Part 3

COASTAL SEDIMENT PROBLEMS

Chapter 21

MIGRATING SAND WAVES OR SAND HUMPS, WITH SPECIAL REFERENCE TO INVESTIGATIONS CARRIED OUT ON THE DANISH NORTH SEA COAST

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Abstract- The transport of sediment by flowing water commands great interest in connection with the control of floods, land reclamation, and the construction of harbours and coast protection works. A distinction can be drawn between littoral drift in rivers and in the sea.

The sediment transportation in rivers has been investigated by several authors, e.g. Shields, Meyer Peter, Kalinske, and Einstein, see (16) pp. 769-834. Einstein's latest theories have given reliable results in practice (9).

As pointed out by Einstein (7), there cannot be much difference, physically, between transportation of sediment in rivers and longshore drift at sea shores, apart from the littoral zone with its extremely complex conditions.

In the attempt to understand the complex problem of sea shores the practice so far has been to split them up into several reaches and investigate them separately. This work has given a number of results of practical interest in connection with littoral drift and coastal protection technology, see (2), (3), (5), (6), (11), (13), and (16).

According to Einstein, Johnson and Chien (8) there exist two types of sediment load, one that bears a certain relationship with the discharge (bed-material load), and the other which does not (wash load). The result of flume study indicates that the transport rate of wash load, just as that of the bed-material load, can be calculated according to the Einstein bed-load function (9), if the instantaneous bed composition is known. On the other hand, the bed-material load is equally available in the entire bed, but only the surface bed layer contains any significant amount of wash-load material. Any change of flow or of sediment supply may immediately change the composition of the wash-load material in the bed. The bed composition as determined from the instantaneous condition of the channel has no lasting significance so far as the wash load is concerned, and this makes the prediction of the wash-load rate from the bed-load function impossible.

The following deals with a mode of bed-load transportation which, as far as can be seen, takes place in large "waves" or humps.

Introductorily are mentioned investigations made in the United States on migrating sand bars and sand waves in rivers, and investigations in Holland on migrating sand bars on the bottom of the sea.

The major part of the paper deals with migrating sand humps along the North Sea coast of the peninsula of Jutland, Denmark, see Fig. 3.

The following terminology is used:

migrating bars	are migrating unsymmetrical sand waves at the bottom of the sea, on a river bed or in a test flume
migrating waves	are migrating symmetrical sand waves on a river bed or in a test flume
migrating undulations in the shoreline	are migrating waves in the shoreline configuration, which again may be due to a type of transverse bar
migrating humps	are migrating sand accumulations at the bottom of the sea. They may be identified as migrating depth contours or as wave-shaped changes in the area of the beach profile down to a fixed depth.

MIGRATING SAND BARS AND WAVES IN RIVERS AND IN TEST FLUMES

IN RIVERS

Lane and Eden have written (14) about the transportation of sediment in the Lower Mississippi and stated that 350 mill. tons of sediment is transported per year, mostly by suspension. It had long been known, however, that some of the bed-load material drifted in a series of waves extending across the stream. Generally the upper side of the waves is gently sloping and the downstream side is steep. In the following they are termed bars.

It is generally believed that the particles roll or are swept up the flat upstream slope and over the crest of the bar, and then are deposited on the steeper downstream slope where they are covered by the particles that follow. These particles then remain at rest until uncovered by the movement of the bar in the downstream direction, when they are again moved up the sloping face and over the crest.

Surveys showed that at Bullerton (Arkansas) the slopes on the upper side were gentle and on the downstream side very steep. The bars crossed the river at angles, usually at approx. 45°, with the axis of the stream. In some cases small bars appeared on the upstream slope of the main bar. Some profiles showed a tendency of bars to travel in groups of two or three. The rate of motion, distance between crests, and height of crests were quite variable. At Bullerton some surveys showed that the rate of travel was much greater on a rising than on a falling stage. The bar height and the distance between the crests were, for instance, 8 ft. and 1000 ft. The maximum height of crests at any stage was found in the locality of swiftest current. For varying stages, the maximum heights were found when the river had been at a high stage for a considerable period of time. The effect of a very rapid rise on the height of the crest was to decrease it and also diminish the distance between crests. In cases of rapid rises of 14 and 18 ft. the bars were flattened so as to be scarcely distinguishable. The distance between crests was also subject to very great irregularities. Generally, it seemed to vary with their height.

Table 1 gives a summary of the dimensions of bars or waves and rates of material movement in average sand bars in different localities.

Table 1. Sand bar and littoral drift data. The Mississippi.

Observed at	Max. height ft.	Wave length ft.	Travel ft./ day	Material movement cu.yds./ day	Susp.load movement cu.yds./ day	Bed-load in per cent of susp.load
Fulton	4.7	1250	22	1600	810 thous.	0.2
Helena	5	3300	17	3500	382 - to 1782 thous.	0.2-0.9
Lake Providence	10.3+)	2000	19.4	7400	500 - to 1500 thous.	0.5-1.5
Carrollton	10	1000	15	1850	-	0.1-0.4

+) average height.

At Helena (Arkansas) the bars decreased in size for a falling river and increased with rising stages.

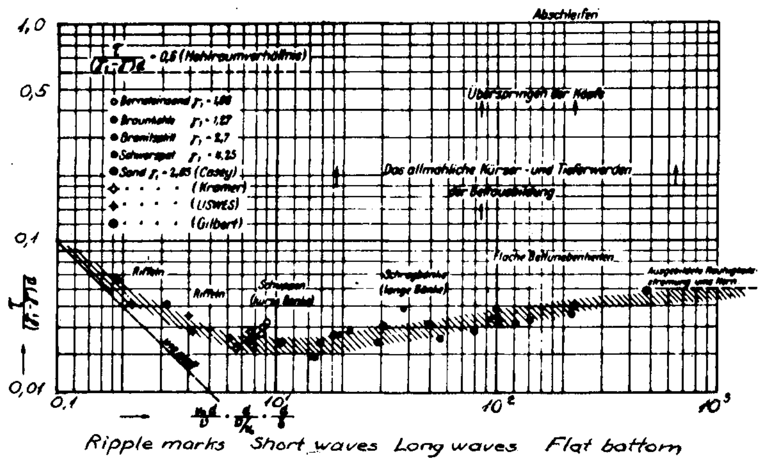

Fig. 1. Shields' experiments.

