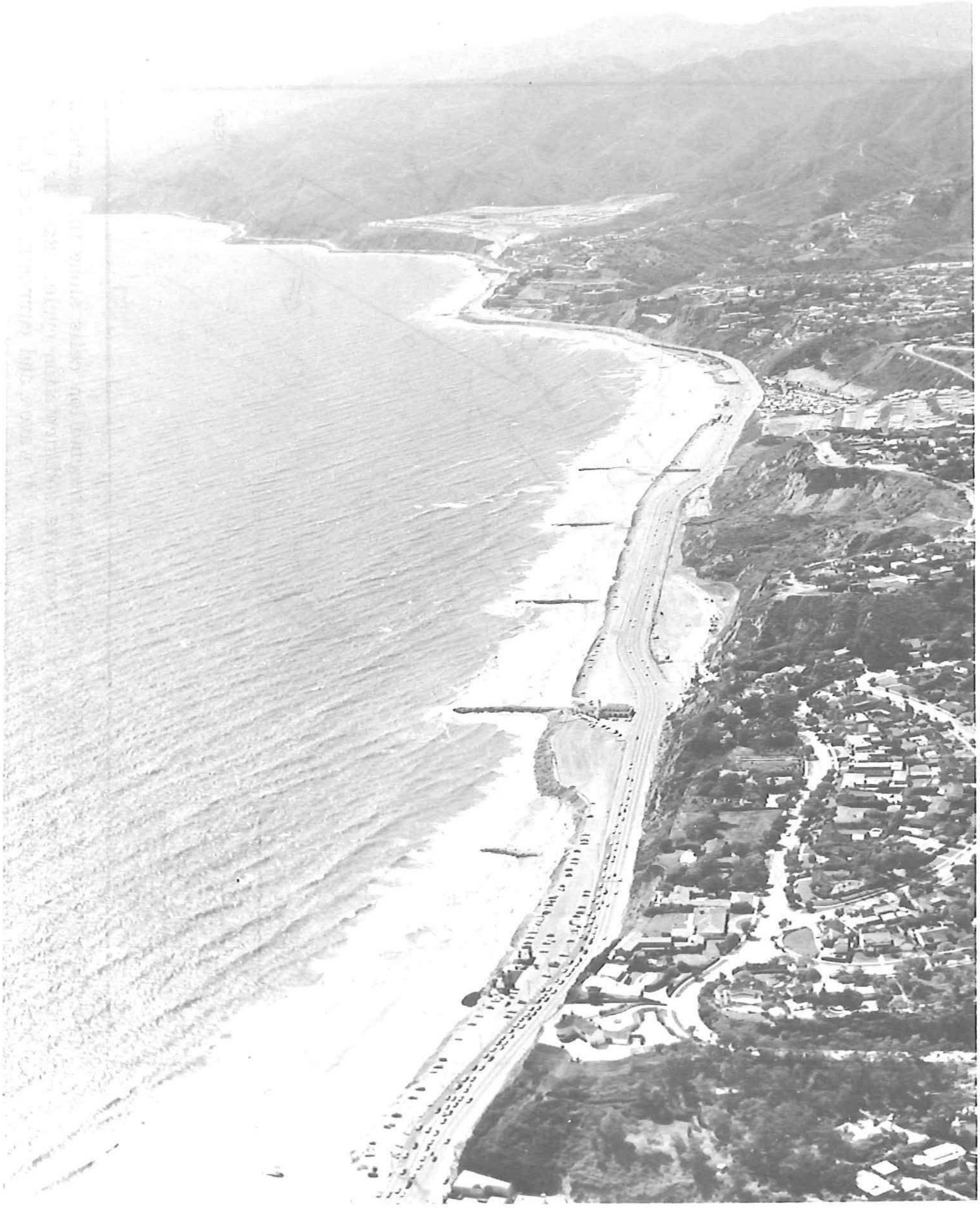

Figure 5. Aerial photograph of shoreline at Santa Monica Bay, California, showing groins designed to permit rerouting of Highway Route 60 around the landslide at Pacific Palisades. Alignment of sand beach trapped between the groins indicates littoral transport of sand is towards the viewer.

For the special case of the longshore transport of sand in the surf zone, the breaking wave supplies the power for placing sand in motion, as well as the longshore current that carries the sand load.

