CHAPTER 24

COLLECTIVE MOVEMENT OF SEDIMENT IN LITTORAL ENVIRONMENT

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ABSTRACT

Collective movements of sediment occur in the form of sand waves in the nearshore zone and affect beach topography to a significant extent. Bar-type sand waves move only in the onshore direction and account for various accretive profiles on the subaerial beach. When the beach is eroded, these sand waves are simply disintegrated on the subaerial beach, instead of migrating back in the form of sand waves. These characteristics of bar-type sand waves help explain dynamic behavior of beach profiles with respect to profile configuration, sediment storage, and beach width. Cusp-type sand waves are considered to be a product of interaction between longshore currents and an erodible bed. Their presence causes variability in beach profiles along the shore between those containing a prominent bar and those without a bar. Migration of these sand waves may well produce pulsational transfer of material along the shore.

INTRODUCTION

In spite of a large number of studies in the past, the mechanism governing dynamic changes in beach topography has not been generally explained. The basic difficulty may be attributed to the fact that the contribution of the behavior of individual sediment particles to modification of the bottom boundary is not sufficiently understood.

Investigations by the writer indicate that the interaction between sediments and topography in the nearshore zone may involve the role of sand wave activity. Although the detailed mechanism of the formation of sand waves in the presence of both wave and current actions is not yet known, the effects of these sand waves on beach topography are significant enough to warrant attention.

Sand waves of nearshore origin display characteristics which are essentially similar to those of the so-called "dunes" which occur in a sand bed acted upon by wind (Bagnold, 1941) or by unidirectional current (Simons and Richardson, 1960). It appears that in the nearshore zone, particularly inshore of the breaker line, where sediments are moved in large quantities, dynamics of beach topography are better explained in terms of collective behavior of sediments associated with sand waves, rather than of discrete movements of individual particles such as suggested by the null-point concept (see, for instance, Eagleson *et al.*, 1963).

Sand waves occurring in the nearshore bed are distinguished into two groups: those attributed mainly to wave orbital motion and those to longshore currents. In the absence of accepted terminology, they are called, respectively, "bar-type" and "cusp-type" sand waves.

BAR-TYPE SAND WAVES

Formation of Bar-type Sand Waves

Bagnold (1947) was probably the first to describe in detail the properties of bar-type sand waves. In a wave-tank experiment using sand of low density, he observed a series of "bars" forming on the bed and migrating in the onshore direction. They were clearly distinguished from the so-called "plunge-line bars" which are formed by and remain stationary near breaking waves. He stated:

> ..as the bars developed, the sand on their down-wave sides was first seen to halt, and then to begin to drift backwards towards the bars. The sand on their up-wave sides continued to drift forward onto them, so that the bars were fed from both sides at the expense of the sand in the hollows. There was also a general forward drift up and over the bars which made them advance.... Regarded from a viewpoint moving with the slowly advancing bar, the sand composing it must move over and backwards through it in just the same way as that of a wind-blown barchan dune which was described by the Author in 1941.

A field investigation conducted by the Coastal Studies Institute on a beach at Nags Head, North Carolina, disclosed evidence of bar-type sand waves. This beach is situated on a long, gently curved coast of the Outer Banks and is exposed to the Atlantic Ocean on the east. Details of field technique were published previously (Sonu and Russell, 1965).

It was generally observed that the bar-type sand waves were formed during a period of wave decay immediately following storm activity. Figure 1A shows an actual example of the formation of a bar-type sand wave observed on the Nags Head beach. Between February 27 through 29, wind waves with relatively large steepness persisted (Fig. 1B), and the beach was generally eroded on both its subaerial and subaqueous beds (profiles 1 through 3). As soon as the wind waves began to decay, a sand wave emerged on the foreshore bed (profile 4), then migrated steadily onshore (profile 5) and seemed to climb onto the subaerial slope (profile 6). Eventually it moved upward as far as the run-up limit of existing swashes, then remained stabilized there until it was destroyed by the next storm.

As seen in Figure 1, the bar-type sand wave had the appearance of a dune, its cross section consisting of a steep front slope and a gentle rear slope. The depth/height ratio varied considerably, between 1 and a maximum of 2.85, which is far less than the maximum of 5.0 reported in a fluvial bed (Simons and Richardson, 1960). There was a tendency for the depth/height ratio to decrease as the sand-wave crest approached the shoreline. Although the reason for this phenomenon is not evident, it seems to corrobo-

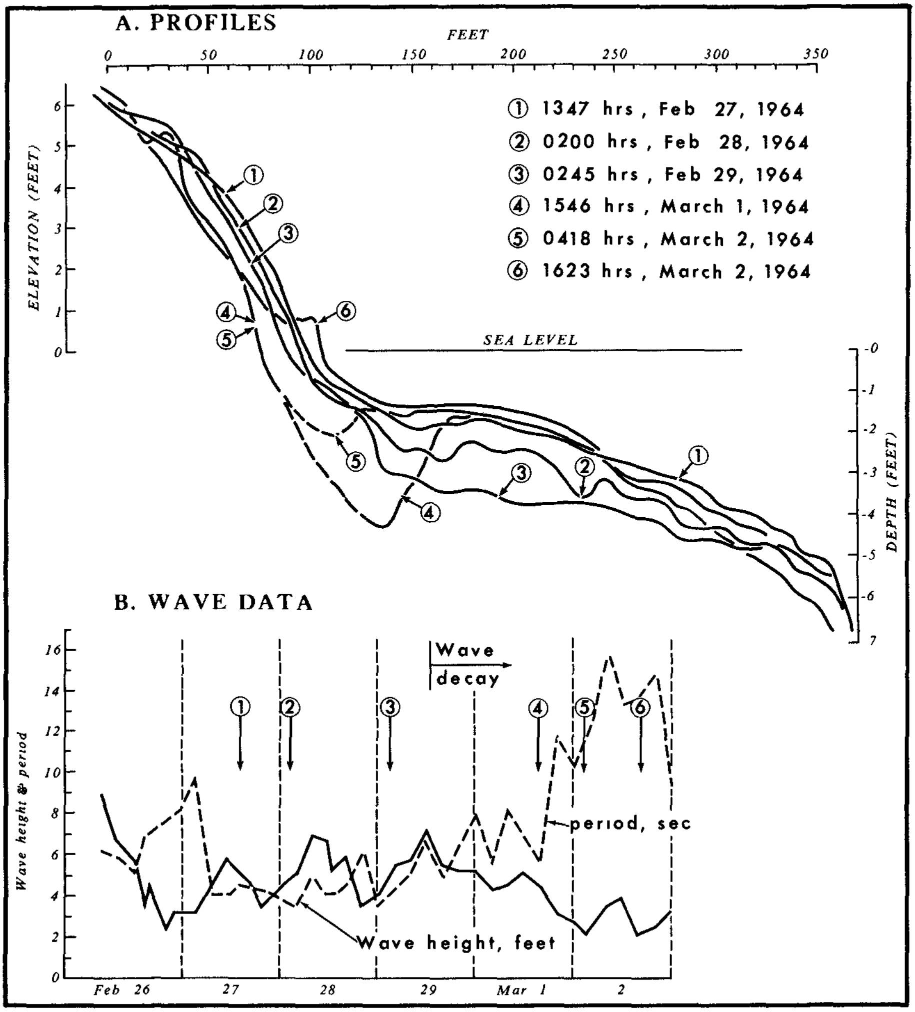

Figure 1. Formation of bar-type sand wave during decay of storm waves, Nags Head, North Carolina

rate the observation in a fluvial model that "the dune will only grow until its crest is within a certain distance from the water surface, unless three-dimensional flow exists" (Simons and Richardson, 1960).