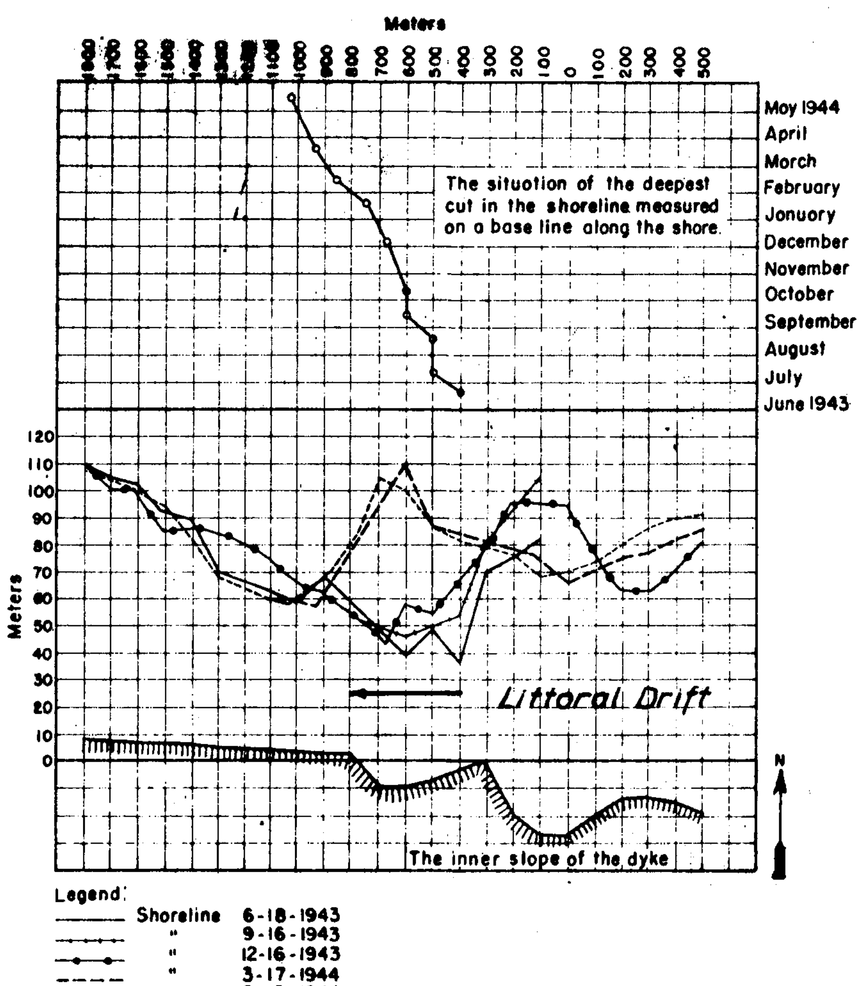

Fig. 2. Migrating undulation in the shoreline.
The Northern Nissum Inlet barrier, Denmark,
1943-1944.

At Lake Providence (Louisiana) the condition was such that when a constant stage was maintained for some time, the bars formed at regular intervals and moved most rapidly, their height increasing with the stage, a later repetition of that stage producing the same wave height, shape, and spacing. If the stage changed slowly they gradually changed their size to correspond with the new stage but in a sudden rise of considerable magnitude they were destroyed by erosion and replaced by a new series appearing when the crest of the rise was reached. In case of a sudden fall of considerable size they were obliterated by deposits and were replaced by a smaller set corresponding to the lower stage. The amount of material moved was thus greatest at the time of a sudden increase in velocity and least when the current suddenly decreased.

IN TEST FLUMES

Shields. In his laboratory investigations on bed-load transportation (20) Shields observed the configuration of the bed. Fig. 1 (Shields) shows the relationship between $\frac{\tau}{(\gamma_1 - \gamma)d}$ and $\frac{V_* d}{\nu}$ (the Reynold number of grains) where τ is the shear stress, γ_1 the specific weight of the grains, γ the specific weight of the water, d the grain diameter, $V_* = \sqrt{\frac{\tau}{\rho}}$ when ρ = the mass density of water and ν the kinematic vicosity. When $\frac{V_* d}{\nu}$ was less than 10, ripple marks were formed. With $10 < \frac{V_* d}{\nu} < 100$, first, shorter waves and then, longer waves were formed, and with $\frac{V_* d}{\nu} < 100$ the bottom was level.

Langbein-Gilbert. In his article entitled "Hydraulic Criteria for Sand Waves" (15) Langbein writes the following (cited partially from Gilbert, see (10)).

"When the conditions are such that bed load is small, the bed is molded into hills, called dunes, which travel downstream. Their mode of advance is like that of eolian dunes, the current eroding their upstream faces and depositing the eroded material on the downstream faces. With any progressive change of conditions tending to increase the load, the dunes eventually disappear and the debris surface becomes smooth. The smooth phase is in turn succeeded by a second rhythmic phase, in which a system of hills travel upstream. These are called antidunes, and their movement is accomplished by erosion on the downstream face and deposition on the upstream face. Both rhythms of debris movement are initiated by rhythms of water movement" - and later: "The load carried by Gilbert's flume was at capacity and varied in accordance with hydraulic factors, such as the velocity, depth, and gradient. There are many formulas available connecting these variables. However, it might be expected that some difference would be found in the relative efficiency for transportation of the phases of collective movement, the dunes, smooth, and the antidunes. If such existed, a break in the relation between capacity and related hydraulic elements would be expected; however, examination of Gilbert's data reveals no such difference in efficiency of transportation. For this reason, studies of sand waves may have little practical significance in fluvial morphology. However, sand waves are indicative of torrential flow and supercritical slopes, which are important factors, for example the same discharge could be carried in a channel of identical shape and material, with the same total energy (depth + $\frac{V^2}{2g}$), under which conditions it would have a lesser slope and lower velocity and its capacity and erosion ability would be reduced accordingly".

In (10) Gilbert mentions that associated with the "dunes" were greater "debris waves" also travelling downstream and each involving the volume of many dunes (see the remarks above about conditions in the Mississippi). In the bed of the long trough, series of them could bee seen; in the short trough, one or two might appear. These secondary waves may also exist with antidunes.

Laboratory tests of recent date have shown that in open channel flow there are two different types of bottom undulation. The first phase occurs at small rates of transport and performs as "sand bars". They are highly unsymmetric with gentle upstream slope and a downstream slope close to the angle of repose of the bed material. The flow lines do not follow the bottom configuration. The water surface remains more or less smooth although separating at the crests of the bars. Because of the separation the bars form a certain slope resistance to the flow.

When the flow increases, the sand bars disappear and the bed becomes level again.

If the flow increases further, another type of bottom undulation appears. It is symmetric in form, and may attain a considerable height. In this case the flow lines follow the bottom configuration and this also results in waves of the water surface.

Owing to the fact that there is no separation, the sand waves on the bed offer no additional resistance to the flow. These waves are highly unstable. They appear for a short time, and may disappear again.

From the above it seems that Shields's and Gilbert's experiments are justified to a certain degree.

The mechanisms causing the formation of sand bars and sand waves are still not elucidated, especially as regards the bars.

MIGRATING SAND BARS AND WAVES ON THE BOTTOM OF THE SEA

MIGRATING UNDULATIONS IN THE PART OF THE BEACH PROFILE ALONG THE SHORELINE

Investigations on the Danish North Sea coast seem to show that a distinction may be drawn between three different movements of the shoreline:-

a. migrating undulations in the shoreline (transverse bars)
b. seasonal fluctuations of the shoreline, and
c. long-periodic shoreline movements owing to erosion.

If we examine a map of the shoreline we shall observe that it is not straight but has many undulations or "waves". The length of the "waves" on the Danish North Sea coast is usually between 300 and 2000 m. Sometimes these waves have both a crest and a trough and sometimes only a crest or only a trough. Often they perform as a type of transverse bars, see (19).

Periodical measurements of migrating undulations on the Danish North Sea coast seem to show that the maximum height on the free unprotected coast is 60 - 80 m, on the coast protected by groins somewhat more, owing to the accumulation of material along the groins.

Fig. 2 shows a migrating undulation on the shoreline of the Nissum Inlet barrier on the Danish North Sea coast (Fig. 3) where the point is indicated by insert No. 1, in five different situations. The "wave length" was about 900 m, the height about 60 m and the rate of advance in one year in the direction of littoral drift about 700 m. In that part of the North Sea coast it looks as though the rate will vary between 0 and 1000 m a year. There may be some connection between the migrating undulations and breaches in the longshore bar, possibly due to erosion by rip currents because the wave trough is often formed behind a breach and the crest just ahead.

As soundings and levellings of the beach were not carried out, it is impossible to determine the quantity of material transported in the crest.

The seasonal fluctuation of the shoreline and the retrogradation of the shoreline considered were about 20 m and about 2 m, i.e. much less than the movements caused by the undulations. This again means that it is impossible to draw any definite conclusion about the erosion over many years solely on the basis of shoreline movements.