A theoretical model for the longshore transport of sand was developed following the reasoning leading to equations (1), (2), and (3). In the case of longshore transport, the total rather than the unit width transport is desired, and the expression for the dynamic longshore transport rate becomes

$$I_\ell = (\rho_s - \rho) g a_l S \; . \; . \; . \; . \; . \; . \; . \; . \; (MLT^{-3}) \qquad (6)$$

where $(\rho_s - \rho)g$ is the conversion factor for immersed weight as in equation (1), a_l is the correction for pore-space and may be taken as 0.6 approximately, and S is the bulk volume of sand transported in unit time. I_ℓ has units of immersed weight per unit time, or power per unit length. The longshore transport model (Inman and Bagnold, 1963, p. 454) indicates that the longshore transport of sand is proportional to the longshore component of wave power, per unit length of beach P_ℓ

$$I_\ell = KP_\ell \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; (MLT^{-3}) \qquad (7)$$

The few field calculations presently available (Watts, 1953; Caldwell, 1956; Moore and Cole, 1962), together with the laboratory data (e.g. Savage, 1962), indicate that the longshore transport of sand is directly proportional to the longshore component of wave power, as indicated by equation (7). The known data are plotted in Figure 3, and fit the relation

$$I_\ell = 0.25 \; P_\ell \qquad (7a)$$

The dynamic longshore transport rate was calculated from equation (6) and is expressed as immersed weight transported per unit time (lb_f/sec). The longshore component of wave power was computed for the breaker zone and is expressed in power per unit length of beach (ft.lb_f/ft.sec). The equations for wave power are usually written for the root-mean-square wave height, which is the wave parameter most commonly measured in the laboratory. However, the power computation for the field data appears to be based on significant wave height and thus may be too high by a factor of 2. On the other hand, the practice of representing the entire power spectrum in terms of a single significant wave may result in the omission of important energy contributions from waves of different frequency, causing the computations to be too low. A rigorous evaluation of this relation is essential to beach planning. It would permit the evaluation of longshore transport potential directly from the budget of wave energy for existing beaches, as well as for contemplated new beaches. Meanwhile, estimations of longshore transport rates based on equation (7a) appear to give values that are approximately in agreement with transport rates determined by siltation rates in harbors (e.g. Bowen and Inman, 1965).

At present the volume of longshore sediment transport along oceanic coasts is estimated from observed rates of erosion or accretion, most commonly in the vicinity of coastal engineering structures such as groins and jetties. Such observations indicate that the transport rates along most ocean beaches range from about 60,000 to 1,000,000 cubic yards of sand per year. The average transport is about 200,000 cubic yards per year. The sources and sinks for these large amounts of sand are discussed in the following section.

SOURCE AND BUDGET OF NEARSHORE SEDIMENTS

Application of the principle of conservation of mass to the sediments in the littoral zone has proved to be a very useful tool in evaluating the relative importance of the various possible sources of sediment and agents of transport. The procedure, sometimes referred to as the budget of sediments, consists of assessing the sedimentary contributions (credits) and losses (debits) and equating these to the net gain or loss (positive or negative balance) of sediments in a given "littoral cell". A "littoral cell" is defined as a coastal segment that neither receives sediment from, nor contributes sediment to adjacent cells by longshore transport. The surprisingly large amounts of littoral sediment trapped by coastal engineering structures, such as harbors, groins, etc., have led to our present insight into the high rates of littoral transport by waves and currents.

Along the California coast the principal sources of beach and nearshore sediments have been the rivers which brought large quantities of sand directly to the ocean; the sea cliffs of unconsolidated material, which are eroded by waves; and material of biogenous origin (shell fragments and skeletons of small marine animals). Occasionally, sediment may be supplied by erosion of unconsolidated deposits in offshore shallow water. For example, beach sediments on the coasts of Holland are derived in part from the shallow waters of the North Sea. Generally, west coast continental shelves are too steep for offshore deposits to be of importance, although the shelves off the east coast of the United States may contribute some sand to the beaches. Windblown sand may be a source of beach sediment, although winds are usually more effective in removing sand from beaches than in supplying it.

Streams and rivers are the most important source of sand for beaches in temperate latitudes. Surprisingly, the contribution of sand by streams in arid counties is also quite high. This is because weathering in arid climates produces sand-size material and low rainfall supports a minimum cover of vegetation. The occasional flash floods in arid climates may transport large volumes of sand. During the flood of 1938 the Los Angeles River is estimated to have deposited about 6,600,000 cubic yards of sediment in outer Los Angeles Harbor (Troxell, 1942, p. 380). The same flood produced a deposit of about 10,000,000 cubic yards in the delta of the Santa Clara River south of Ventura.

Cliff erosion probably does not account for more than about 1 to 30 per cent of the material on most beaches. Wave erosion of rocky coasts is usually slow, even where the rocks are relatively soft shales. On the other hand, retreats greater than one yard are not uncommon in unconsolidated sea cliffs. Historical records show that some cliffs of unconsolidated material at Cape Cod have retreated as much as 1000 feet in the last 100 years (Shepard, 1963, p. 176). On the other hand, Shepard and Inman (1951), in a study along the coast north of La Jolla, California, determined that the contribution from cliff erosion was only about 2 per cent.

During recent years, sand dredged from new harbors has constituted a major portion of the total littoral drift of sand in some areas. Between 1939 and 1945, dredging from the San Diego Bay contributed 28,000,000 cubic yards of sand to the beach along the Silver Strand.

