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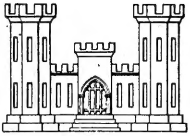

THE BULLETIN OF THE BEACH EROSION BOARD

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FOREWORD

The following article is a translation of a speech, based on a presentation of the theory by Professor Munch-Peterson at the Academy for Technical Sciences, 5 April 1938, and delivered by Mr. Sv. Svendsen, Division Engineer, Statens Vandbygningsvaesen, at the annual meeting of the Association of Government and Harbor Engineers, held 27 August 1938 at Helsingfors. Mrs. Valfrid Palengren Munch-Petersen Petersen's widow, has kindly granted permission for translation and publication of the article. The original article was translated at the University of California, and the permission of the University to publish the translation is acknowledged.

No previously published English translations of this important treatment are known. Despite the long interval since original publication it is believed that Professor Munch-Petersen's study of the problem of littoral drift is of sufficient importance to beach and shore protection engineering to justify its present publication in English. The translation has been edited freely in the interest of economy of space and for easier understanding of the reasoning.

MUNCH-PETERSEN'S LITTORAL DRIFT FORMULA

Professor Munch-Petersen carried on research in the field of material drift along the ocean coasts for nearly 40 years. As a young engineer working with the Municipal Water-building Service in Thyboron he studied this important question in cooperation with his two close friends, Engineer Palle Bruum and Harbor Engineer P. Vedel. Vedel became interested in the idea of the two engineers, that it is wave energy and not the ordinary ocean currents, that is the chief cause of material drifting along ocean coasts. Mr. Vedel held this view when he wrote his excellent paper regarding island harbors.

Professor Munch-Petersen wishes to share the honor with his two late friends for development of the theory in its first form. However, the following development of the theory must be credited to Professor Munch-Petersen alone. The first theory was made public at the Baltic Engineer Congress in Malmo, Sweden, in 1914. Munch-Petersen's formula when applied to different coasts has given results which are consistent with direct observations, and abroad, as well as in Denmark, it has been recognized as the best theory for predetermination of sand drift at project sites on sand-drift coasts.

Material drift along the ocean coast is defined as the movement of coastal material (stone, gravel, sand and clay, etc.), which can be observed directly, or through successive measurements at relatively short periods of time. The material drift defined above, does not include the bottom material drifting at great depths under the influence of different kinds of currents such as tide and other gravitation currents, temperature currents, salinity currents, wind currents, etc. In the long run, these currents have a rather great influence on the coasts, and are not without interest, but as a rule their effect is subordinate in comparison to the material drift which occurs along the coasts. Furthermore, it is very seldom possible to control the bottom material moving at great depths, and consequently, this movement does not interest the engineer so much as the coastal material drift. In general the currents caused by the wind do not have any influence upon the material drift along the Danish coasts, although these currents are of a greater importance than the deep-water currents. The primary cause of coast material drift is the wave movement and associated wave currents.

In connection with the problem of material drift, it is essential to find out how the waves affect the coast when they approach it. There are two main kinds of waves, deep-water waves and ground-water waves. In certain respects, these kinds of waves are of a quite different nature.

The deep-water wave, or the wave which turns in circles (trochoidal), is the wave which occurs in deep water after leaving the area in which it was generated by wind action. This is the wave which we generally call swell. Its nature is explained by the fact that the water particles on the surface turn in circles, the diameter of which is equal to the height of the wave h (see Figure 1). The water particles return to their original position and it is only the shape of the wave that moves forward, not the water particles. The profile of the wave is described by a point in close connection with a circle-concentric with one of the circles shown but greater than these— as the circle rolls on a horizontal line at a speed, v, equal to the speed of the wave. The profile is called a trochoid.

The length of a wave is the distance between two wave crests or two wave troughs; it is represented by L. The height of the wave, h, is the distance between the crest and the trough of the wave. The length of the wave divided by the speed of travel of the wave shape is called the period, T.

The movements of the wave are not confined to the surface alone, but continue downward as the diameter of the circle steadily decreases. Theoretically the diameter becomes zero at a tremendous depth, but in general one can say that wave motion has ceased at a certain depth which is dependent upon the dimensions of the wave. In our imagination we can form a picture of the movement by thinking of an elastic string which is fastened at this depth while the other end moves around the top circle. All other points on the string will then draw circles with diameters which decrease proportionally with the depth. The drawing (Figure 1) must be regarded as purely schematic; as a matter fact, the displacement does not decrease in a straight line with the depth.