The length/height ratio of the bar-type sand wave was not determined, since this type of sand wave usually occurred as a single pair of trough and crest, the former preceding the latter. The speed of migration was less variable than other parameters, usually remaining on the order of 4 ft/hour.

Generally, the greater the storm waves, the more prominent were the subsequent activities of sand waves. However, available data are not sufficient to determine quantitative relationship between characteristics of sand waves and those of incident waves.

Effects of Bar-type Sand Waves on Beach Profile

Figures 2 and 3 show two distinct behaviors of sand waves observed on the Nags Head beach. The one shown in Figure 2 consisted of a prominent trough and a dune-shaped crest following it As this wave approached the shore, the trough first landed on the subaerial beach. As a result, the subaerial beach was eroded, while the ensuing crest caused a steady accretion on the foreshore bed. Bagnold (1947) reported a similar phenomenon in the experiment already quoted. He stated:

> Whenever the sand of foremost approaching bar reached the beach, or, in other words, whenever the nearest distinguishable bar was one bar pitch from the beach, the beach suddenly began to build up and the waterline advanced quickly up-wave. But, thereafter, it began to erode, the sand moving outward down the slope towards the next oncoming bar. The maximum recession of the waterline occurred when the oncoming bar was half a bar-pitch from the beach, so that the beach behaved as if it were an imaginary fixed cross-section of the bed through which the bars are advancing. As a result, the beach profile was never mature, but was constantly changing in a periodic manner.

According to Bagnold, observations by Zenkovich off the Crimea corroborated his observation on the model "that the movement of the sand coastline is closely linked with that of the bar series out at sea, and that beach erosion or beach building depends on the position of the bar series relative to the beach." On the Nags Head beach, a wave crest preceded by a prominent trough such as seen in Figure 2 disappeared completely upon arrival at the shoreline, therefore failing to produce alternate erosion and accretion of the beach.

The sand wave shown in Figure 3 had a relatively obscure trough and a prominent crest, therefore bore resemblence to a solitary wave. Although there was a slight tendency for the crest to attenuate as it approached the shore (profiles 2 and 3), it eventually forced its way onto the subaerial slope. Thereafter, it continued the movement upward while steadily growing in size (profiles 4 through 6). This wave had a characteristic

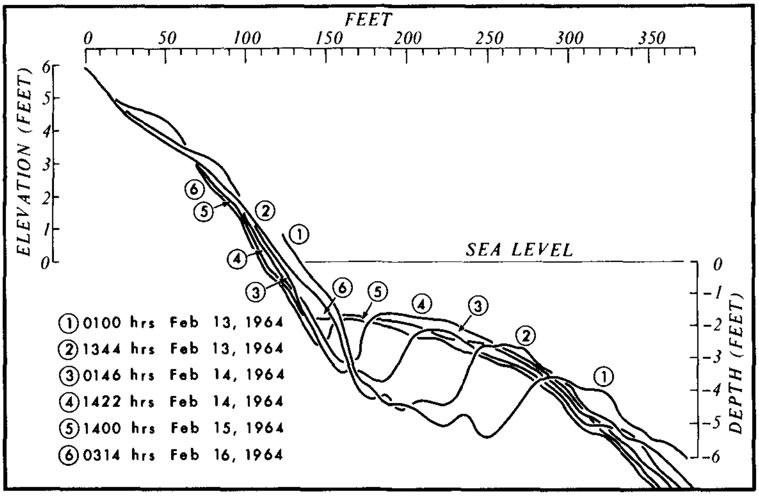

Figure 2. Bar-type sand wave with a prominent trough, Nags Head, North Carolina.

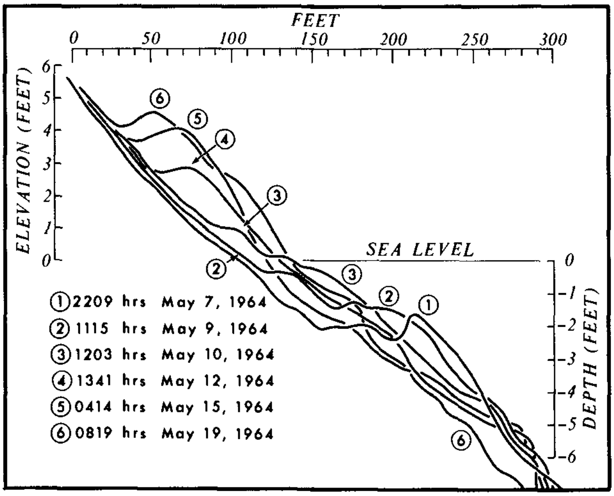

Figure 3. Bar-type sand wave with a prominent crest, Nags Head, North Carolina.

similar to the translatory property of a solitary wave in that it transported in its crest a large amount of material, which produced a "berm" on the subaerial slope

Analysis of beach profiles observed at Nags Head indicated that the translatory sand waves such as are shown in Figure 3 were most typical and were most important with respect to their effects on beach profiles. The major activities of the translatory sand waves which were of particular importance were (1) migration upward on the subaerial slope, (2) fluctuation in the size of crest, and (3) disintegration. Migration placed the wave crest--or a berm--at various elevations on the beach. It was found that, depending on the location of a berm on the lower, intermediate, and upper elevations, beach configurations of concave, linear, and convex appearances were produced, respectively. Fluctuation of the wave crest affected the prominence of these curvatures. Disintegration of the wave crest resulted in the formation of a smooth, concave profile. Consequently, as shown in Figure 4, six major categories of profile configuration were distinguished. Alphabetical notations A, B, and C represent, correspondingly, concave, linear, and convex profiles, and those letters with prime, the prominence of a berm in these profiles. Practically all the 291 observed beach profiles could be classified into these categories of distinctive configuration.

The beach profiles displayed characteristic patterns of transition which were associated with the described behaviors of bar-type sand waves. The direction in which the transitions of a beach profile occurred are shown by arrows in Figure 4, the solid arrows denoting accretive transition and the broken arrows, erosional transition.

The changes initiating from A', B', and C' occurred either as accretive changes directed from A' to B' or from B' to C', or as erosional changes from A' to A, from B' to B, or from C' to C. Transitions from C' to B' or from B' to A', which might imply backward migration of a wave crest, failed to take place. In other words, as the profiles A', B', and C' were eroded, the material composing their berms was simply dispersed seaward, without taking the form of a receding sand wave. Consequently, erosion initiating at profiles A', B', and C' led to attenuation of a berm at each respective elevation and eventually to the formation of profiles A, B, and C, respectively.

On the other hand, the changes initiating at A, B, and C occurred either as accretive changes directed to A', B', and C', respectively, or as erosional changes directed from B to A or from C to B. Transitions such as from A to B or from B to C failed to occur.

In general, erosion of the subaerial beach occurred during a period of growth of incident waves, and accretion, during a period of wave decay This is shown in Figure 5, which compares changes in the subaerial topography with those in incident wave heights. The beach topography is represented in terms of the volume of sediment existing between the shoreline and the limit of swash run-up above datum level. Wave heights were recorded with a step-resistance gage of the Coastal Engineering Research Center, installed approximately 150 m from the shoreline. The curves in Figure 5 suggest a negative correlation between the subaerial sediment and wave heights.