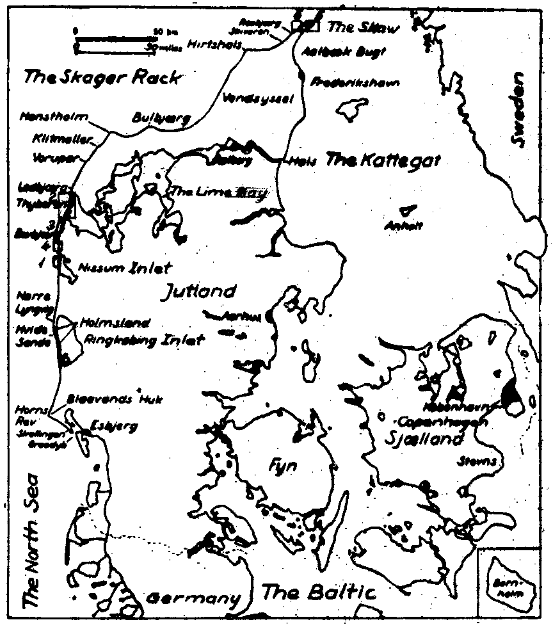

Fig. 3. Map of Denmark

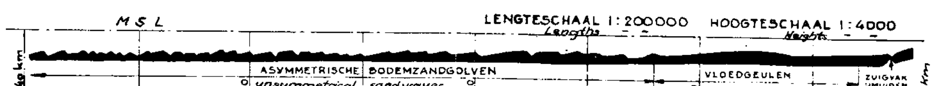

Fig. 4. Migrating sand bars on the bottom off the coast of Holland.

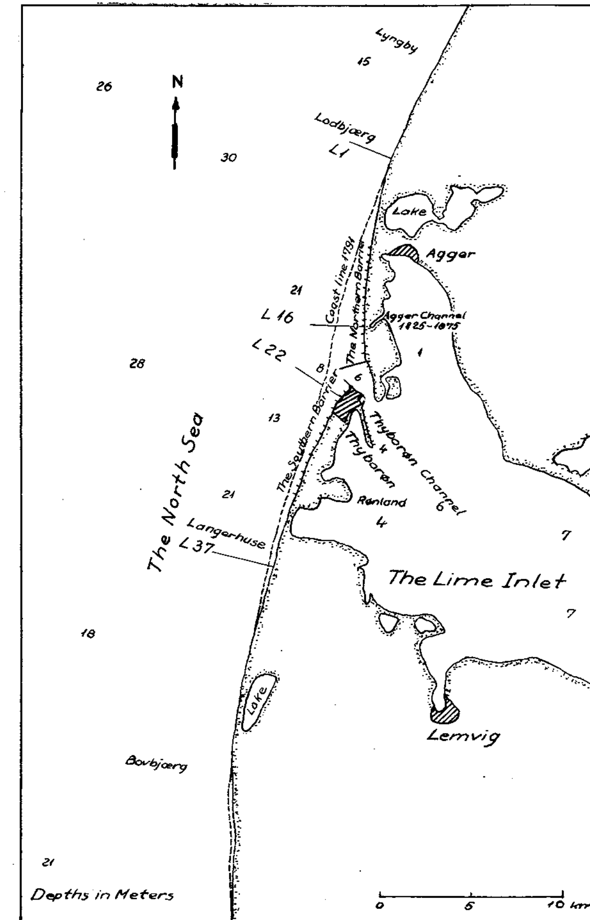

Fig. 5. The Lime Inlet barriers with adjacent coasts.

MIGRATING SAND BARS ON THE FAR OFF-SHORE BOTTOM

Thierry and van der Burgt write the following in their report to the XVIIth International Navigation Congress, see (21) and Fig. 4:

"It is quite probable that there is not only a sand drift along the natural coast curve between Hook of Holland and Den Helder and presumably along the other parts of the Netherlands coast, on the beach and in the breaker zone, but also that sand is being carried towards the coast from the sea bottom far off-shore.

The sand drift, which has its resulting component in the northerly direction, may be divided into:-

a. sea drift from far off-shore - 40 km and more - to about 12 km off-shore, where the slope of the sea bottom is about 1 in 4500, the depth decreasing from 23 to 17 m below low water,

b. coastal drift from about 12 km to 3 km off-shore, where the slope of the bottom is also 1 in 4500, the depth decreasing from 17 to 15 m below low water,

c. breaker drift in the breaker zone, wide 2.5 to 3 km from the coast, including the part where the sea bottom slopes under 1 : 225 from 15 m to 4 m below water and the steeper part up to the back shore,

d. wind drift on the beach, where the elevation is over 1 m above the mean sea level.

The sand which is brought towards the coast by these four kinds of drift, will move north as a local widening of the beach and will, as it passes by, be seen as a temporary advance and retreat of the shorelines".

The above-mentioned bars are probably current-phenomena.

MIGRATING SAND HUMPS ON THE BOTTOM OF THE SEA ALONG THE SHORE

The Lime Inlet barriers, 1897 - 1938:- The Lime Inlet barriers, Fig. 5, are indicated by insert No. 2 in Fig. 3. The Lime Inlet barriers separate the North Sea from the Lime Bay. The barriers are built up of sand to a level of about 5 ft, underlain by low-stressed, inlet-deposited Litorina clay (level - 19 ft). Fig. 5 shows the position of the shoreline in 1791, when the barrier was unbroken, and the shoreline of to-day. The existing open channel was formed by a barrier-breach in 1862. Immediately after the breach the barriers began curving inwards towards the channel, so that to-day the shoreline at Thyboroen, the fishing harbour on the point of the Southern Barrier, is situated about 2 kilometers farther landwards than in 1791. The curving of the barriers is caused by erosion in connection with such difference in water level (up to about 5 ft) between the sea and the inlet as exists during westerly gales, the result being that the water with its contents of suspended material is sucked into the inlet, where the solids are deposited in large shoals, see Fig. 5. At present about 1 million cubic yards of sand are deposited annually, whereas the annual average erosion of the barriers is 1 to 2 meters on the Southern Barrier and 2 to 3 meters on the Northern Barrier. The development of the barriers with adjacent coasts is explained in detail in (5). On the barriers soundings have been carried out since 1874 in lines spaced about 600 m.

Tables 2 and 3 show the width of the 0 - 9 m area between depth sounding line No. 1 (in the following indicated by L1) and L16 on the Northern and between L22 and L37 on the southern Lime inlet barrier, see Fig. 5, in 1927, 1934 and 1938. As the shoreline is almost straight, the corresponding Figures 6 and 7 show the configuration of the 9 m-depth contour along the barriers. It can be seen that the depth contour, especially on the Southern Lime Inlet barrier, is provided with "waves", length 2 - 3 km. The surveys are too limited for a detailed analysis of the shape of the wave.

Table 2 Width of the 0-9 m area on the Northern Lime Inlet barrier in meters.