Since the deep-water wave motion does not reach the ocean bottom, it of course cannot influence the latter; however, the wave motion is an expression of the energy which has been given to the water by the wind. This energy can be expressed in the form:

$$E = \frac{h^2 L}{8} \left(1 + e^{\frac{2\pi z}{L}}\right)$$

where z is the depth of the water at a certain point. We can see that when z is large in comparison to L, the part in the bracket can be ignored and we have:

$$E = \frac{h^2 L}{8}$$

The speed with which the wave moves, that is, the speed with which the energy transferred from the wind to the water moves forward, can be expressed as:

$$v = 1.25 \sqrt{L}$$

If new energy is not transferred to the water from the wind, the wave will lose height because of internal friction. If energy is transferred from the wind the shape of the wave will be maintained, or possibly, increased. The wave influenced by the wind is a little different from the trochoid, being more flat on the backside and more steep in front. If the influence of the wind is very strong, the wave can fall forward (white caps). However, the wind can only blow the waves up to a certain size, and the size is different according to the nature of the different oceans.

It is obvious that the wave will change if the depth of the water decreases so much that the wave will reach the bottom. If the wave runs in on a sloping beach, the lower water particles can no longer turn in circles, and will have to move in straight lines along the bottom. The higher water particles will turn in ellipses, which approach closer and closer to circles the higher up they are. When the horizontal movement extends nearly to the surface, the wave has changed from a deep-water wave to a ground-water wave. The change between these waves is in general very uniform.

It is the depth of the water alone which determines the speed of the ground-water wave, i.e.

$$V = \sqrt{gd}$$

where d is the depth of the water, and g is the acceleration due to gravity.

As the ground-water wave involves water motion clear down to the bottom, it is obvious that the wave movement must influence the latter. The wave is retarded by the bottom, and in doing so it uses some of its energy to move loose bottom material if this is to be found. When the wave is greatly retarded, the crest of the wave falls forward, this is called breakers (surf). The location of the breakers is dependent upon the depth of the water, the elevation of the bottom and also on the height of the wave and the strength of the wind. As a result the distance of the breaker from the coast is not only different on different coasts, but on the one and same coast it moves in accordance to the immediate conditions. One can say that it is a fact that the breakers occur where the depth of the water is 1.5 - 2 times the height of the wave.

The energy of the ground-water wave can be expressed as:

$$E = \frac{h^2 L}{8}$$

When the wave breaks for the first time, all its energy has not yet been exhausted. A smaller wave continues towards the coast line until the water is not deep enough to permit this wave to exist. Then the wave breaks again; this process can go on several times before the wave finally dissipates all of its energy. As all the energy is taken away from the wave on the part of the coast where the wave-movement reaches the bottom, it is obvious that the energy in the original unbroken waves can be used as a measure of the wave attack on the ocean bottom and the coast. In other words, there must be a relation between the energy contained in the original deep-water wave and the transport of the material on the bottom of the sea; in brief; between wave energy and material movement along the coast. However, not all the wave energy is used for the material movement; much energy is lost in the generation of foam, heat, electricity, etc.

Similarly to the conditions in a river, the bottom material in the ocean can be moved either suspended in water, or rolling and sliding along the bottom of the ocean. The more violent the sea, the greater amount of energy in the wave, and the heavier the material it can move. The energy which the wave looses when it first breaks is used partly for disturbing the bottom of the ocean and partly to start another direction depending upon the wind. These coast currents are transferred wave energy, and consequently the effect of the currents is a function of the wave.

It is not only at the place where the wave breaks that the movement of material occurs. Before the ground-water wave breaks, it can move materials not only forwards and back again, but also in a certain direction. The reason for this is something which is characteristic of the ground-water wave; namely, the forward speed of the wave crest is greater than the backward speed of the wave trough. This can be noticed easily by direct observation. When the water is clear, it can be seen from ships that seaweed, etc. suddenly moves rapidly when the wave crest passes, while the return movement when the wave trough passes is slower and longer lasting. Also, divers can notice sudden strong pressure inwards when the wave passes. This has been shown in Figure 2. The speed of the water particles is plotted as abscissa and time as the ordinate. The areas a, b. c, and c. d, e, show the distances which the water particles move forward in the crest of the wave and backward in the trough of the wave. These areas must be equal in size, but the speeds are not the same. Let us imagine that the bottom of the ocean is horizontal and that V-min is the slowest speed which the water must have to move a particle of a certain weight and size. Then it is obvious that such a particle will be moved forward a distance which is equal to the space f-b-g, and then backward a little, equal to the space h-d-i. As these two spaces are not of the same size (the first one is the largest) the particles will be moved forward a distance which is as long as the difference between the spaces. It follows that if the waves are so large that the speed along the bottom is greater than V-min, the particles of the dimensions mentioned will be moved toward the shore.