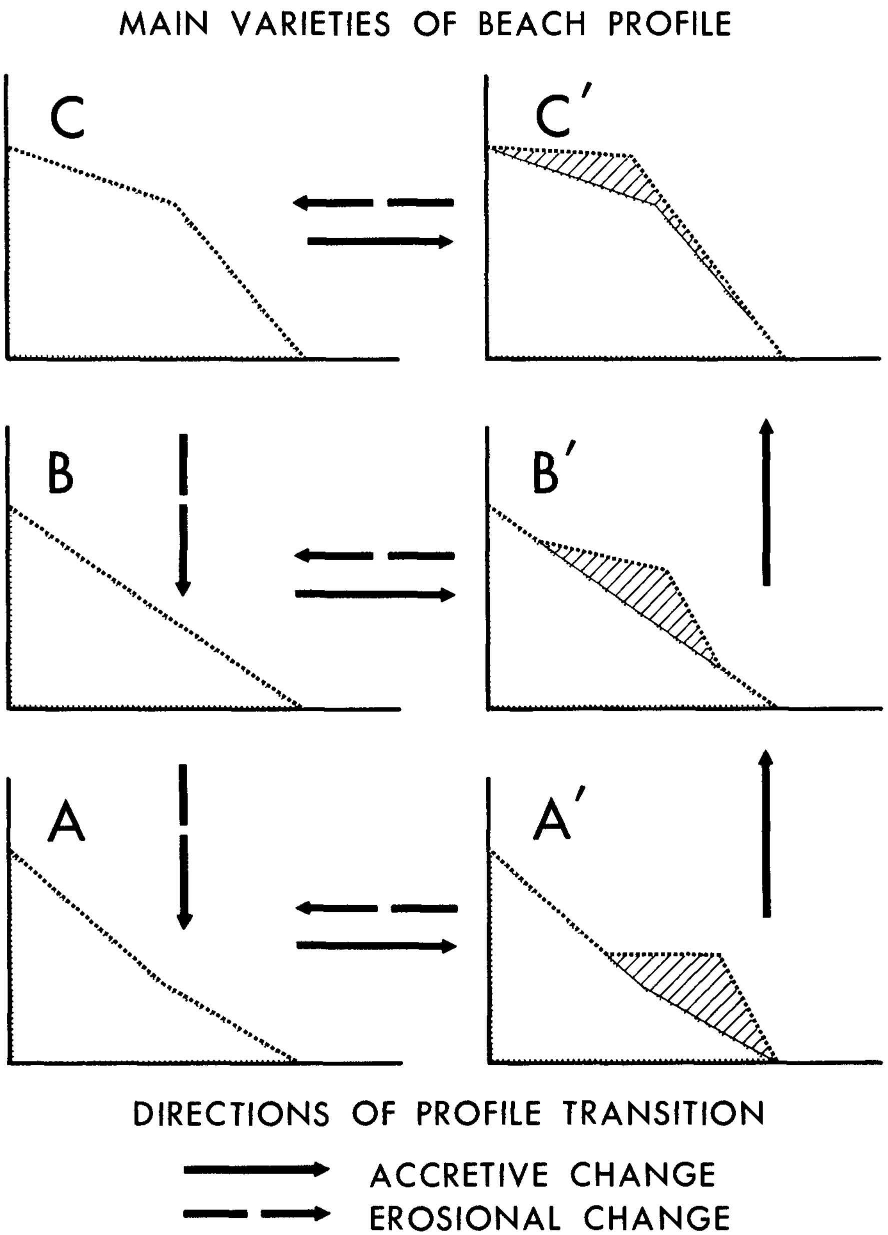

Figure 4. Sketch of six major types of profile.

However, when this correlation was measured statistically, it proved to be too low to be of significant value. It was found that the response of a beach profile to wave action depended not only upon wave heights but also upon the characteristics of an existing profile, particularly the profile configuration. This relationship is shown in Figure 6. The ordinate represents the sediment storage in the subaerial profile (as already defined), denoted by Q. The abscissa represents the beach width, a horizontal distance measured between the datum-level shoreline and the limit of swash run-up, denoted X. When plotted in the Q - X plane, the profile data at Nags Head were found to fall into groups which were identified with the six major configurations previously classified (see also Fig. 4). The numerals in Figures 5 and 6 denote transitions of profile configuration in the order of occurrence.

Short-period fluctuations of beach topography seen in Figure 5, which were repeated at an average interval of 14 days, are found in Figure 6 as consisting of cyclic transitions in terms of profile configuration. Especially, the beach changes associated with severe storms tended to produce closed cycles. For instance, a series of beach responses which occurred during a storm from January 10 through 20 (Fig. 5) is traced in the Q - X plane along transitions 4 through 8, which formed a closed cycle B'→B→A→A'→B', followed by upward migration of a berm, which finally led to C'. The storm of February 10 through 20 also produced transitions 11 through 14, which formed a cycle C'→C→B→B'→C'.

According to Figure 5, long-term beach changes also displayed a cyclic feature. For instance, a cycle with a period of approximately 90 days occurred between the end of December, 1963, and the end of March, 1964 (see Fig. 5). There is an indication that this cycle was probably repeated, since it is seen that following a trend of erosion between the end of January and the end of March there occurred a trend of accretion until the end of the field investigation in April and May. This feature is attributed to the characteristics of transition vectors in Figure 6, in which those involving pairs of A', B', and C' are directed upward only and those involving pairs of A, B, and C, downward only. Given a series of wave excitations causing alternate erosion and accretion over a sufficient length of time, long-term beach changes to be traced in the Q - X plane are bound to produce a counterclockwise cycle through A→A'→B'→C'→C→B→A. The period of this long-term cycle is thought to depend upon wave heights and intervals between successive storms.

Sediment Properties Related to Bar-type Sand Waves

The size characteristics of sediments sampled on the beach surface demonstrated close relationships with the bar-type sand waves thus far described. Figure 7 compares the grain size histograms of these sediments with profile configurations. The numerals represent sampling positions. In descending order, the profiles indicate a sequence of upward migration of a wave crest (profiles I through III), followed by its disintegration (profile IV) and final disappearance from the profile (profile V). Corresponding to this sequence, the grain size histograms changed from a unimodal shape with coarse diameters, through a bimodal shape with intermediate diameters, and finally to a unimodal shape with fine diameters. The shaded areas in the profiles indicate a zone where deposition of coarse material took place. It is seen that this area initially expanded onshore, accompanying the sand wave migra-

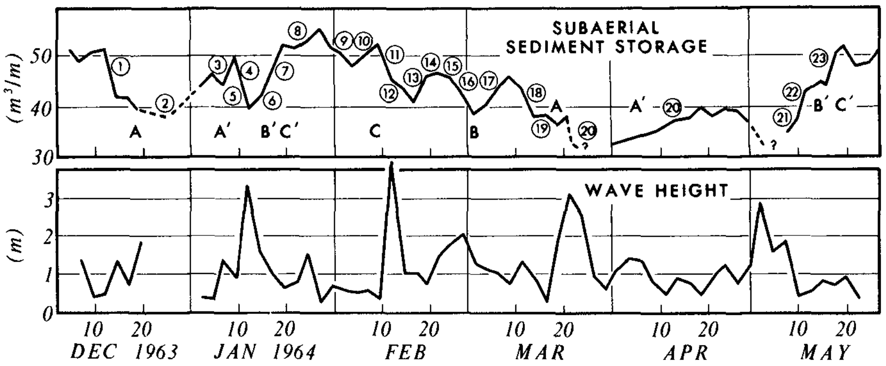

Figure 5. Time series of subaerial sediment storage and wave heights, Nags Head, North Carolina (see also Figures 4 and 6).