Profile / Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1927	630	510	550	430	490	400	495	640	650	675	610	720	775	740	790	920
1934	545	550	520	455	480	440	530	555	510	490	580	620	570	650	720	870
1938	700	610	580	580	575	555	550	510	560	625	515	580	725	760	840	880

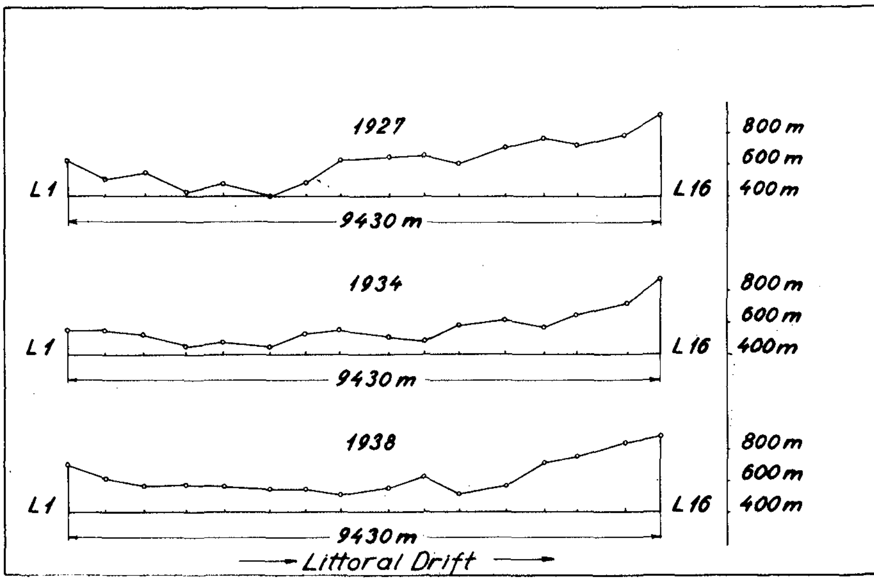

Fig. 6. "Waves" in the 9 m-depth contour of the Northern Lime Inlet barrier, Denmark, 1927 - 1938.

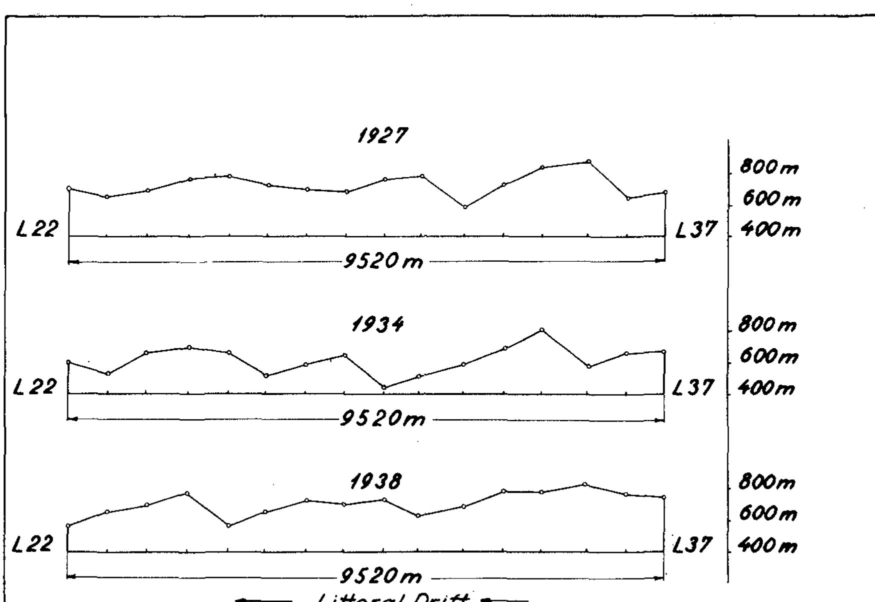

Fig. 7. "Waves" in the 9 m-depth contour of the Southern Lime Inlet barrier, Denmark, 1927 - 1938.

Table 3 Width of the 0-9 m area on the Southern Lime Inlet barrier in meters.

Profile / Year	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37
1927	710	660	690	770	790	735	700	690	770	790	590	730	840	880	650	680
1934	600	535	660	700	660	520	590	650	440	510	595	695	805	580	660	670
1938	575	660	700	770	580	650	720	700	730	630	690	780	780	830	770	755

South of the Southern Lime Inlet barriers, 1921 - 1934 - Fig. 10 shows the different total movements of the shoreline and the 10 m-depth contour 1921 - 1934 on the coast indicated by insert No. 3 in Fig. 3. It can be seen that the movement of the 10 m-depth contour has taken place in "waves" of 2 - 3 km length. There seems to be no connection between the shoreline movements and the 10 m-depth contour.

In Table 4 is indicated the average annual vertical erosion (minus sign) or deposition (plus sign) in cm up to 9 m-depth in different lines of soundings between L 1 and L 16 on the Northern Barrier and between L 22 and L 37 on the Southern Barrier, see Fig. 5, in several periods between 1897 and 1938. These vertical scours are calculated as indicated in Fig. 16. The corresponding Figures 8 and 9 show that the erosion or deposition is "wave-shaped" along the barriers, which may be due to migrating wave-shaped sand humps along the coast. The wave length is again between 1.5 and 3 to 4 kilometers.

Table 4 Annual scour in the 0-9 m area, the Northern and Southern Lime Inlet barriers (cm).

Years / Coast	1897 1903	1903 1909	1909 1916	1916 1921	1921 1927	1927 1934	1934 1938	1938 1942
1- 2	0	2.5	3.5	18	5.5	9	1	
2- 3	2	3.5	2.5	21	5.5	5.5	7.5	
3- 4	8.5	8	0.5	13	4	8.5	13.5	
4- 5	14.5	8.5	4.5	13.5	-1.5	10	10	
5- 6	20	11.5	1.5	19	-2	7.5	-4	7.5
6- 7	20	10.5	0	16	2	7.5	2.5	5.5
7- 8	7.5	10	3.5	10.5	2.5	7.5	0	11.5
8- 9	2	12	8.5	-4.5	5.5	7	-2.5	
9-10	10.5	5.5	10	-0.5	4.5	8	-2.5	
10-11	17	3.5	10	3.5	1.5	11	-2	
11-12	16	7	12.5	-5	6.5	8.5	1.5	
12-13	19.5	4.5	17	-8.5	5.5	10	-1.5	
13-14	19.5	8.5	13	-0.5	3.5	8.5	-2.5	
14-15	13.5	10	9	3	8	6	-5.5	
15-16	10.5	8	12.5	1	4	8	-6	
L_1^{16}	12.5	7.4	7.9	5.5	4.1	8.1	0.2	
22-23	4.5	10.5	6.5	-8	14.5	9	-8	
23-24	6	8	4.5	-3.5	9	6	-12	
24-25	6.5	6.5	-1	3.5	5	4.5	-10	
25-26	8.5	3	2	-2	5.5	5	-5.5	
26-27	6	6	-2.5	2	2	10.5	-1.5	
27-28	0	5.5	-4.5	8.5	2.5	11.5	-5	
28-29	0	3	-1	1.5	11	6	-8.5	
29-30	8.5	2.5	2	-5	8	7.5	-5	1938 1950
30-31	11	3	0.5	-0.5	4.5	9	-2	
31-32	7.5	4	-2	6	6.5	5	-4	8
32-33	1.5	3.5	-1	9.5	3.5	4	-6	7
33-34	0	4	1	6	2	5.5	-2.5	4
34-35	2	-2	4	1	4.5	5	-1.5	
35-36	-1.5	4	0.5	8	3.5	4	-1	
36-37	-5	11	1.5	5	3.5	8	-4	
L_{22}^{37}	3.8	4.9	0.7	2.1	5.8	6.6	-4.9	