The littoral sand is transported along the coast until it reaches a "sink" of some kind. In the sense of the budget of littoral sand, a sink is any mechanism that takes sand from the longshore transport regime. Along the California coastline there are two principal sinks: loss from the beach by wind transport inland and losses into the heads of submarine canyons that traverse the shelf. It is estimated that wind transports over 200,000 cubic yards of sand per year inland along the 35-mile coastline from Pismo Beach to Point Arguello, California, and over one million cubic yards per year inland along the coast of Vizcaino Bay, Baja California, Mexico. The transport rate of the sand was shown to be related to the wind power by a relation of the form of equation (2) (Inman et al, in press). The loss down submarine canyons is described in the following section.

BUDGET ALONG THE PRECIPITOUS COASTLINE OF SOUTHERN CALIFORNIA

Studies show that the southern California coastal region can be divided into several discreet sedimentation cells, each containing a complete cycle of littoral transportation and sedimentation (Figure 4). The principal sources of sediment for each littoral cell were the rivers which periodically supplied large quantities of sandy material to the coast. The sand is transported along the coast by intermittent wave action until the littoral river of sand is intercepted by a submarine canyon, which diverts and channels the flow of sand into adjacent submarine basins and depressions.

A typical littoral cell begins with a stretch of rocky coast where the supply of sand is limited (Figure 4). In a down coast direction, determined by the prevailing waves, the beaches gradually become wider and the coastline straightens where the streams supply a sufficient amount of sand. Submarine canyons terminate the littoral cell by capturing the supply of sand, thus causing the next littoral cell to begin with a rocky coast devoid of beaches, etc. Four cells can be defined for southern California (Inman and Chamberlain, 1959).

A detailed study was made of the San Pedro cell and Newport Submarine Canyon. Prior to the building of flood control dams, sand was brought to the coast by the major rivers, the Los Angeles, San Gabriel, and the Santa Ana, and then transported along the coast to the south and east by wave action and wave-generated currents. The bulk of the littoral load was deposited in Newport Submarine Canyon, which appears to function as a conduit through which the sand is transported into deeper water. Only minor amounts of material are transported to the southeast around the heads of Newport Submarine Canyon and onto Newport Spit. Calculations of longshore transport using equation (7a) give a net southerly transport of 300,000 cubic yards/year at Sunset Beach in Newport littoral cell. This is in good agreement with estimates of the Corps of Engineers based on the rates of erosion of sand placed in the area (Herron and Harris, 1962).

TYPES OF BEACH AND COASTLINE

The alignment of the land margin; structural elements, such as headlands; and the meteorological and wave environment are all reflected in characteristic beach and shoreline geometry and dynamics. These effects are well demonstrated along the shoreline of California.

The differences in wave climate between northern and southern California are particularly well shown in the character of the beaches and continental shelves. To the north of Point Conception, high breakers produce wide surf zones and relatively gentle beach slopes compared to southern California. Exceptional northern areas where waves are generally low are restricted to isolated embayments such as Drakes Bay, San Francisco Bay, and Halfmoon Bay. In contrast, the southern beaches are steep and relatively narrow. Offshore islands attenuate swell and local seas are seldom high, since intense winds are uncommon.

The position of headlands has an important effect on beaches. Coastal areas with limited sediment supply or with closely spaced headlands have only small pocket beaches. Where the headlands are far apart and sand supply adequate, the beaches are wide and long. As examples, the three headlands of resistant rock, Point Sal, Purisima Point, and Point Arguello, act as large, natural groins interrupting the longshore transport of sand and causing long, straight beaches that trend perpendicular to the prevailing waves which come from the west northwest. The effect of this beach alignment is to reduce the ratio between the net longshore wave power and the total longshore wave power, and hence to reduce the longshore transport of sediment. The headlands also channel westerly winds over the relatively wide beaches causing large amounts of sand to be blown inland and lost from the beach area.

UTILIZATION OF BEACH AND INSHORE WATERS

To the average citizen beach and inshore waters are playground areas or simply pleasant places to go to enjoy the beauties of an unspoiled natural environment. To the businessman or military man other uses are of greater importance and interest. All uses are enhanced if the areas can be given a degree of stability and permanence and be kept free of man-made pollution of all kinds.

Common recreational uses include swimming, surfing, sun bathing, picnicing, tide pooling, shell hunting, boating, water skiing, fishing, clamming, etc. While the requirements for recreational uses of beaches are not all compatible, aesthetics in terms of picturesqueness, cleanliness, absence of overcrowding, absence of water and air pollution are all important, but hard to define, concepts in recreational planning for beaches. It is apparent that a clean, sandy beach near a wooded headland has far greater appeal than a "Coney Island" type. In view of the population pressures on marine recreation, serious consideration should be given to the formation of new shorelines for recreational purposes in heavily populated areas. In southern California and Hawaii, new shorelines should include provisions for surfing and swimming; while in northern California, Oregon, Washington, and the New England states, the emphasis should be on access for walking, clamming, and picnicing, which are more likely uses.