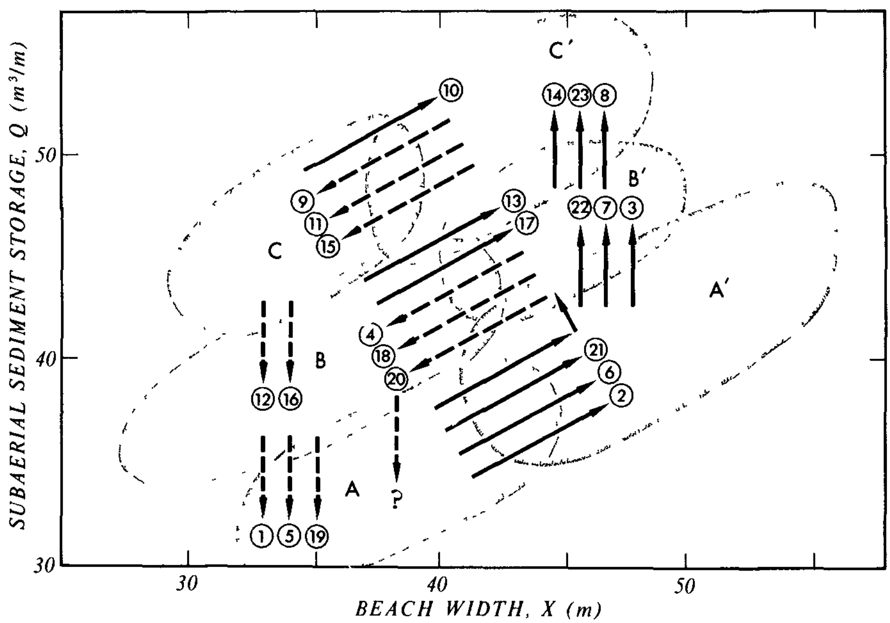

Figure 6. Profile data as a function of sediment storage, beach width, and configuration, Nags Head, North Carolina.

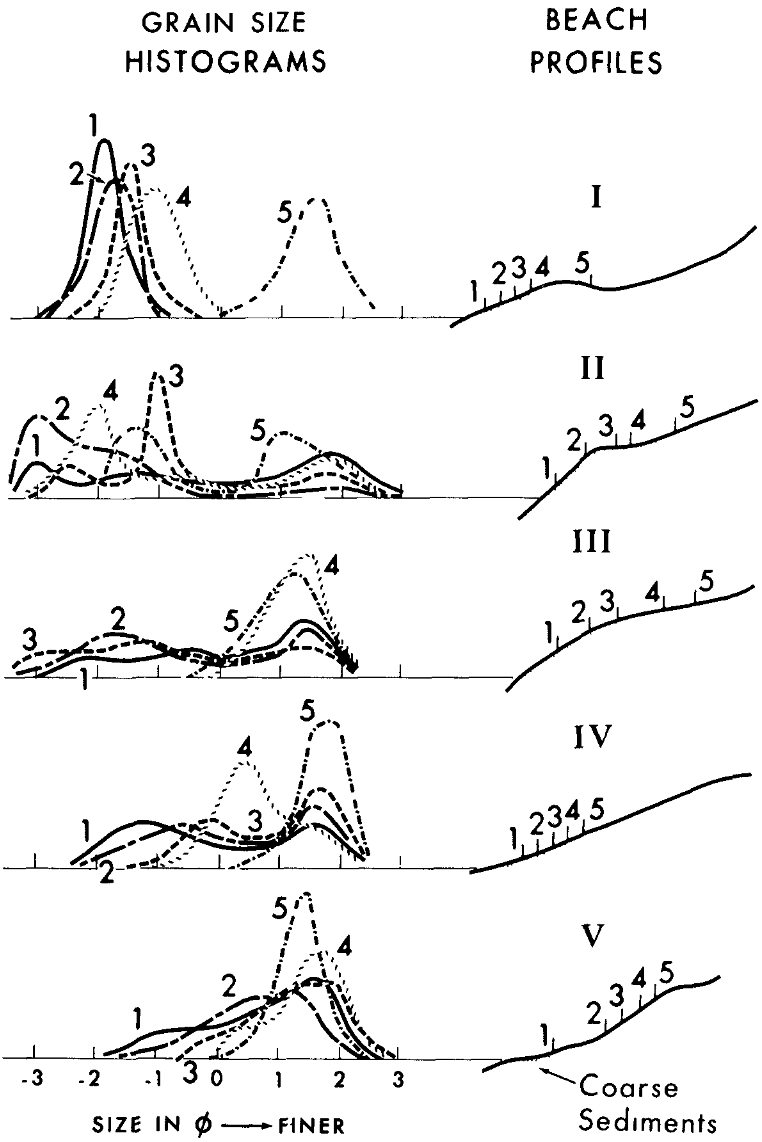

Figure 7. Comparison between grain-size histograms and their corresponding profiles, Nags Head, North Carolina.

tion, and later withdrew seaward as the sand wave was obliterated. Finally, in the concave profile (profile V), deposition of coarse sediment was essentially missing on the subaerial beach.

There is no doubt that the coarse material was of subaqueous origin and arrived on the subaerial beach with a sand wave. These coarse materials do not seem to have mixed with fine materials to produce a homogeneous mixture. The bimodality of sediment samples which contained both coarse and fine materials suggests that these materials may have existed as separate layers in the subaerial bed.

It seems unlikely that the presence of coarse materials is essential for the initial formation of the bar-type sand wave. However, it may well be that it is a factor which favors growth and movement of a wave crest once it has arrived on the subaerial beach. Since the water carried by swash over a layer of coarse sediments in part will seep through it in its return seaward, the drag exerted by swash oscillation will produce a net onshore transport of material on the subaerial slope. Consequently, growth and onshore propagation of the wave crest may be facilitated. This inference is supported by the result of a field experiment conducted by Longuet-Higgins and Parkin (1962), in which permeability of the subaerial surface was varied artificially by means of a tar-coated sheet inserted in the sand layers. They found that the waves quickly eroded the material overlying this sheet while disturbing the material on either side to a lesser extent.

CUSP-TYPE SAND WAVES

Formation of Cusp-type Sand Waves

In contrast to the bar-type sand waves, which are attributed to wave orbital motion, there exist sand waves which are believed to be associated with longshore currents. These sand waves develop periodic crests and troughs in a series along the shore and tend to migrate in the direction of existing longshore currents. Unlike bar-type sand waves, the crests of cusp-type sand waves are oriented obliquely to the shoreline, and often extend across the entire width of the surf zone between the shore and the longshore bar.

Because of its interference with an existing beach topography, the presence of cusp-type sand waves is manifest in the form of sinuous shorelines and crescentic bars. An example is shown in Figure 8. A cuspate projection of the shore and a shoal in front of it, both representing an accretive feature, correspond to the wave crest, and an embayment and a depression on the foreshore bed, representing an erosional feature, correspond to the wave trough. These features were studied previously by Hom-ma and Sonu (1962) and were designated "rhythmic beach topography."

Evans (1939) was probably the first to describe the formation of cusp-type sand waves in detail. His observations on the east shore of Lake Michigan indicated that the formation was "particularly noticeable when the wind blows at an angle to the shore." At such times, unequal

Figure 8. An example of cusp-type sand wave, Akita, Japan (courtesy of Japan Geographical Institute).

erosion on the shore first formed separate indentations and the material taken out of them was "carried and deposited in ridges along the course of currents which leave the shore, forming cusps and ridges." Eventually, topography such as shown in Figure 9 was formed, in which the spacings between successive projections ranged between 100 and 400 feet. Evans stated:

> At first, deposition off the points C_1 and C_2 is not very great, but as erosion continues the irregularity of shoreline thereby produced causes a more rapid growth. As the process goes on subaqueous deposition of sand continues at the ends of the cuspate forms. They are thus lengthened, and submerged ridges are formed which increase in length to the northwest. As soon as the formation of a ridge starts, the incoming waves begin driving it toward the shore. As a result it becomes dune-shaped with the steeper face at B where the sand lies at the angle of repose....The water brought over the ridge by the incoming waves caused a current at A, which was in some cases strong enough to superimpose current ripples in the troughs of the oscillating ripples. This water in finding its way out again to deeper water produced an undertow at D....It is evident that some of the sediment carried by this current enters into the building of the next subaqueous ridge extending out from C_2.