In this connection there must be noted a theory proposed 40 years ago (1898) by the Italian engineer Paolo Cornaglia. The background for Mr. Cornaglia's theory is the well-known observation that on certain parts of a coast no material is deposited, and if the coast consists of loose materials, part of this material is being eroded. At other places, however, no materials are being carried away but material is deposited. From these observations Mr. Cornaglia developed a theory according to which the coasts where material drift occurs can be divided into "flat coasts" and "steep coasts". The steep coasts are retreating unless they consist of a material of strong resistance, because no material is deposited. Flat coasts on the other hand are advancing. Mr. Cornaglia states that the limit between steep coasts and flat coasts is where the bottom of the ocean slopes at about 1 to 40.

If a particle lies on a sloping ocean bottom, gravity will try to pull the particle out into the deep. The outward pull will be stronger the steeper the bottom is. This tendency to seaward movement can be combined with the influence of the waves as shown in Figure 2. When the bottom is sloping it is harder for the waves to move the particle landward and easier to move it to sea. Only minimum speeds are now needed. On flat coasts the particles move landward, but on coasts with a certain steepness the space f'-b-g' is greater than the space h'-d-i', which means that the material moves seaward.

Finally, it may happen that the two spaces are equal in size. In this case the particles will be moved equally both ways over a middle position, and the resultant transport will be nil. As the influence of the waves on the bottom decreases with the depth of the water, while the influence of gravity is unchanged, this position of no resultant movement for a certain steepness of the bottom, etc. will occur only at a certain depth, or depth curve, which Mr. Cornaglia calls the "neutral line". Inside this line the particles move landward and outside it they move seaward.

It will be understood that on each coast there are to be found numerous neutral lines, as there is a neutral line for each size of wave, each size of material, etc. It is, of course, especially interesting to know the position of the neutral line which is so far seaward that beyond it even the finest piece of sand will be moved seaward, even when the strongest hurricane is blowing toward the shores. On very steep coasts, according to Mr. Cornaglia, this neutral line will be so close to the coast line that the whole front of the shore is eroded, provided that the material of the shore is not very hard. This is often the case around headlands as the slope of the bottom is most often steepest here. At these places one can very seldom find desposited materials.

This is Mr. Cornaglia's theory in brief; it seems sound, but examination shows it is not valid. It seems to be unimportant in the movement of a particle deposited on the bottom, whether the latter slopes at 1 to 10, 1 to 40, or 1 to 70. A simple calculation shows that the influence of gravity is minimal compared to the pressure created by the waves. Furthermore, experience shows that deposits are to be found on very steep coasts (Stevns, Møen and other places). The fact that deposits are seldom to be found near headlands can be explained better by the so-called "material-moving power", which will be discussed later. At headlands this "power" will usually move in such a direction that the coast material will be moved away from the point to both sides. A typical example is the headland near Rønne on Bornholm, where the harbor is completely free of sand in spite of the fact that there is sand on both sides. (Figures 7 and 8). Furthermore, we must take into consideration the strong undertows which occur on steep coasts when sea gales are blowing. This undertow is partly the result of the wind and partly of the seaward bottom flow of the water which the waves have piled up. If the wind approaches land at a 90 degree angle, this undertow can be so strong that it can drag heavy material with it.

When Mr. Cornaglia states that material is deposited on flat coasts and eroded from steep coasts one can answer that flat coasts are flat because deposits are being made, and that steep coasts are steep because material is being eroded. This means that reason and result can change places, and then the whole thing seems more reasonable.

If the direction of travel of the waves is oblique to a steep coast, the sand will most likely be moved away by the coastal currents, while gravel and small stones, which are too heavy to be moved by the currents, are left behind. Therefore, the presence of stones and no sand, or the absence of loose coast material, shows that the coast is steep. One must here keep in mind that the waves are strongest on steep coasts and consequently here they are capable of handling heavier material. When land winds are blowing, the undertow will move landward, and as a result, quantities of sand will be deposited on the coast. On flat coasts the bottom tows are not so important and consequently, the sand which has been moved to the coast by the waves either will be deposited here or moved along the coast.