Commercial uses include harbors, shipping, and highways; industrial uses include fishing, mining, and waste disposal; while military uses include practice areas for amphibious landings, sea plane landings, etc. These uses all have quite different requirements from recreational uses, and proper planning should result in separation insofar as possible.

CONFLICTS OF INTEREST AND COMPATIBILITY OF USE

The many kinds of use of shoreline require careful analysis if we are to utilize our shorelines efficiently. Even within the category of recreation, it is clear that swimming, boating, and fishing are not always compatible in the same waters. In general, recreational, commercial, and industrial uses tend to be incompatible unless carefully planned. Planning should define areas that can be posted so that activities such as water skiing, boat racing, etc., are kept out of shipping lanes; and these, in turn, should be restricted from swimming areas. Until recently there has been little conflict between commercial and sport fishing; however, with the increased use of inshore waters, it will become necessary to separate these kinds of activities as well.

Harbors and beach recreation - Relatively deep water nearshore is desirable for harbors, while the converse is true for beaches. Harbor entrances constructed through beaches interrupt the longshore transport of sand. Proper design of breakwater and sand by-passing can minimize conflict and create protected waters for both recreation and shipping. The dredging of littoral sands that frequently accompanies the construction of new harbors and the enlargement of existing harbors provides a significant portion of the sand on southern California beaches. It may be possible in some cases to schedule dredging at intervals over long periods of time to coincide with demand for beach sand.

The present trend in shipping toward large deep-draft vessels suggests that some industrial harbors should utilize offshore islands and deep anchorages rather than dredging inland harbor areas.

Highways - There tends to be a concentration of population in centers distributed along coastal areas. Logically there is a demand for roads connecting these centers of population, as well as for providing access to beach areas.

In most instances use of beach frontage for rights-of-way should be discouraged. In cases where land alignments of near-beach highways would be inordinately expensive because of difficult terrain or high-priced real estate, over-all economy may result if the construction is on offshore moles, the costs of which can be shared with harbor and recreational development (see U. S. Corps of Engineers, 1963).

PRESERVATION OF EXISTING BEACHES AND DEVELOPMENT OF NEW SHORELINES

Many of the basic factors applicable to the preservation of existing beaches are also fundamental to the development of new beaches. These are: a) sufficiently gentle offshore slopes to establish equilibrium energy profile (equation 4), b) adequate supply of sand, and c) the corollary factor of relatively low longshore transport of sand (equation 7). These contrast with industrial and commercial shoreline facilities, such as harbors, where steep offshore slopes and deep waters nearshore are desirable features.

BEACH PRESERVATION

Since existing beach areas have gentle offshore slopes, their preservation usually centers around measures that provide continuing sources of sand and/or decreasing rates of longshore transport. To some extent these involve widening and changing the alignment of beaches and thus the creation of new beaches.

Methods of providing sand sources - There are a number of methods that promise to provide continuing sources of sand for beaches. There are several possibilities of utilizing other untapped natural resources of sand, such as the layer of sand that in places covers the continental shelves (Taney, 1965) and sand blown inland and stored in coastal dunes. There is also the possibility of dredging sand that has been trapped behind dams, as well as the procedure already mentioned of dredging sand from harbors.

However useful as immediate remedies, all of these sources will eventually be consumed. It seems wise to consider measures that will prevent the loss of sand that is already on the beach before it is lost in submarine canyons. For example, sand could be trapped artificially just before entering the submarine canyon head and replaced on an up coast beach by hydraulic pumping. Such a procedure has been suggested for sand that is lost down Newport Submarine Canyon (Herron and Harris, 1962). In some cases it may be feasible to dam the narrow inshore portions of some submarine canyons and thus prevent sand losses.

A comprehensive study should be conducted of our natural sand resources including the pre-modern deposits of sand that occur on the continental shelf. It is possible that a combined operation involving the mining of offshore sands for their mineral value, then placing the spoils on the beach, would be economically feasible. The study of the mechanism of sand movement down submarine canyons and methods of intercepting this transport should receive high priority.

Methods of decreasing the longshore transport rates of sand - The rate of longshore transport of sand is directly proportional to the longshore component of the wave energy dissipated in the surf zone. Therefore, any measures that: a) decrease the angle that the breaking waves make with the beach (breaker angle), or b) decrease the wave energy, will decrease the longshore transport of sand.

Groins have proved to be the most common engineering structure that produces a decrease in the breaker angle (Figure 5). Groins consist of walls of rock rubble or sheet piling that extend seaward from the upper beach, usually to a point some distance seaward of the breaking waves. Groins temporarily interrupt the longshore transport of sand; and if properly designed, permit the trend of the beach fillet between groins to become aligned perpendicular to the breaking waves, thus decreasing the breaker angle and, consequently, the longshore transport of sand.