A general picture of material movement to be inferred from the Evans observation is illustrated in Figure 10. The material leaving an embayment and being carried to a submerged shoal is further moved across the crest of the shoal and deposited on the leeward slope. Thus, a zonation of alternate erosion and accretion may occur along the sand wave train, erosion characterizing the up-current slope of the shoal, and accretion, the leeward slope. The result will be a migration of this system in the direction of longshore currents, similar to the propagation of a sand wave train which takes place in a fluvial bed.

Alongshore displacement of sinuous shorelines and crescentic bars has been reported by various investigators, although it has not necessarily been recognized as a sand wave mechanism. Rates of migration (U) derived from various published sources are plotted in Figure 11 against intervals between successive projections, i.e., wave lengths (L). The distribution of these data suggests a relationship:

$$U \propto L^{-4/5} \tag{1}$$

or, approximately

$$U \propto L^{-1} \tag{2}$$

Thus, the rate of migration is found to be inversely proportional to the wave length, i.e., the larger a sand wave, the slower its movement. Essentially the same finding is recognized with respect to the dunes associated with a unidirectional flow (for instance, see Simons and Richardson, 1960).

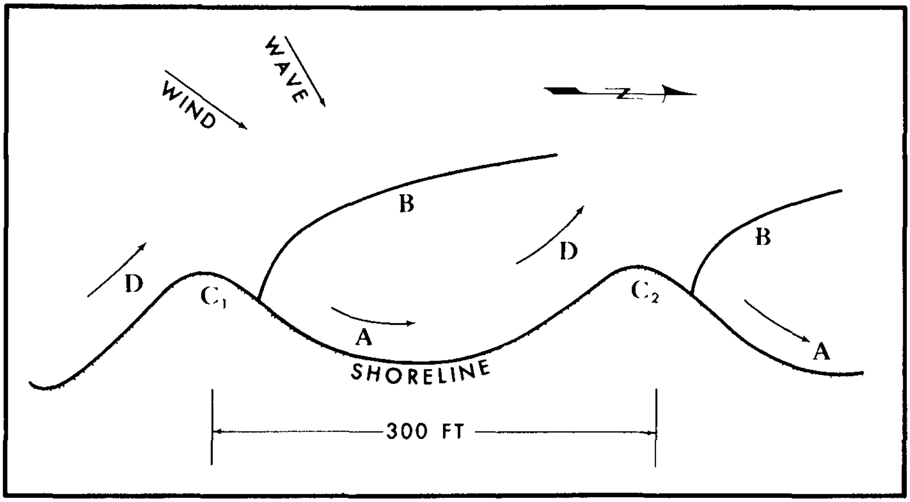

Figure 9. Formation of cusp-type sand wave on Lake Michigan shore (after Evans, 1939).

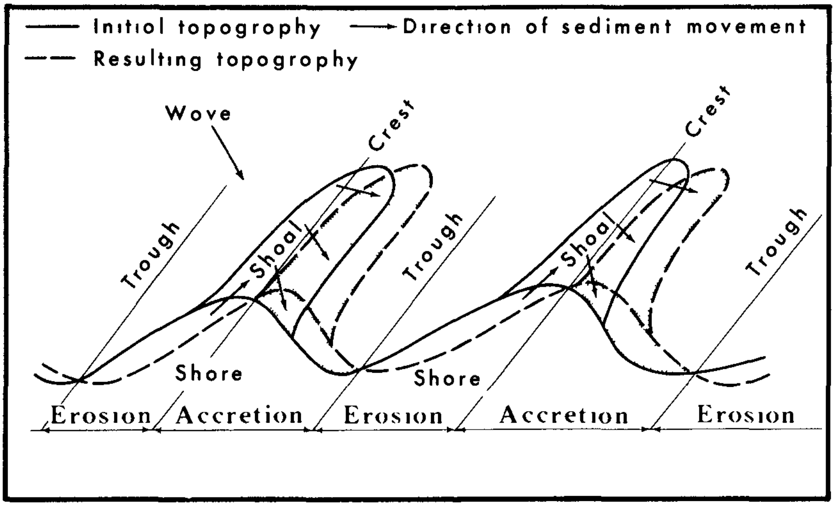

Figure 10. Alongshore migration of cusp-type sand wave.

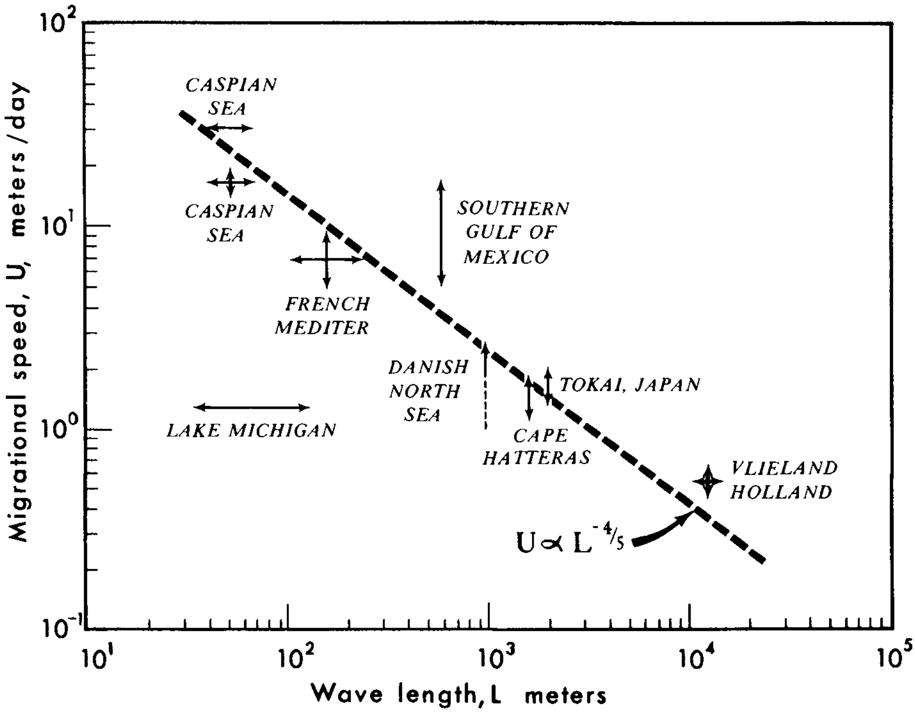

Figure 11. Rates of migration of cusp-type sand wave versus wave length.

It is recalled that sand waves forming in a fluvial bed are represented uniquely as a function of Froude number F_r, i.e.,

$$F_r = V/\sqrt{gh} \tag{3}$$

in which V is the mean flow velocity, g the acceleration caused by gravity, and h the mean water depth. Simons and Richardson (1960) determined in a flume experiment various ranges of Froude numbers associated with a variety of bed forms for a median grain diameter of 0.45 mm. Following their result, Figure 12 shows current velocities and water depths necessary to create different bed forms in a unidirectional flow.