It may be concluded from the foregoing that on coasts with a very small difference in tide, the material drift occurs almost exclusively as a result of the power of the waves. Wave attack on the bottom starts at the depth the bottom first reaches the movement of the wave. This defines the seaward limit of the belt or zone inside which material movement occurs. The zone will be broader as the coast is more flat, as the stronger is the action of the wave, and as the finer and more easy to move is the bottom material.

Professor Munch-Petersen describes the influence of the waves on a sloping bottom as follows. When the waves break, the bottom material will be disturbed and moved along the coast, partly by the wave current, and partly, together with what is pushed forward along the bottom, by the wave. The direction of the latter is determined by the 90 degrees angle obliquity of approach of the wave, the obliquity being determined by the wind. One can get a good picture of the material movement if one looks upon the wave as an excavating machine and the wave current as a conveyor belt which moves the material which the excavating machine has loosened. When the machine (the wave) reaches the shore, it throws the material in a more or less oblique direction up on the shore. On the shore part of the material is caught in the wave backwash. Then it is caught by the conveyor belt and moved along the coast until a new wave comes along, etc. Erosion or accretion is solely dependent upon the difference in quantity of material that is deposited and that is carried away. If there is no soft material where the waves come from, they will, when they reach soft material, absorb a lot and material will be carried away.

It follows that one cannot determine the volume of material drift from the material found on the shores. On a coast that has no loose materials whatsoever, the material drift can very well be considerable. This one can see (unfortunately often, too late) when the movement of the material has been blocked by a harbor jetty. This action will result in sand deposits on coasts that are nearly free from sand.

When the wind blows in an oblique direction toward the coast, the material will be moved along the coast in the direction the wind blows. Close to the shore the waves will be turned to approach the shore at more or less a 90 degree angle to the depth curves. However, this cannot be done without the bottom or the bottom material being influenced, and moreover the waves will usually approach the shore somewhat obliquely. It is obvious that the closer the wave approach is to perpendicular the more energy there will be for disturbing coast material. On the other hand, the ability of the waves to transport material along the coast will increase, as the obliquity of the wave to the belt in which the material drift increases. Experience shows that material movement increases when the angle between the direction of the wave and the coast decreases, and that it is close to its maximum when this angle is zero, i.e. when the original wave (the deep-water wave) moves parallel to the shore. As the wave enters the belt in which the material drifts, it will very soon be forced to turn so much that erosion of the bottom material will occur, and this action will be followed by transport of the material.

The dependence of material drift on the direction of the wind can be illustrated as suggested in Figure 3, which approximates a cosine curve with the exception that winds in the second quadrant are added because land winds which blow nearly in the direction of the coast influence the material drift. However, the question of the dependence of the material drift upon the direction of the wind is not yet clear. Several investigators are of the opinion that a maximum drift occurs when the wave approaches at an angle of 45 degrees, this condition corresponds to a cosine-sine curve and not to the cosine curve shown.

Let us now consider what Mr. Munch-Petersen calls "The Material Moving Power". This is a notion which, one can say, has brought the study of the problem of material drift a very long step forward, and it has consequently been the object of consideration by several foreign investigators. The problem is to establish a formula defining the transportation ability of the waves, (whether or not there is material to be transported is another question). If we consider a straight, regular coast without appreciable headlands, then we can, according to what has been said before, express the wave's ability to transport material as:

$$M = k \cdot 1/8\, h^2 \cdot L \cos \alpha$$

where h and L are respectively the height of the wave and the length of the wave; α is the angle between the direction of travel of the unbroken wave and the direction of travel of the deep-water wave (which is nearly the same as the direction of the wind); and k is a coefficient, which is very close to a constant. As we do not know either the height or the length of the waves at different times, e.g. over a year, and as it is very difficult to measure them, we will have to revert to the reason for the wave, the wind.

Although there is much material concerning the dimensions of waves in relation to certain strengths of wind over a certain length of time, this question is in no respect solved. The observations that we do have all point to the fact that the waves increase proportionately with the speed of the wind, while the length and period increase with the duration of the wind. There must also be considered another factor which is of great importance in the creation of waves, namely what is called the "free space", or fetch of the wind. This is understood to be the distance between a certain place on the coast and the opposite coast, measured in the direction of the wind. (Figure 4). It seems obvious that the height of the waves must be dependent upon the fetch, and experience proves that this is correct. The largest waves, for the same strength of the wind, come from the direction of longest fetch. There is not complete agreement about how the length of the fetch, or free space is related to the size of the waves, but most students are of the opinion that we must take the free space into consideration since we cannot count on fetch distances exceeding a certain maximum limit. This limit is not surpassed by fetches from the coasts of the Baltic. However, on the west coast of Jutland, which is exposed to northwest winds which have free space clear to Greenland, one should set the limit at about 1000 kilometers (625 miles) as one cannot count on steady winds for longer distances.