Any structure that dissipates wave energy before the waves reach the beach will result in a decreased transport of sand along the beach. There are a variety of structures that dissipate wave energy before the waves reach the beach. These include curtains of air bubbles, submerged reefs and dikes, and detached breakwaters. A detached breakwater is one located some distance offshore and aligned parallel to the shore. The type examples are the Winthrop Beach, Massachusetts, Breakwater constructed in 1931-33 and the Santa Monica, California, Breakwater which was built in 1933-34 for a small boat harbor.

A detached breakwater dissipates wave energy by causing waves to break along its entire length. Thus, there is an absence of wave energy or a "wave shadow" directly behind the breakwater. Diffraction of waves to either side of the breakwater and the variability in the direction of approach of the incident waves gradually eliminates the shadow zone in a down-wave direction. If the structure is sufficiently distant from the shore, the wave shadow does not fall upon the shore; and there is relatively little effect at the shoreline. If the structure is close to the shore, the wave shadow falls directly on the shore and causes the sand to accrete behind the breakwater (Figure 6). Experience along the southern California coast indicates that pronounced accretion does not

Figure 6. Aerial photograph of a breakwater at Venice, Santa Monica Bay, California. Wave shadow in lee of breakwater has caused a tombolo to form joining breakwater to the beach.

occur if the structure is situated offshore a distance equal to or greater than 3 to 6 times the length of the detached breakwater. An example of the accretion behind a detached breakwater is shown by comparison of surveys in the vicinity of the Venice Pier Breakwater (Figure 7). This breakwater is 600 feet long and was constructed in 1905 to protect the Venice Amusement Pier. The breakwater was originally about 1000 feet seaward of the mean lower low water line. Although it remained "detached", the effect of wave shadow and the pilings of the Venice Pier caused the beach to build about 300 feet seaward as shown by the 1935 survey (Figure 7). In 1948, deposition of 14,000,000 cubic yards of dredged sand caused the beach to build seaward so that its general alignment north and south of the breakwater was about 900 feet from the breakwater. The resulting wave shadow caused the additional accretion behind the breakwater until the shoreline joined the breakwater, forming an artificial tombolo with the breakwater at its apex as shown by the 1953 survey. The Venice Pier has since been removed, but the artificial tombolo formed by the detached breakwater exists today.

INLET STABILITY

The size of the entrance channels into tidal lagoons that border sandy shorelines is related to the volume of the tidal prism of the lagoon. The situation seems analogous to that for rivers, where the sectional area is related to the stream discharge. In the tidal inlet there appears to be a balance between the scouring actions of the tidal currents, that tend to keep the channels open, and the longshore transport of beach sand, that tends to close them. An entrance channel that maintains a constant cross-sectional area, while crossing a sandy beach, has attained an equilibrium with the tidal flow and is sometimes referred to as a scouring channel. Equilibrium does not imply a stability of channel location, but only a constancy in the relation between tidal flow and channel cross-section. It has been observed that entrance channels migrate in the direction of the dominant longshore transport, unless the channels are stablized naturally by headlands or artificially by jetties.

O'Brien (1931), using 16 harbors known to have channels that approximate scouring conditions, showed that the cross-sectional area of the entrance (below mean sea level) was proportional to the volume of the tidal prism raised to the 0.85 power. The tidal prism was taken as the area of the tidal lagoon or bay multiplied by the diurnal range of tide for Pacific coast harbors and by the mean range for Atlantic coast harbors. O'Brien's data ranged from San Francisco Bay with a tidal prism of 8.1×10^{10} ft^3 to Newport Bay with a prism of 2.0×10^8 ft^3. More recently, the equilibrium relation for a much smaller harbor, the boat basin at Camp Pendleton near Oceanside, California, was measured. The Camp Pendleton boat basin was surveyed in 1956 following a long period without preventative maintenance during which the channel entrance was permitted to attain a condition of equilibrium with the tidal flow. Similar measurements were obtained for Mission Bay entrance four years