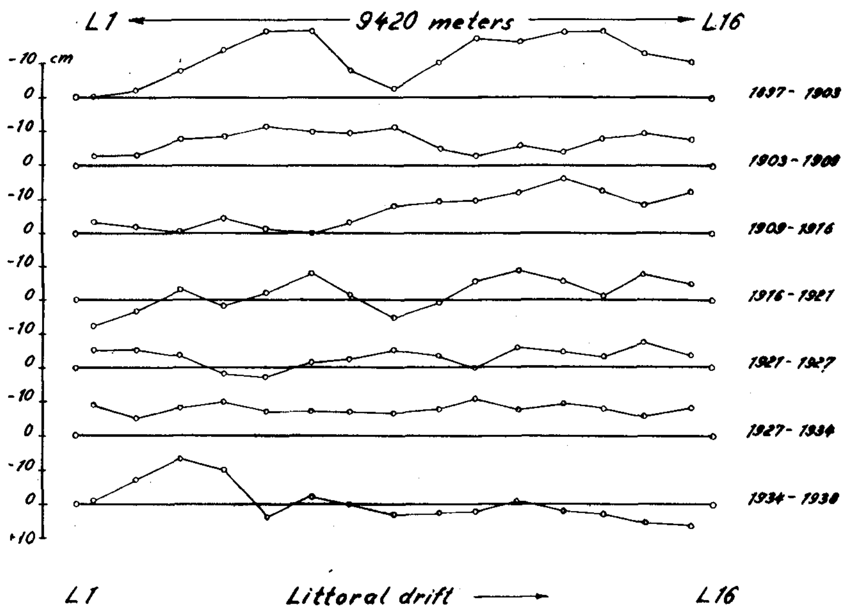

Fig. 8. "Waves" in erosion or deposition up to - 9 m on the Northern Lime Inlet barrier.

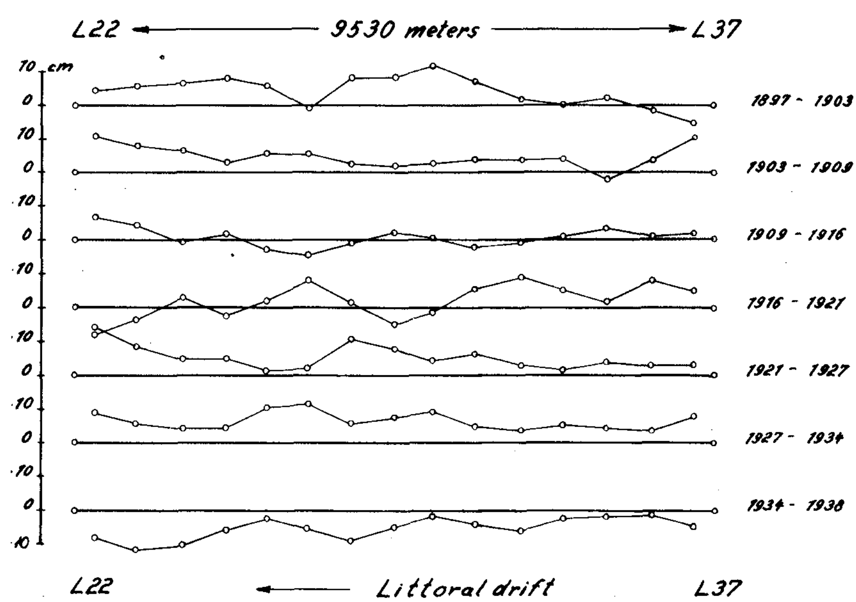

Fig. 9. "Waves" in erosion or deposition up to - 9 m on the Southern Lime Inlet barrier.

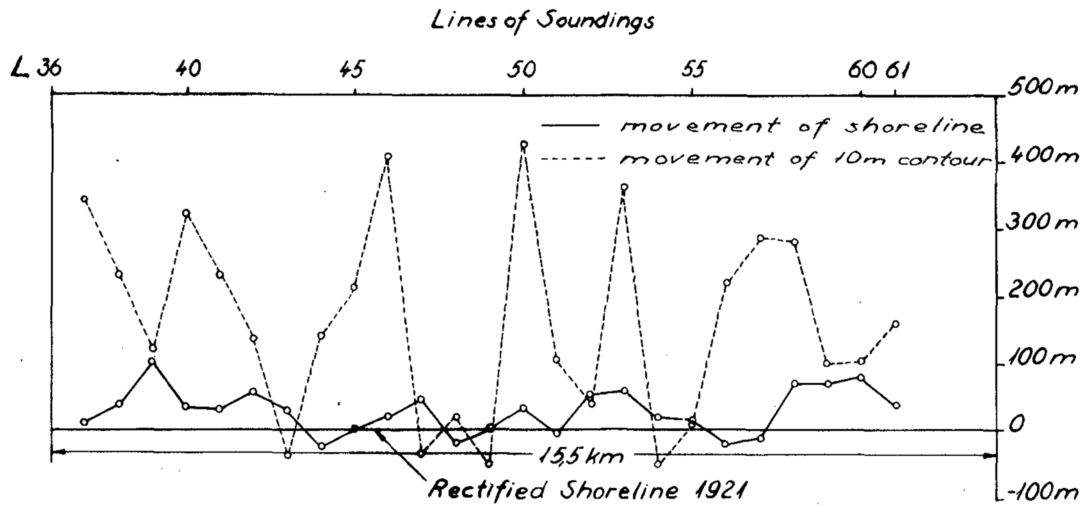

Fig. 10. Movements of the shoreline and the 10 m-depth contour of the coast south of the Southern Lime Inlet barrier, 1921 - 1934.

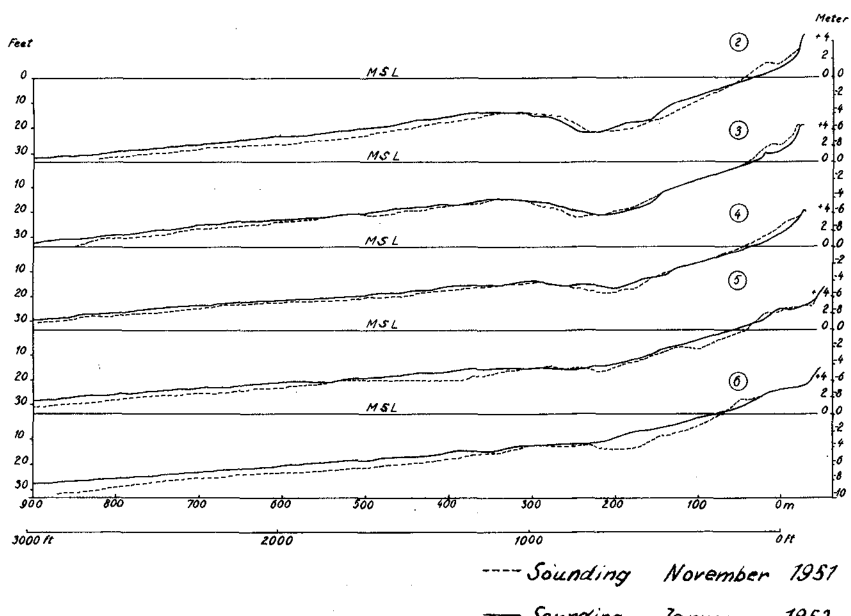

Fig. 11. Fluctuations of beach profiles south of Bovbjaerg, Denmark, between 11/15, 1951 and 1/25, 1952.