It appears that an analogy may be drawn between the cusp-type sand waves and the dunes associated with unidirectional flow. According to Figure 12, the deeper the water depth, the greater the velocity required for the formation of dunes. It then follows that for a given velocity, the gentler the foreshore slope, the longer the wave crest and the more prominent the formation of sand waves. In the experience of the writer, a gentle foreshore slope is an essential condition for the formation of cusp-type sand waves, along with sustained activity of longshore currents.

According to Figure 12, the current velocity required for dune formation in the nearshore zone--say, up to a depth of 5 feet--ranges up to approximately 4 ft/sec. This velocity may appear too high for ordinary longshore currents to attain, therefore incompatible with the common observation of cusp-type sand waves. A partial explanation is that whereas the longshore current of high velocity may take place only briefly, the sand waves thus produced would remain for some time. Furthermore, it appears that high velocities in longshore currents could occur more frequently than generally thought possible. Statistics based on actual measurements of currents at Nags Head are shown in Figure 12. A total of 350 individual measurements were made under various wave conditions for 6 months between December, 1963, through May, 1964 (see Sonu et al., 1965). It is found that a velocity equal to or in excess of 4 ft/sec could occur at a frequency of 8 per cent, i.e., 28 times during a 6-month period. Similarly, frequencies of occurrence of current velocities required for the formation of sand waves down to depths of 4 feet, 3 feet, and 2 feet are estimated at 12, 18, and 26 per cent, respectively. A study by Sonu and Russell (1965) disclosed indications of cusp-type sand waves on the Nags Head beach.

The foregoing discussion may apply mainly to sand waves having asymmetrical crests. These sand waves have relatively short wave lengths--say, up to several hundred meters. The wave lengths and amplitudes are presumably functions of size and movement of bed material, and perturbations and intensity, of turbulence in the flow. However, no quantitative criteria of general validity are known.

Sand waves with wave lengths of several kilometers have been reported to occur in depths between 3 and 10 meters (Hom-ma and Sonu, 1962). Whereas sand waves of shorter lengths would move rather rapidly and change readily in response to waves and currents, these large sand waves are relatively

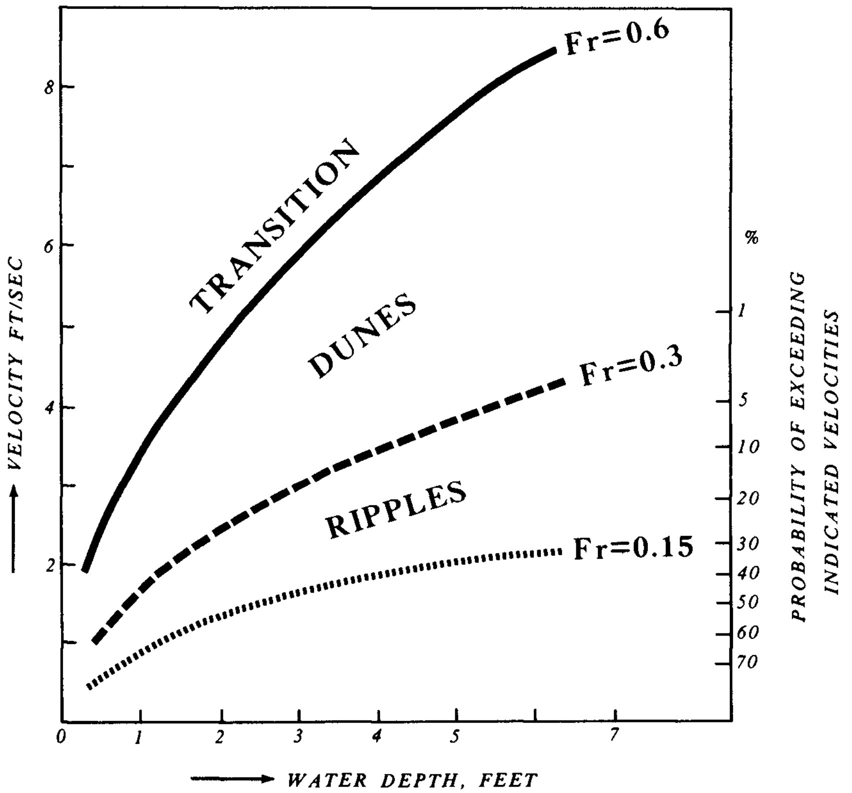

Figure 12. Water velocities, depths, and Froude numbers required for development of bed forms (after Simons and Richardson, 1960).

stable both in position and form. They also feature symmetrical crests.

When both long and short sand waves take place in the nearshore bed, they may produce dual rhythms in the shoreline. Figure 13 shows an example from the Tokai beach, Japan (Mogi, 1960), where two separate rhythms were found to be superimposed on one another. One was approximately 250 meters long and the other, approximately 2.5 km long. Usually, the crescentic pattern of the outer bar reflects the effect of long waves, and that of the inner bar, the effect of short waves.

Stride (1963) reported that the long sand waves of symmetrical crests occur in depths to about 200 m, where the corresponding Froude number is much below that required in flumes. Cartwright (1959) suggested that these sand waves may be formed in response to internal waves which develop in the presence of vertical density stratification in the water layer. The possibility was mentioned that a sufficient stratification may occur because of sediment suspension by wave action. According to Cartwright, this mechanism requires the following criterion:

$$h_2 \ (2\ q\mu /\ U_1^{\ 2})^{1/2} > \frac{\pi}{2} \qquad (4)$$

in which h_2 is the thickness of the upper layer, g the acceleration caused by gravity, μ the vertical density gradient defined as

$$\mu = -\frac{1}{2}\,\rho'(y)/\rho(y) \qquad (5)$$

in which $\rho(y)$ is the specific gravity of the fluid at elevation y, $\rho'(y)$ is the vertical density gradient, and U_1 is the fluid velocity. According to Hom-ma (1960), measurements of suspended sediment at an average depth of 3 meters off the coast of Niigata, Japan, yielded an average concentration of 176 ppm in the 1-meter layer above the bed and 108 ppm beyond this layer. Assuming a linear density gradient between the center of the 1-meter layer below and that of the 2-meter layer above, the density gradient μ is calculated from equation (5)

$$\mu = 2.3 \times 10^{-2} \ (m^{-1}).$$

From equation (4) we get:

$$\mu > \left(\frac{\pi}{2}\right)^2 \frac{U_1^{\ 2}}{2\ g\ h_2^{\ 2}} \qquad (6)$$

Substituting h_2 = 2 m, g = 9.82 m/sec^2, and U_1 = 0.3 m/sec, the right hand side yields

$$2.8 \times 10^{-3} \ (m^{-1})$$

Thus, it is possible, at least theoretically, that conditions favorable for

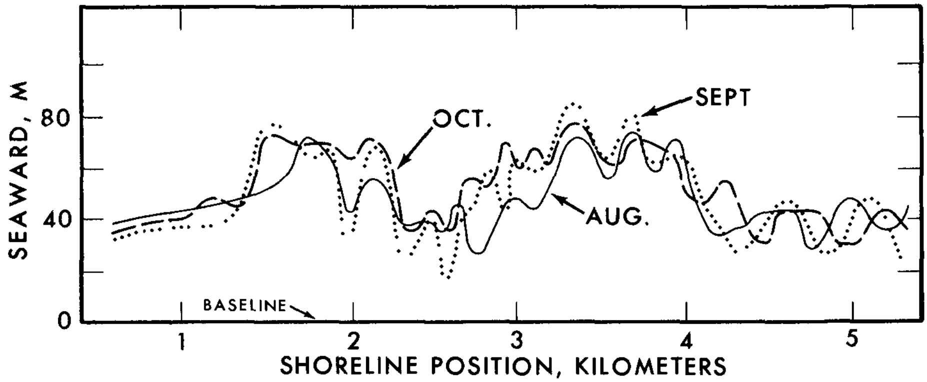

Figure 13. Dual rhythms in shoreline at Tokai, Japan (after Mogi, 1960).