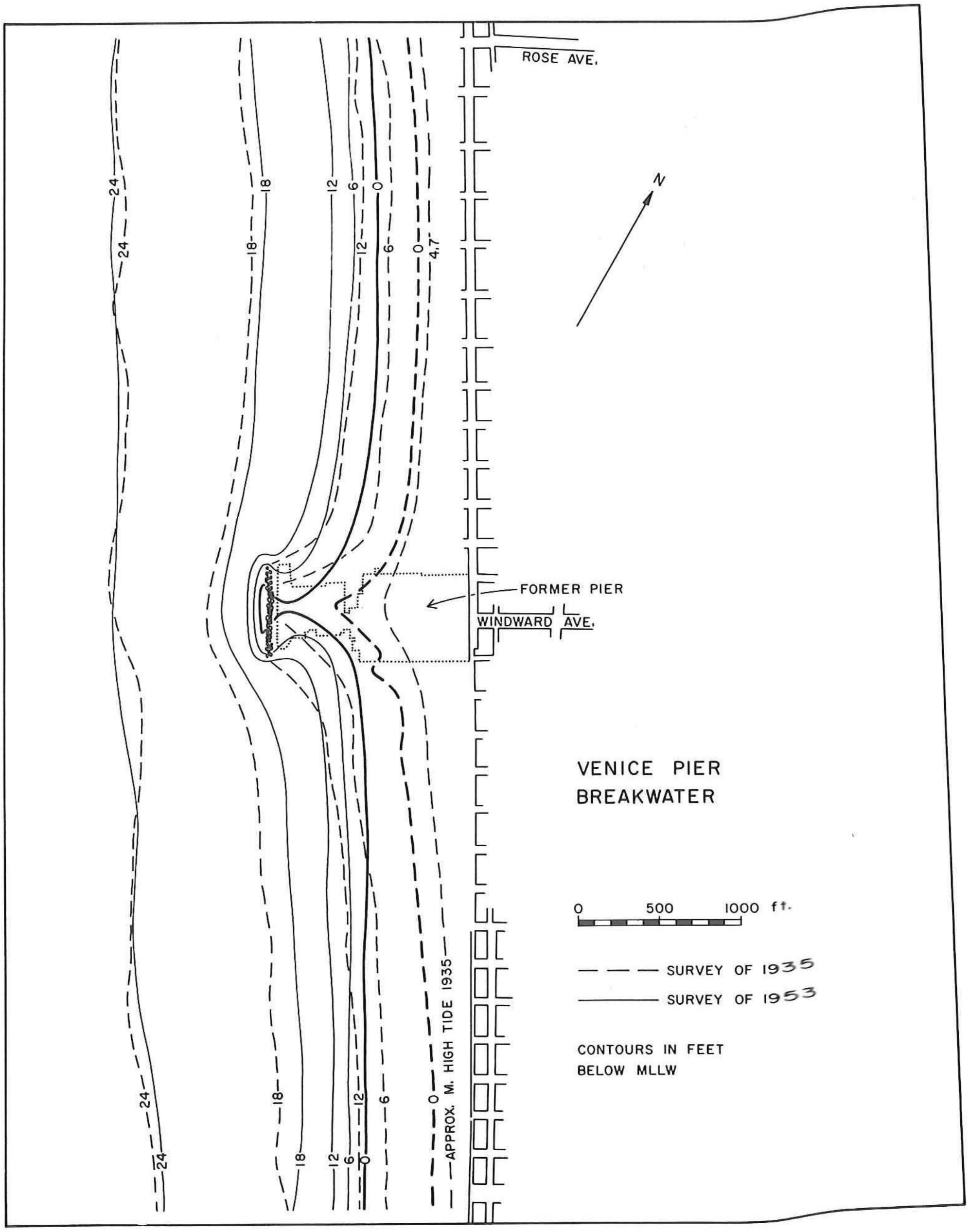

Figure 7. Comparative surveys of Venice Pier Breakwater showing the effect of a detached breakwater on the adjacent beach. Surveys by Los Angeles County.

after the completion of construction of new jetties bordering the entrance channel and prior to the commencement of maintenance dredging.[5]

The new data is in surprisingly good agreement with O'Brien's original data (Figure 8). This suggests that the relation for small tidal prisms can be represented with sufficient accuracy by

$$A = 4.1 \times 10^{-4}\ T^{0.86} \quad . \ . \ . \ . \ . \quad (L^2 + L^3) \qquad (8)$$

where A is the minimum cross-section area in square feet of entrance channel measured below mean sea level and T is the volume in cubic feet of the tidal prism between the diurnal range of tides. It is interesting to note the analogy to streams, where the sectional area of the stream varies as a power of the discharge. From theoretical considerations Langbein (Myrick and Leopold, 1963, pp. 15-17) shows that the sectional area of a stream should vary as the 0.95 power of the discharge. This value is in good agreement with field measurements in rivers and small tidal creeks (Redfield, 1965).

CREATION OF NEW BEACHES AND SHORELINES

The reclamation of land from the sea has been a problem of considerable interest for centuries. The Dutch with their major land reclamation projects (polders) are the outstanding examples of accomplishment in this field. Unfortunately, the use of dikes to withhold the sea is only economical for large areas of shallow water and, hence, does not generally apply to California, with the possible exception of portions of San Francisco Bay. On the other hand, it may apply to the U. S. Gulf coast.

A procedure for creating new land, by earth fill behind solid offshore bulkheads, has received extensive application along the Inland Sea of Japan. There, entire mountains have been removed to fill the area behind the bulkheads. This procedure is attractive for industrial development, as it provides flat land for buildings and permits deep-draft ships to load near factories. This procedure should apply to many industrial portions of the world.