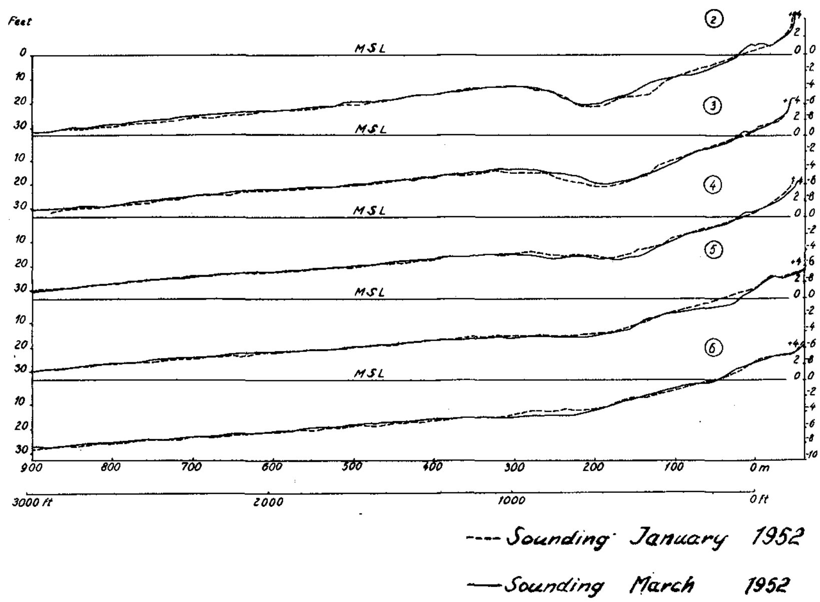

Fig. 12. Fluctuations of beach profiles south of Bovbjaerg, Denmark, between 1/25, 1952 and 3/28, 1952.

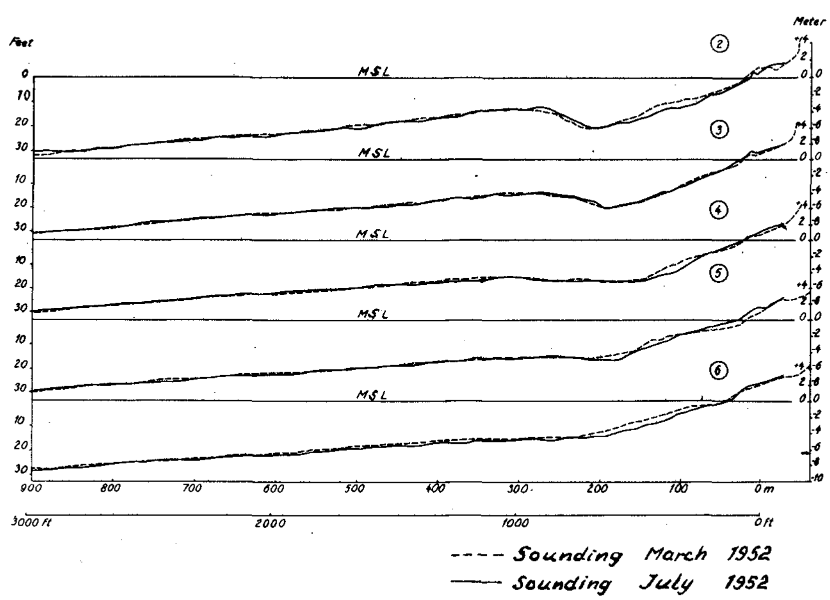

Fig. 13. Fluctuations of beach profiles south of Bovbjaerg, Denmark, between 3/28, 1952 and 7/15, 1952.

Bovbjaerg, 1951-1952 - Four soundings were carried on the West Coast in lines spaced 100 m. In Fig. 3 the point is indicated by insert No. 4. The results of these soundings are shown in Figs. 11 - 13. A comparison of the soundings in November 1951 and January 1952 (Fig. 11) shows that the profiles of November 1951 are summer profiles with "beach ridges". It can be seen that the longshore bar has migrated away from the shore during the winter season. The soundings in January 1952 and March 1952 (Fig. 12) show very similar winter profiles. A comparison of the soundings in March 1952 with those of July 1952 (Fig. 13) shows that the March profiles are winter profiles and the July profiles summer profiles with "beach ridges". It can be seen that the longshore bar has migrated towards the shore (compare with Fig. 11).

It is difficult to tell how far from the shoreline seasonal fluctuations take place (9 m ?). In Figs. 11 - 13 there is no equilibrium between the quantities eroded from the beach and those deposited on the sea bottom and vice versa. The accumulations in the outher sections of the winter profiles may be caused, however, by supplies of sand from the bottom outside the 9-m depth contour.

It seems as if material migrates on the bottom along the shore in "waves" or humps.

Table 5 Width of the 0-6 m area south of Bovbjaerg in meters.

Period \ Profile	2	3	4	5	6	7
11/15 1951	430	420	415	335	370	
1/25 1952	455	475	480	475	485	
3/28 1952	490	470	470	480	505	460
7/15 1952	465	455	470	470	470	410

Table 6 Width of the 0-9 m area south of Bovbjaerg in meters.

Period \ Profile	2	3	4	5	6	7
11/15 1951	730	785	815	805	740	
1/25 1952	775	815	880	880	885	
3/28 1952	850	850	860	895	895	
7/15 1952	860	820	850	870	900	900

Tables 5 and 6 show the width of the 0 - 6 m and 0 - 9 m bottom areas. The corresponding Figures, 14 and 15, show the configuration of the 6 and 9 m-depth contours.

Fig. 14 gives the impression, although not very clearly, that the 6 m-depth contours have the shape of a wave progressing slowly in the direction of the littoral drift. The wave seems much more distinct in the 9 m-contour, Fig. 15. The wave length is difficult to state, but it may be 1.5 - 2 km.

In an attempt to prove the existence of a sand hump on the bottom the cross sections corresponding to the beach profiles were calculated. In Fig. 16 the area to the 9 m-depth contours is A_1 m^2, and the distance from a fixed point (indicated by ●) to the 9 m depth contour is a_1 m. If another sounding of the same beach profile gives the corresponding figures A_2 and a_2 the variation, $\Delta S_{9\,m}$, in the 0 - 9 m area is

$$\underline{\Delta S_{9\,m} = (a_1 - a_2) \times 9 + A_2 - A_1}$$

Table 7 Erosion and deposit in the single beach profiles in square meters.

0 - 6 m area

\- Erosion
\+ Deposit

Period \ Profile	2	3	4	5	6	7	Volume change 2-6 1000 m^3
11/15-1/25	+ 29	-124	+ 50	+238	+347		+ 38
1/25-3/28	+189	+270	- 8	-155	- 61		+ 31
3/28-7/15	- 42	+ 12	+ 88	-235	-162	- 50	- 22

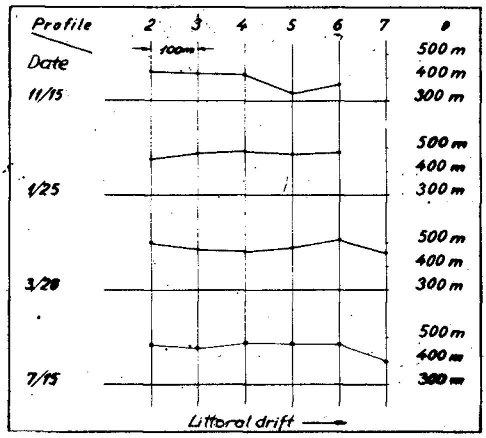

Fig. 14. Migrating "wave" in the 6 m-depth contour south of Bovbjaerg, Denmark, 1951-1952, owing to a progressing sand hump.

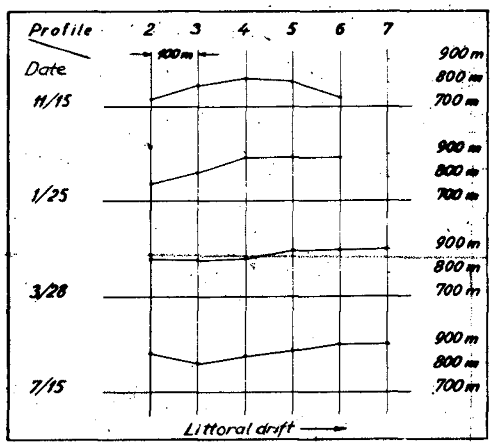

Fig. 15. Migrating "wave" in the 9 m-depth contour south of Bovbjaerg, Denmark, 1951-1952, owing to a progressing sand hump.