On the basis of experience with the North Sea and Scottish lakes Mr. Thomas Stevenson has set up the formula

$$h = C \sqrt{f}$$

where f is the free space in quarter-miles, and C is a coefficient which for gales and great water depths (trochoidal waves) has the value 0.45. On the Danish coasts it seems that C should have the value 0.25 when f is measured in kilometers and h in meters.

Following these considerations, we may substitute the following expression for the previous formula for M

$$M = C \cdot S^2 F \sqrt{f} \cdot \cos \alpha$$

where c is a coefficient, S the speed of the wind, and F the frequency of occurrence of the latter. F is the average frequency (in %) in the direction of the fetch, and S is an average defined as:

$$S = \sqrt{\frac{\Sigma F S_f^2}{\Sigma F}}$$

for each fetch direction. (S_f is the speed corresponding to any frequency F)

Munch-Petersen explains the formula in the following manner. For deep-water waves (throchoidal waves), the height of the waves increases proportionally with the speed of the wind, and as mentioned before, the depth of the water where the attack on the bottom starts is proportional to the height of the wave. From this it follows that this latter water depth also must be proportional to the speed of the wind. The speed of the ground-water wave is proportional to the square root of the water depth; furthermore, the influence of the wave on the bottom of the ocean obviously must be proportional to the square of the speed of the wave, and in accordance with the above discussions to the depth of the water. Subject to conditions of equal slope of the bottom the area between the coast line and the line where the waves break (i.e. the zone of material drift) will be proportional to the depth of the water on the line where the wave breaks. Since the influence of the wave on the bottom, as well as the area in which this influence occurs, are proportional to the depth of the water; then the quantity of material put into motion by the wave, can be set proportional to this depth squared, or to the speed of the wind squared. Still the material-transport must be proportional to time, that is to the frequency of the wind. Finally the height of the wave, which is C $\sqrt{f}$, and the obliquity, cos α, must be added. With the notation given in Figure 5, we have, for any chosen direction of the wind,

$$t = k \cdot F \cdot S^2 \cdot \sqrt{f} \cdot \cos\alpha \cdot \Delta\varphi$$

and for the resulting material-transporting power components in all directions of the wind

$$T = K \sum (F \cdot S^2 \sqrt{f} \cdot \cos\alpha \cdot \Delta\varphi)$$

Since weather-forecasting stations usually give wind data for 8 directions of the compass, it is practical to use these for our calcuations. If we know the values of F and S in these directions, we can with a rather high degree of accuracy draw the continuous curve of F and S in the polar-coordinates plot shown as Figure 5. However, it is sufficiently correct to use the average values for each compass-direction. It can be seen from Figure 6, that if the coast line coincides with the mid-direction between two of these 8 directions, we will only have to summarize 4 sectors, whereas we must use 5 sectors in all other cases. To summarize the two utmost sectors, we must add the factors $\alpha/45^\circ$ and $(1 + \frac{\alpha}{45^\circ})$, where α is the angle between the coast line and the closest mid-direction. This determination can be made by calculation, but it is more illustrative to set it up in a diagram, using the components which are determined for each direction of the wind as vectors. From the construction we can judge immediately the influence of any single direction of the wind on the material drift.

We shall now show the formula can be used in practical cases. In the following table is given the strength and frequency of the wind at 17 stations in Denmark. These figures are the averages resulting from daily wind observations over a period of 5 years. It will be noted that winds from northwest increase from Grenen and south, while the winds from the west and southwest decrease in the south.