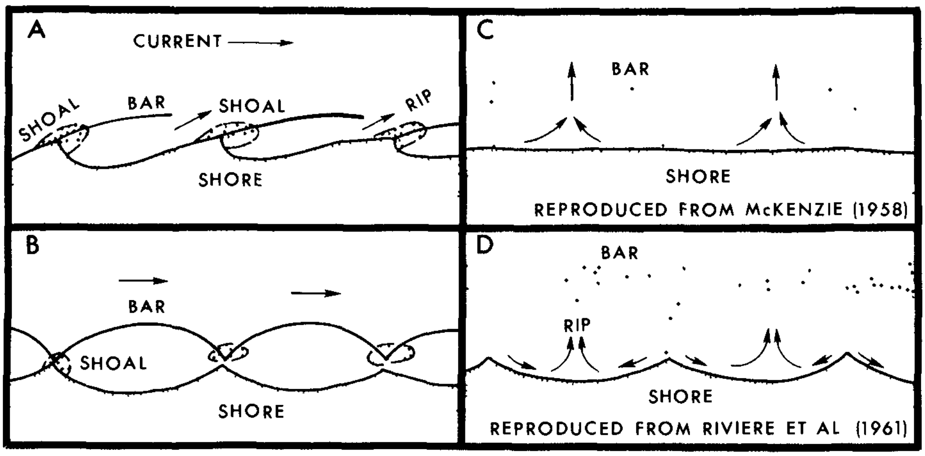

Figure 14. Typical effects of cusp-type sand wave on beach topography.

the formation of symmetrical sand waves arise in the nearshore zone. Because of the need for internal stratification, such sand waves may develop initially away from the shore and extend their influence shoreward. However, verification of this mechanism will require further studies.

Effects of Cusp-type Sand Waves on Beach Topography

Beach topography is affected by cusp-type sand waves in a variety of ways. Figure 14 shows typical examples.

One of the most remarkable effects occurs on the bar. The wave crest which extends out from a cuspate projection reaches the bar, and at the same time the bar is breached by a rip current immediately upstream of this junction. As a result, the bar is deformed into separate crescentic units such as shown in Figure 14 A. Usually, this type of topography indicates the existence of sustained activities of longshore currents in a single direction. The acute curve of the shoreline indentation faces downstream. The wave lengths are relatively small, ranging between approximately 40 meters (Black Sea, Egorov, 1951; Lake Michigan, Evans, 1939) and 600 meters (Tobasco, Mexico, Thom, 1966).

Mode B in Figure 14 features a series of crescentic bars linked with each other along the shore. The points of the bar usually form a broad shoal which may connect with a cuspate projection or remain away from the shore. The shape of the cross section across a shoal is symmetrical. Wave lengths may range up to approximately 3 km (Niigata and Tokai, Japan, Hom-ma and Sonu, 1962).

Mode C in Figure 14, reported by McKenzie (1958) on the New South Wales coast, Australia, may well be a slight modification of mode A, probably caused by additional activities of swells which arrived normal to the shore. A rip flowing in the breach across the bar is known to be so strong as to induce a sliding action of the sides of the channel. Mode D, reported by Riviere et al. (1961) on the French Mediterranean coast, again may be a modification of mode A or C, probably associated with a weak rip activity which caused deposition on the bar crest.

In general, the basic structure of a beach topography affected by cusp-type sand waves may be summarized as shown in Figure 15 (see also Hom-ma and Sonu, 1962). A major characteristic of such topography is that a remarkable distinction exists between profiles across a cuspate projection and those across an embayment. The former (profiles A-A') displays a well developed berm on the subaerial beach and a shallow shoal on the foreshore bed, where a bar may be absent. The latter (profile C-C') displays a narrow berm, a concave subaerial profile, and a relatively deep subaqueous bed. Occasionally, in this profile, a berm may be completely absent and, instead, an escarpment may be found. A step is usually more prominent in this profile than near a cuspate projection. Consequently, the profile across a cuspate projection bears accretive features similar to those of the so-called summer profile, and that across an embayment, erosional features similar to those of the so-called winter or storm profiles.

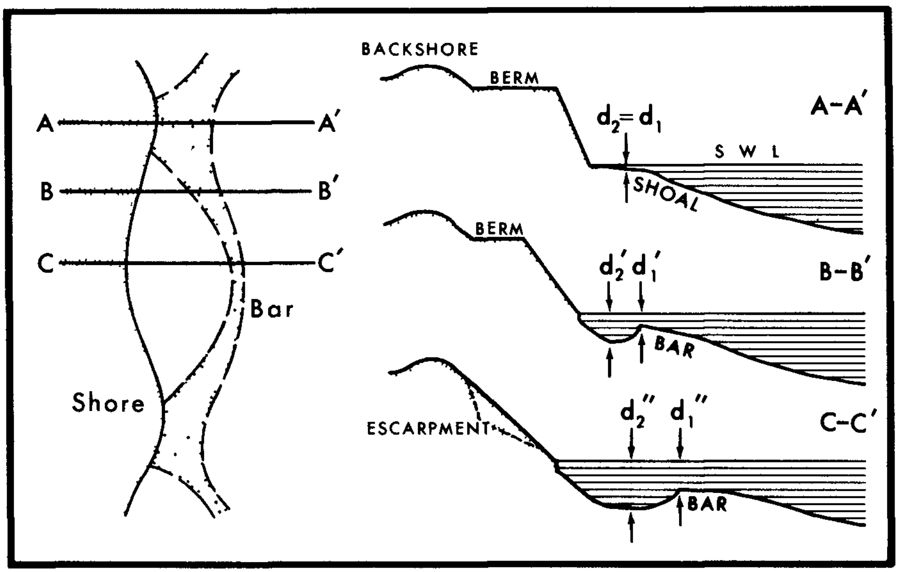

Figure 15. Structure of beach topography affected by cusp-type sand wave.

Of further interest is the distinction in the properties of bar in these profiles. The bar displays most prominent relief in the profile across embayment. With distance away from this profile, the prominence of bar relief decreases steadily, so that the depths over the crest (d_1) and the trough (d_2), as well as the depth difference between them ($d_2 - d_1$), show the following relationship (see Fig. 15):

$$d_1'' > d_1' > d_1$$

$$d_2'' > d_2' > d_2$$

$$(d_2'' - d_1'') > (d_2' - d_1') > (d_2 - d_1)$$

Finally, in front of a cuspate projection, the relief disappears, i.e.,

$$(d_2 - d_1) \rightarrow 0.$$

Consequently, in the presence of cusp-type sand waves, the beach topography will contain both profiles having a bar and those without a bar.

There exist relatively few studies regarding the effects of sand wave migration on beach changes. In a study dealing with behaviors of subaqueous beach profiles at Nags Head, North Carolina, Sonu and Russell (1965) suggested that abrupt changes in profile configuration observed in a stationary traverse could be attributed to migration of sand waves across this traverse during wind waves of oblique incidence. They reported that when this effect was suspected the beach change observed in the traverse was many times more pronounced than the changes associated with higher waves arriving normal to the shore.