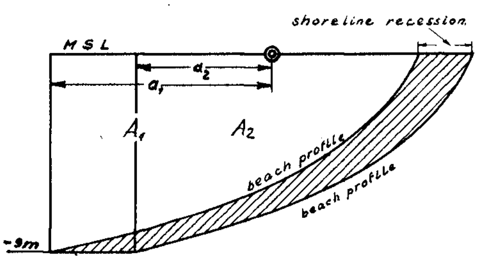

Fig. 16. Calculation of fluctuations in areas of the beach profile up to a fixed depth.

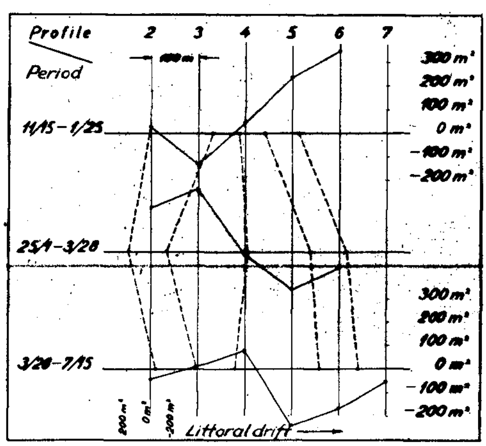

Fig. 17. Migrating "wave" in the 0-6 m area south of Bovbjaerg, Denmark, 1951-1952, owing to a progressing sand hump.

Table 8 Erosion and deposit in the single beach profiles in square meters.

0 - 9 m area

- Erosion
+ Deposit

Period \ Profile	2	3	4	5	6	7	Volume change 2-6 1000 m^3
11/15-1/25	+155	+ 72	+312	+565	+817		+144
1/25-3/28	+411	+258	- 96	- 88	-103		+ 23
3/28-7/15	- 48	- 16	- 96	-143	-131	-234	- 34

Tables 7 and 8 show the calculated erosion or deposition. Plus signs indicate that deposits have taken place, minus signs that erosion has occurred. In the last columns of Tables 7 and 8 the volume change is calculated, and it can be seen that deposits have taken place in the winter season, November 15, 1951 to March 28, 1952, while erosion has occurred in the summer season, March 28, 1952 to July 15, 1952. Yet, as can be seen from the following, these fluctuations are not really seasonal fluctuations.

Fig. 17 shows the erosion or deposition up to - 6 m. In this figure the full lines indicate the changes along the shore, while the dotted lines indicate the fluctuation of the single profile. The full lines show that the changes have the shape of a wave migrating in the direction of the littoral drift. At the same time, the dotted lines show just the fluctuation which might be expected from the migration of the wave indicated by the full lines.

Fig. 18 shows just the same features for the area of the beach profile up to - 9 m. The wave-shaped fluctuations are here even more distinct than for the 0 - 6 m area. The above proves that a wave-shaped sand hump migrates along the shore in the direction of the littoral drift.

The Old Skaw, 1952-1953 - In Fig. 3 the point is indicated by insert No. 6.

On the coast three to four longshore bars exist and the littoral drift is very strong in a northward direction.

Four soundings were carried out on the Skager Rack coast in lines spaced about 100 m. Two of these soundings are shown in Fig.

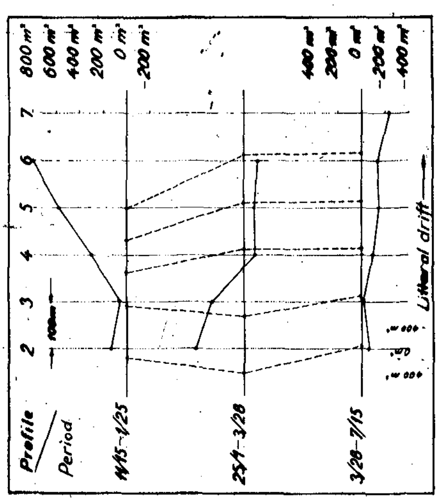

Fig. 18. Migrating "wave" in the 0-9 m area south of Bovbjaerg, 1951-1952, owing to a progressing sand hump.

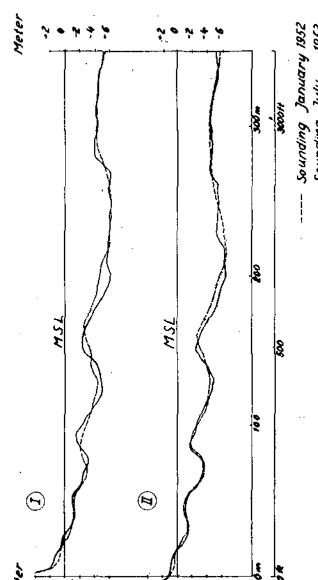

Fig. 19. Beach profiles at The Old Skaw, January and July, 1952.

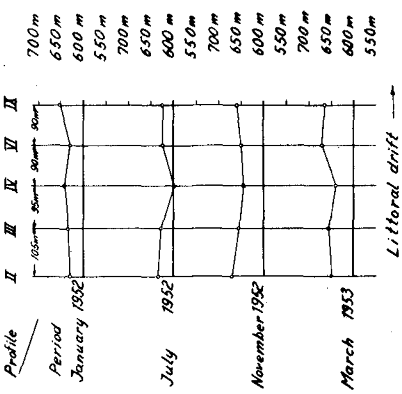

Fig. 20. "Wave" in the 5 m-depth contour at The Old Skaw.

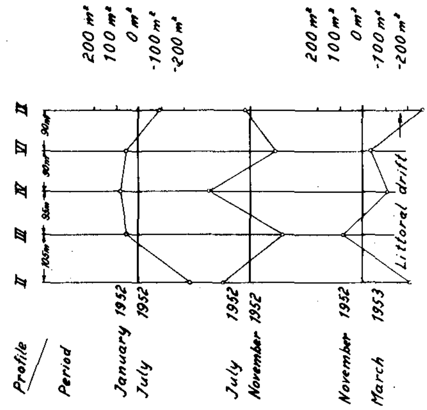

Fig. 21. Migrating "wave" in the 0-5 m area at The Old Skaw, Denmark, 1952-1953.

19. The sounding in January 1952 (dotted lines) shows winter profiles, the sounding in July 1953 (full lines), summer profiles. It can be seen that the longshore bars have migrated towards the shore in the summer season and that the summer beach is higher than the winter beach, cf. Fig. 11.

It is difficult to tell how far from the shoreline seasonal fluctuations occur, but they do occur at least up to the 6 m depth contour. Erosion takes place in the winter season, in the 380 m long test-area and amounted to about 30 thousand cubic meters between November 1952 and March 1953, i.e. about 80 cubic meters per running meter of the coastline. In the summer season no erosion takes place.

As mentioned above the profiles are provided with three or four longshore bars and are, therefore, very irregular and there may be only slight chances of recognizable migrating humps. Fig. 20 shows the configuration of the 5 m-depth contour and may suggest migration in the littoral drift direction but as the time intervals are comparatively great, it may not be the same wave that appears in different situations in Fig. 20.

Fig. 21 shows erosion or deposition in the beach profile up to - 5 m. Depositions have plus signs, erosions minus signs. The figure suggests migrating humps along the shore but it is difficult to establish the direction of travel.