From these data, the material-moving power has been computed for 43 locations on the Danish coast, of which 22 locations are on the west coast of Jutland, 8 on the east coast, 3 on the north coast of Sjaelland, and 10 on the Baltic coasts of Sjaelland, Møen, Falster, Lolland and Bornholm. Figure 7 shows all the vector-polygons and the resulting material-moving powers, including their components, perpendicular to (eroding) or parallel to (material drifting) the coast. The diagrams are drawn to the same scale and one can see that the powers on the west coast of Jutland, which is exposed to the free space to England, Scotland and partly also the Atlantic, are very great in comparison to the powers within Skagen. Figure 8 shows the material-moving power at the different locations as vectors (in size and direction). Relatively strong headlands which are worth being mentioned are Hirtshals (stonelike clay), Hanstholmen, Bulbjerg and Lodbjerg (line), all on Jutland; on Sjaelland, Gilbjerg and Spodsbjerg (stone like clay); Stevns (lime and chalk) and Møen (chalk), on Bornholm granite, sandstone, and stone-like clay (Rønne).

On Figure 8 it can be noted that material transport on the west coast of Jutland is mostly towards the south from Lodbjerg to Blaavands Huk; farther south the influence of the tides is so strong that these coasts cannot be treated in this paper. From Lodbjerg north, nearly without interruption, the material-drift moves north up to Grenen. Thus, material must pass by Hirtshals and Hanstholmen, and these will consequently remain points free of sand and with steep slopes until the sand is prevented from passing. Grenen, (Figure 9) which has as we know an east-west direction, is a relatively stable terminal in spite of being made of soft material (sand, gravel and small stones) as there is a certain balance between arrival and departure of material. On the Skagerak side the material is moved to the point from the west, while winds from northeast and east move it down along the Kattegat coast where it is stopped partly by Skagen harbor. The point (Grenen), however, is not stable but moves slowly northward and then southward. The reason for this is variation in deposition and erosion over a period of years.

At Thyborøn, Figure 10, the material-drift has caused severe difficulties. Before 1825 there was no connection with the ocean in the west as the Limfjord was a fjord, but in this year the so-called Agger channel was made. Forty years later this channel was blocked by sand, but , before this happened, a new channel was cut

AVERAGE SPEED AND AVERAGE FREQUENCY OF WIND OVER 5-YEAR PERIOD

Observationssted	N		NE		E		SE		S		SW		W		NW		Calm
	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	F
Skagen	3,00	7,4	3,22	9,8	3,13	9,0	3,14	10,4	3.47	12,7	3,32	15,4	3,78	20,7	3,72	11,9	3,6
Raabjerg Knude	2,99	5,6	3,14	8,5	2,93	11,5	2,99	11,5	2,69	13,7	3,48	12,9	4,34	25,1	4,51	8,0	3,2
Hirtshals	3,54	5,4	3,08	9,5	2,69	9,8	2,44	11,4	2,70	14,4	2,87	15,2	3,76	20,1	4,48	12,3	1.9
Hanstholm	2,52	4,6	2,69	10,2	2,66	11,3	2,29	14,3	2,17	9,7	3,00	14,7	3,48	20,4	3,58	13,1	1,7
Lodbjerg	3,35	7,6	2,94	6,9	2,88	12,1	3,00	12,1	3,38	11,8	3,70	12,3	3,88	17,5	4,40	17,9	1,8
Bovbjerg	3,54	8,6	2,83	7,2	2,94	10,3	3,20	14,3	3,35	11,5	3,94	14,3	4,17	13,0	4,37	19,0	1,8
Lyngvig	2,90	6,4	2,48	7,2	2,87	9,2	2,96	13,1	3,06	9,2	3,56	15,3	3,75	16,9	3,94	19,4	3,3
Blaavandshuk	2,70	8,7	2,03	7,1	2,42	9,9	2,95	13,2	2,77	9,4	3,13	14,6	3,36	16,3	3,49	18,8	2,0
Esbjerg	2,71	10,0	2,18	7,9	2,58	10,8	2,96	9,8	3.08	8,2	3,70	13,4	3,49	15,7	3,72	16,2	8,0
Fornaes	2,84	7,8	3,06	6,5	3,23	8,7	3,33	12,0	2,97	13,3	2,79	18,2	2,80	20,8	2,79	10,1	2,6
Anholt	3,84	7,6	3,70	7,9	4,10	8,2	4,30	13,9	3,92	10,4	4,09	15,8	4,26	17,7	4,32	16,1	2,4
Refsnaes	3,53	6,6	3,45	7,9	3,11	10,6	3,18	10,6	3,48	14,7	3,85	17,7	3,86	14,5	4,05	12,1	5,3
Nakkehoved	3,30	9,3	3,09	5,8	2,72	7,5	2,62	14,4	2,44	12,5	2,56	19,6	3,30	14,1	3,36	12,6	4,2
Stevns	2,88	6,3	2,96	6,0	3,60	12,1	3,50	10,9	2,78	7,7	3,04	18,0	2,98	20,8	2,82	14,9	3,3
Gedser	2,52	8,4	3,33	4,9	3,42	15,3	3,24	12,0	3,19	10,7	3,80	13,6	4,14	17,2	3,62	15,7	2,2
Hyllekrog	2,16	4,5	2,46	4,0	3,27	11,6	3,04	11,8	3,12	12,9	3,83	20,0	3,26	18,4	2,62	7,0	9,8
Christianso	2,9	6,0	3,3	10,0	3,0	10,0	2,7	11	2,8	9,0	3,6	17,0	3,8	26,0	3,2	17,0	5,0