However, dikes and bulkheads do not usually increase the length of shoreline or provide for extensive areas of quiet water. Construction of offshore islands has promising possibilities along the California coast. Islands would provide new land, new shoreline, and protected waters in their lee.

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[5] Values of entrance channel area and tidal prism volume for the Camp Pendleton boat basin (February 1956) and Mission Bay (March 1954) are respectively: $A = 464\ ft^2$, $T = 1.14 \times 10^7\ ft^3$; and $A = 1.04 \times 10^4$, $T = 4.56 \times 10^8\ ft^3$. The entrance channel area is the minimum cross-sectional area below mean sea level. The tidal prism is the volume between the diurnal range of the tides. The Camp Pendleton boat basin has since been modified and combined with a larger facility.

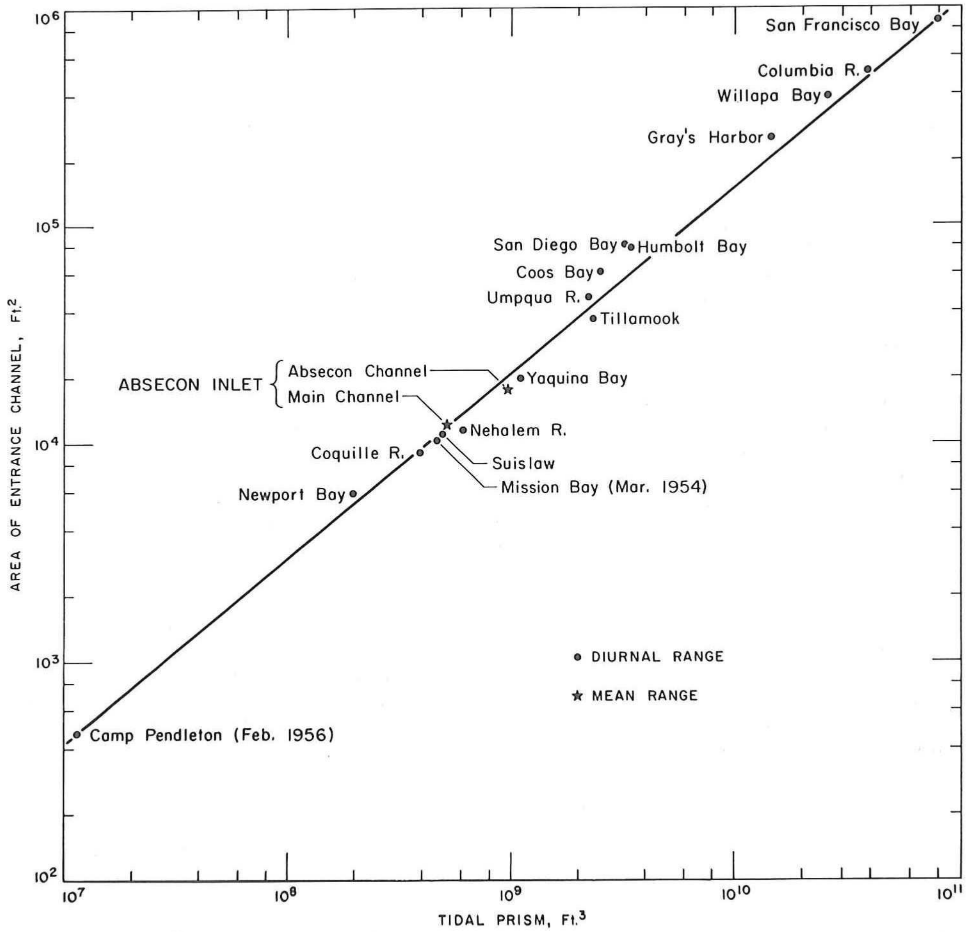

Figure 8. Relation between the minimum cross-sectional area of the entrance channel A and the volume of the tidal prism T. The channel entrance section is measured below mean sea level.

Coastlines having gentle offshore slopes could be extended seaward and stabilized by the construction of a series of detached breakwaters which later become attached (Figure 6). When attached to the shoreline, the breakwaters would form a series of headlands with concentric embayments of beach sand between them. This procedure has not been attempted on a large scale, but merits further consideration.

The creation of new land by building large artificial spits attached to the up-drift end of headlands has attractive possibilities. An artificial spit has been proposed for Santa Monica Bay (U. S. Corps of Engineers, 1963; Dunham, 1965). The proposed spit would be connected to a headland in Santa Monica Bay and extend to the south paralleling the present shoreline for about 4 miles. Its principal advantages are that it would add approximately 8 miles of new shoreline and would provide a large sheltered area for swimming and boating. The principal disadvantages are concerned with the problems of maintaining a beach on the seaward side of the artificial spit. The maintenance of beaches on the seaward portions of new land is of major concern and should receive additional study. A possible solution is discussed in the following section.