WAVE-SHAPED BARS

Fig. 22 is an aerial photo taken from 3000 m height at the Skaw (the northernmost spit of Jutland on the Kattegat coast, see Fig. 3, insert No. 5). There are two longshore (lunate) bars, the outer one of which is wave-shaped, with 200 to 300 m from crest to crest. No observations of gradual changes are available.

Fig. 23 is an aerial photo of a lunate bar formed off the barrier island near Panama City, southwestern Florida, see (19). The lunate bars appear to be a modification of longshore bars, since they may be traced laterally into ordinary longshore bars and are not directly connected with the beach. The author does not know of any investigations of a possible migration of lunate bars.

APPLICATION OF THE RECOGNITION OF MIGRATING BARS, WAVES OR HUMPS IN COASTAL ENGINEERING

It very often happens that shipways or other channels and canals in the sea bottom shoal very fast, but it is impossible to

Fig. 22. Lunate bars in the bottom configuration at the Skaw, Denmark. (Phot. The Danish Army).

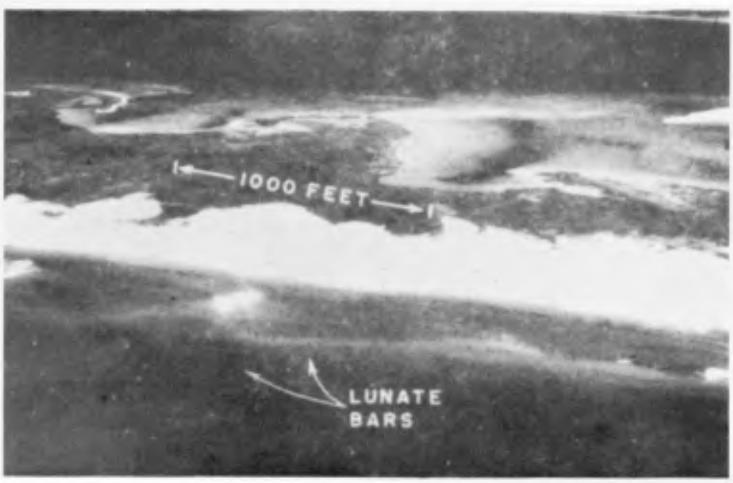

Fig. 23. Lunate bars formed off barrier island near Panama City, northwestern Florida.(Phot. D.L.Inman).

offer any plausible explanation, for instance, change in weather conditions. This has been the case with Grådyb on the Danish North Sea coast, the fairway to Esbjerg, the important outport for agricultural produce to England in southwestern Jutland (see Fig. 3). This phenomenon may be due to one or more very large migrating sand humps, but no surveys are available at present to confirm the theory.

In any case it is important to know whether shoaling is a temporary "wave" phenomenon or it is of a more permanent nature since in the latter case the construction of another fairway will have to be considered.

The sudden and "unaccountable" accumulations at some groups of groins may be explained as a wave phenomenon.

CONCLUSION

(1) Investigations in rivers have shown that under certain hydraulic criteria the bottom is molded into hills or waves. When the waves are unsymmetrical they are termed bars. They migrate in the direction of flow motion. The height, length and rate of travel depend on water depth, velocity and material available and are quite variable.

In test flumes with movable bed, similar wave phenomena appear. At lower velocities unsymmetrical "bars", at higher velocities symmetrical "waves", appear. Some investigations in test flumes showed that the bottom configuration does not give rise to a break in the relation between capacity and related hydraulic elements but the waves were indicative of torrential flow and supercritical slopes.

(2) Investigations in the sea tend to indicate that large bars migrate in deep water towards the shore in Holland, but more detailed data of this phenomenon are not available at present.

On the Danish North Sea coast large undulations in the shoreline migrate along the shore in the direction of the littoral drift in the area of the beach profile near the shoreline. The "wave length" seems to be 0.5 - 2 km, the "wave height" 60 - 80 m.

More detailed investigations on the Danish North Sea coast have proved that large wave-shaped sand humps migrate on the bottom along the shore. The "wave length" seems to be 1.5 - 3 km. The "wave height" may be 1 - 2 meters. Data which might give more detailed information about the quantity transported and the rate of advance are not available at present. There may be a connection between migrating bars in rivers and migrating humps in the sea but the extremely complicated nearshore current circulation systems make it questionable whether offshore sand humps or bars are formed and activated by the same forces as those in streams.

The recognition of the existence of migrating sand humps may be of great practical importance, e.g. for the maintenance of ship-ways and for coastal engineering in general, because of the short time during which filling may occur.

Hence it seems as if more detailed investigations, including current observations for the purpose of detailed hydraulic investigations, ought to be carried out because of the economic interest involved.

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RESUME

ONDES DE SABLE MIGRATRICES ou DUNES DE SABLE

Per Bruun

Les problèmes de transport de sédiment sont d'un grand intérêt pour la régularisation de la marée, la récupération des terres, la construction des ports et la défense des côtes.

Il faut distinguer entre le transport dans les fleuves et dans la mer, mais physiquement, il ne peut y avoir beaucoup de différence entre le transport des dépôts dans les fleuves et le transport le long des côtes de mer, exception faite de la zone littorale avec ses conditions extrêmement compliquées.

Jusqu'à présent, il a été de pratique courante de diviser le problème compliqué des côtes de mer en plusieurs problèmes, et cela a donné des résultats qui ont une valeur pratique au point de vue de la technologie du transport le long du littoral et de la défense des côtes.

Conformément à Einstein, Johnson et Chien, il y a deux types de charriage des matériaux : un qui a une certaine relation avec la décharge (transport de matériaux de fond), et un autre qui ne l'a pas (charriage en suspension).

Le mémoire traite d'un type du transport des matériaux de fond près des côtes de la mer ; le phénomène, à ce qu'on peut constater, se présente sous la forme de larges "ondes" ou dunes.

Dans l'introduction sont mentionnées quelques recherches faites aux Etats-Unis quant aux "ondes" de sable dans les fleuves et aussi quelques investigations en Hollande quant à des "ondes" de sable migratrices au fond de la mer à la hauteur des côtes de la Hollande.

La plus grande partie de la communication traite des "ondes" de sable migratrices le long de la côte de la mer du Nord de la péninsule jutlandaise du Danemark. Ces "ondes" cheminent partiellement le long de la côte dans la direction du transport littoral dans la zone du contour de la cote voisin de la ligne de celle-ci. Il semble que la longueur de l'onde soit de 0,5-2 km., la hauteur de l'onde de 60-80 mètres.

D'ailleurs, des sondages détaillés jusqu'à 9 mètres ont démontré que les larges "ondes" de sable ou dunes cheminent au fond de la mer le long des côtes. On peut voir ces dunes comme des "courbes de profondeur migratrices" : Cf. p. ex. fig. 1 qui montre la ligne de profondeur de 9 mètres à Bovbjaerg, à la côte danoise de la mer du Nord, en quatre positions différentes.

Elles peuvent aussi être interprêtées comme des chargements en forme d'onde dans la zône d'eau près du contour de la côte - en bas jusqu'à une profondeur fixée.

Il apparait que la longueur de l'onde est de 1,5-3 kilomètres. Actuellement, on ne dispose pas de renseignements certains quant à la longueur d'onde, la hauteur d'onde, la quantité transportée et la vitesse d'avancement, mais il semble qu'il s'agisse de grandes quantités (de l'ordre de 50.000 mètres cubes) dans une onde.

La reconnaissance de l'existence des dunes de sable migratrices peut être d'une grande importance pratique, par exemple pour le maintien de la navigation et pour la défense des côtes en général. Les accumulations soudaines de quelques groupes d'épis peuvent être interprétées, comme des phénomènes d'ondes.

On devrait effectuer des recherches plus détaillées - justifiées par des intérêts économiques impliqués.