S - Speed of wind

F - Frequency of currents

(the present Thyborøn channel). The channel led to the development of North Sea fishing and as a result of this a fishing harbor was built here. After the cut was made the entrance lips turned inward as the North Sea coast suffered a strong retreat, and at the same time material was deposited on the inside. Now, there is about 30 feet of water where the tongue was in 1825. Even near Agger, which is situated outside the real Limfjord tongue, the retreat has been about 5 meters a year. Since about 1870 the Danish government has spent tremendous amounts on wave breakers and dikes in order to prevent new breaches of the tongue. Whereas the Limfjord is connected to the North Sea through an open channel, the outlets from the fjords Nissum and Ringkøbing (respectively at Thorsminde and Hvide Sande) are equipped with locks. The outlets are protected against sand deposits by guide piers (see Figure 11 which shows the conditions at Hvide Sande). At both these locks sand deposits are prevented by flashing when the tide is out.

On the north coast of Sjaelland the material drift moves from the west to the east (see Figure 8), and we can here find several characteristic examples of sand deposits; for instance Gilleleije Harbor (Figure 12). In this location the coast on the west side has aggraded about 350 meters, while it has retreated somewhat on the east side.

South of Copenhagen the coast is flat and stony, here and there it is sandy, but at Stevns it rises 30-40 meters over the water in steep cliffs. Here we have a characteristic example of the breaking down of a coast. This is due primarily to wind erosion augmented by the beating waves. Figure 13 shows a profile of the cliff at the Højrup Church before and after it fell down in 1928. The foot of the cliff is now protected by a concrete wall. Farther south, the coast again rises to a considerable height at Møens cliff-- about 115 meters over the ocean. Figure 14 shows a schematic profile of the cliff with a talus that varies in size at different times and different places.

The cliff of Møen is slowly but steadily being eroded. The extent of the erosion process here, as well as at Stevns, is primarily determined by sub-aerial erosion, but the influence of the ocean is a necessary presupposition. All the chalk that falls as a result of the air attack ends up at the foot of the cliff and protects it against erosion until the ocean has washed the chalk away. The retreating balanced profile, which has been created as a result of the attacks by the air and by the sea, consists of the "steep flat" b-c (Figure 14), which is attacked only by the wind, and the "sloping flat" a-b, which is acted upon by the waves when sea winds are blowing. If the line a-b-c is to make a parallel retreat, both flats must be exposed to the same degree of erosion (measured in a horizontal direction) which gives $\alpha \beta$. This means that a little less material is to be taken away from the "sloping flat" than from the "steep-flat". This can happen as the chalk that has fallen down protects the sloping flat. If the profile is to be kept as it is, the ocean will have to transport away the deposited chalk. The less this happens the larger the "sloping flat" will be, and one can easily see that as long as there is a "sloping flat" it will be the air erosion that determines the magnitude of the erosion.

At the cliffs of Møen there are places where there are no "sloping flats", and at such places a great quantity of material can suddenly fall. Even though this is a rather rare event, usually 30-40 years between each fall, many plans have been made on how to protect the cliffs. However, these plans have never been realized, and we must keep in mind that a complete protection of the cliffs against the attack of the ocean would not be desirable as then the white chalk would lose its beauty. However, some defense of the cliff would be justified.

As can be seen from Figure 7 material drifts from the cliffs of Møen northward, but on the south coast of this island near the harbor of Klintholmen where the coast is sandy, the direction is westward. Farther south on the east coast of Falster the material drifts southward down to Gedser Odde (Gedser Point), and on its west coast the material also moves to the tip of the point. On the south coast of Lolland the material drifts eastward mostly resulting in the formation of a small peninsula near Hyldekrog; but on the western parts of this coast the material must be supposed to move to the west which explains the presence of the small peninsula at Albuen.