Figure 16 shows a remarkable example of sand wave migration reported by van Bendegom (1949) on the Vlieland coast, the Netherlands. Continuous beach surveys since 1865 revealed the presence of two gigantic shoreline projections which steadily migrated toward the east. The amplitude of the curved shoreline was as great as 200 meters, and the rate of migration averaged 200 meters per year. As this wave moved along the shore, the beach was steadily eroded for about 40 years, then was accreted for more than 10 years.

DISCUSSION

It is not known how bar-type and cusp-type sand waves may interfere with each other. According to Evans (1939), subaqueous ridges originally formed by oblique storm waves could approach the shore and finally reach it, filling the embayments between cuspate projections. When observed in a single traverse normal to the shoreline, this movement of subaqueous ridges may appear to be similar to the onshore migration of bar-type sand waves already described. However, it is also evident, as shown in the Bagnold experiment, that in a purely two-dimensional situation a bar-type sand wave could be formed. According to Evans, as the wind direction is

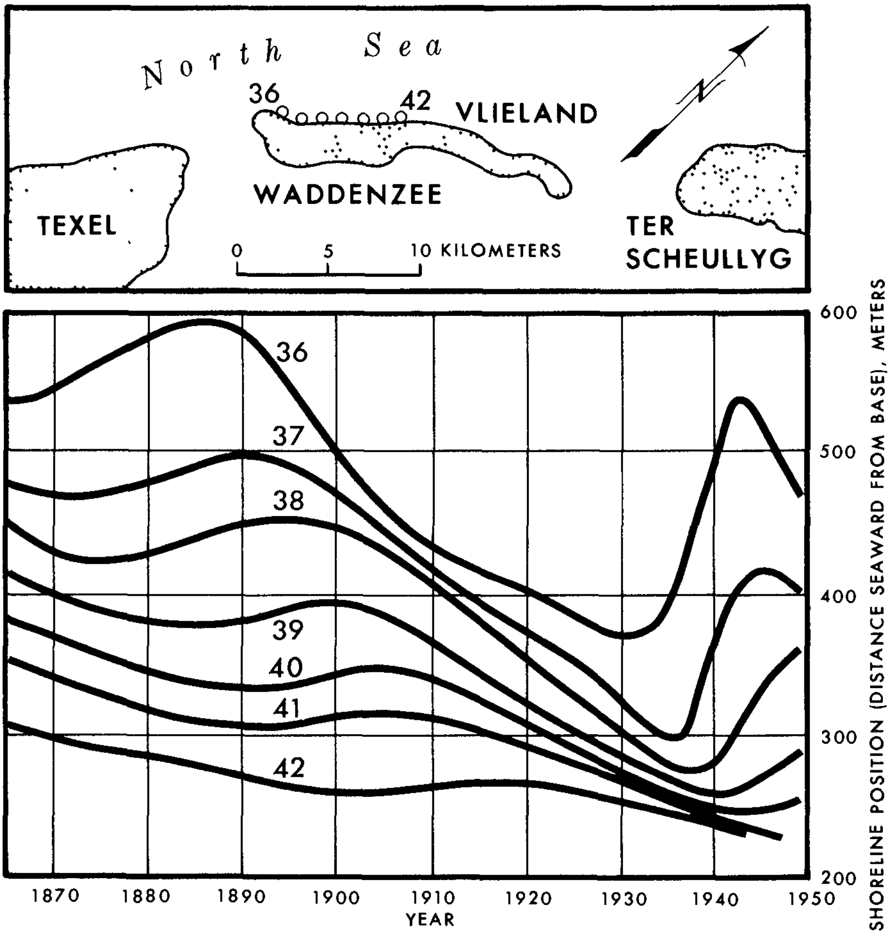

Figure 16. Migration of a gigantic sand wave along the Vlieland coast, the Netherlands (after van Bendegom, 1949).

reversed, "the new system of waves and currents guided by the trough between the subaqueous dune and the shore may succeed in cutting off the ridge at the tip of the cusp, thus forming an isolated shallows some distance out from shore." It is possible that these independent shoals generate activities of bar-type sand waves and, in the event of their progress up the subaerial beach, create convex profiles periodically along the shore.

One of the major implications of littoral sand waves is that the beach processes affected by them are non-uniform and often periodic. Suppose that the cusp-type sand waves migrate along the shore continuously. Since the wave crest contains a large mass of sediment, the littoral drifts may be pulsational when observed across a stationary cross section. A pulsational transport of sediment along the shore was reported by Taney (1962) in a laboratory experiment using radioisotopic tracer on a movable bed. Hom-ma and Sonu (1962) reported that the grain size of sediments sampled along the step exhibited periodic fluctuations consisting of coarse diameters near cuspate projections and fine diameters near embayments. A study by Trask and Johnson (1955) on the Point Reyes beach and that by Miller and Zeigler (1964) on the Cape Cod beach also indicated grain size fluctuations of the subaerial and nearshore sediments along the shore, in which coarse sediments were found near embayments and fine sediments, near projections. The alongshore distribution of longshore current velocities can also be non-uniform in the presence of cusp-type sand waves. This problem was previously dealt with by Sonu et al. (1965). A phenomenon of particular interest is the periodic occurrence of a series of rip currents along the beach. A field investigation currently underway at the Coastal Studies Institute disclosed close relationships between cusp-type sand waves and rip currents. One interesting result was that the rips originate at embayments formed by cusp-type sand waves. They discharge seaward the water which has been brought in predominantly through the crests of these sand waves. A similar model of longshore current system has been previously proposed by Inman and Bagnold (1962), although the role of periodic bottom topography is not emphasized.

It may be argued that the cusp-type sand wave is not found in many beaches, therefore is a special feature. King (1959) and Shepard (1963) suggest that it is typical of a tideless coast. However, it has been shown to occur where the tidal range is as much as 1 meter (namely, Tokai, Japan, Hom-ma and Sonu, 1962; Nags Head, North Carolina, Sonu and Russell, 1965). The periodicity caused by cusp-type sand waves is not always obvious to casual observers. On coasts exposed to an outer ocean, it tends to be obscured by swells which arrive normal to shore. Also, a large tidal range is thought to affect adversely its prominence. The literature reveals indications of cusp-type sand waves in many areas of the world. To the knowledge of the writer, these areas include the following: the Mediterranean coast (King and Williams, 1940; Vernhet, 1953; Riviere et al., 1961), the Dutch coast (van Bendegom, 1949), the Danish North Sea coast (Bruun, 1954), the Black Sea, Caspian Sea, and Azov Sea coasts (Egorov, 1951; Zenkovich, 1967; Shadrin, 1961), the Baltic Sea coast (Seibold, 1963; Aibulatov et al., 1966), the Japan Sea coasts (Hom-ma and Sonu, 1962), the New South Wales coast, Australia (McKenzie, 1958; Thom, 1966), the

Guiana coast (Diephuis, 1966), the Tobasco coast, Mexico (Thom, 1966), and various regions of the United States (namely, Point Reyes Beach, California, Trask, 1956; Cape Cod beaches, Zeigler et al., 1959; Virginia Beach, Harrison and Wagner, 1964; Nags Head, North Carolina, Sonu and Russell, 1965; Lake Michigan, Evans, 1939). Aerial photography is particularly useful in detecting the presence of rhythmic features on the coast. Inspection of U.S. Coast and Geodetic Survey aerial photographs indicates signs of rhythmic beach topography in numerous localities along U.S. coastlines, including a stretch on the Atlantic seaboard from Long Island, New York, to Cape Hatteras, along the Gulf of Mexico coasts of Florida (especially between Panama City and Pensacola), Alabama, Mississippi, Louisiana, and Texas, and along the Pacific coast from Portland, Oregon, to San Francisco, California.

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