Perched beach - The principle of the equilibrium energy profile (Figure 1; equation 4) implies that a beach cannot be maintained with a slope steeper than the equilibrium slope. Thus, the maintenance of a sandy beach on new land extending seaward beyond the natural shoreline is difficult because of the necessary increase in slope. It has been suggested that an artificial beach could be maintained if it was constructed with equilibrium slopes near the breaker zone, but "perched on" or supported at its seaward end by a solid submerged dike that extends some distance above the natural sea floor.

The perched beach concept is a new one to coastal construction and results from observations of similar natural geologic situations in a few areas. Figure 9 shows the equilibrium energy profile of a natural perched beach at Algodones in the Gulf of California. The beach is perched behind a sedimentary rock outcrop that parallels the beach for its entire length. The rock outcrop is about 9 feet below mean sea level, and the waves in this locality are commonly about 3 feet high. The perched beach concept has been suggested for use on the seaward face of the proposed Santa Monica Causeway (U. S. Corps of Engineers, 1963; Dunham, 1965). Model studies (Saville, 1963; Kadib, 1962) and the natural beach at Algodones showed that a deep scour forms in the lee of the submerged dike, while sediment is deposited on the seaward side of the dike. These effects tend to reduce the effectiveness of the dike in retaining a perched beach. Widening the submerged dike may increase its effectiveness.

While certain features of the concept are attractive, it must be recognized that it is untried in prototype and that its behavior in model tests may or may not predict its full scale behavior. Further model

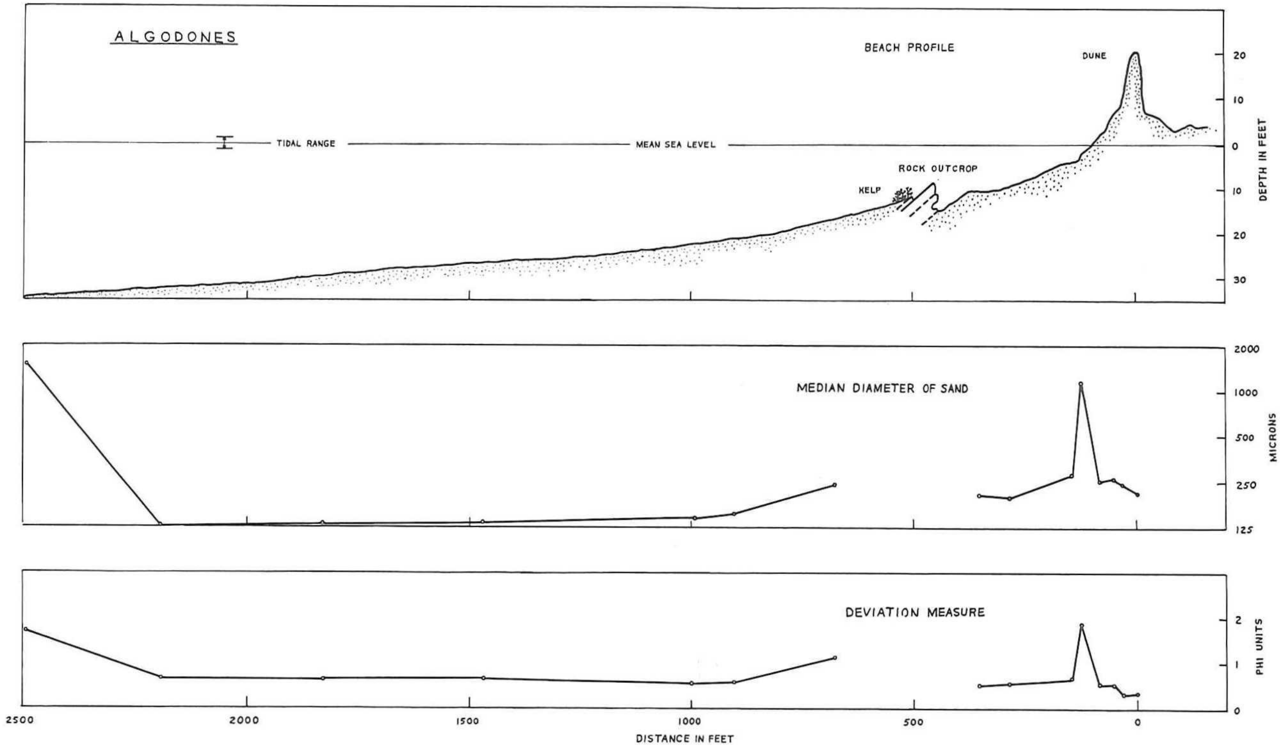

Figure 9. Profile of natural "perched beach" at Algodones in the Gulf of California. Beach is perched behind a sedimentary rock outcrop that parallels the beach. The median diameter of sand is given in microns and the deviation in phi units (Inman, D. L., 1952, "Measures for describing the size distribution of sediments," J. Sed. Pet., vol. 22, pp. 125-145).

studies should be designed to determine the optimum depth and width of the submerged dike.

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