When the drifting coast material meets with an obstacle, for example a groin (Figure 17) then material will be deposited in the corner between the groin and the coast within a belt equal in width to the length of the groin, and as a result the coast line and the depth curves outside it will move seaward. As we know, this is the principle of groins. The more oblique the material-moving power direction in relation to the coast, and the more sand the waves carry, the faster the deposits will be made. If the groin is one of a series it must not be made so high that the wave, when strong winds are blowing, cannot move some sand over it, otherwise the shore on the leeward side will be too low. The fact is that usually the coast line on the leeward side of the groin will be somewhat landward as compared to the coast line on the other side. If this difference becomes too great, the groin will not function efficiently. Figures 12 and 15-17, illustrate the difference on the two sides of a groin.

If the groin is high and extends far out in the water, for instance at a harbor, the supply of sand on the leeward side can then be completely arrested with the result that the coast line will retreat. However, there is a great difference in the influence of the waves in the advance of the coast line to the windward of the harbor and the coast line retreat on the leeward side. The deposit of material on the windward side of the harbor is a direct result of the transport ability of the waves. However, the erosion on the leeward side is an indirect result of the wave-attack and can be explained by the following observations.

In the beginning, nearly all coast material will be stopped by the harbor. Later, when so much material has been deposited that it encroaches in the entrance to the harbor, dredging will usually be required for navigation purposes and this will prevent the sand from being moved across the harbor to the other side. The wave which passes the deep water at the head of the jetty, and moves in the direction of the material moving power, will thus be without material when it reaches shoal water. Here the wave will pick up a quantity of sand proportional to the energy of the wave, and the coast will be eroded to a point A, (see Figure 18) which is determined by drawing the line S-A parallel to the direction of the material-moving power. Usually one cannot protect successfully the coast over the distance K to A, partly because groins cannot prevent the beach beyond their ends from being eroded, and partly because hardly any material is deposited. However, a revetment founded deep into the bottom will sometimes be suitable.

If one wants to avoid the shoaling of entrances to harbors one can build the harbors as island harbors, i.e. harbors that are connected to the mainland by a bridge. The first harbors of this kind (Arnager and Snogebaek, both on Bornholm) were constructed about 50 years ago and have been successful. The island harbors on Bornholm consist of a small basin as illustrated by the harbor of Arnager (Figure 19). The harbor of Hundested, which was first built as an island harbor became too big in proportion to its distance from the coast with the result that sand was deposited and today it is connected with the mainland.

The proposed formula for material-moving power is in agreement with the conditions observed over the entire Danish coast. Furthermore, the formula has also been tested on the coasts of the Russian Arctic Ocean and on the coasts of the Caspic Sea. The formula has furthermore shown good agreement on all coasts of the Baltic Sea. The formula is being taught at technical colleges in Russia and Germany.

Mr. Paulis Revelis, top engineer of the Latvian water building department in Riga, has written a thesis concerning the material-drift along the coasts of Latvia, and he has used Mr. Munch-Petersen's formula. The total coast line of Latvia is about 300 miles (500 kilometers), and about 270 kilometers of this is coast open to the Baltic. The remainder is open to the Bay of Riga. (The west coast of Jutland from Grenen to the border is about 400 kilometers.) The Latvian coast consists of soft material; sand, gravel and small stones with a clay-underlay. As there are several large harbors on the coast one will understand that the question of material-drift is of a great interest. Figure 20 shows the Latvian coast from Lithuania on the south to Esthonia on the north. The coast open to the Baltic is in the north and terminated by a rather sharp point, Kolkasrags, outside which there is to be found a sandbank more than 6 kilometers long, on the tip of which a lighthouse has been built. The conditions remind one of Skagen. The direction of the material-moving power is northwards with the exception of a short reach near Pape. In the Bay of Riga the material drift is to the south on the west side, but a little beyond Riga it turns north.

Figure 21 shows the vector-polygons for the area. Dotted lines are found in some of the polygons. This is done since the sea off Latvia is frozen at some places during part of the year and then no material drift occurs.

Conditions around the fishing harbor of Pape are interesting. (Figure 22.) Initially it was thought that the littoral movement, here as well as on the rest of the coast, was toward the north and consequently there was built a jetty on the south side of the exit to the Pape Sea. As the material movement is in fact toward the south, the jetty turned out to be a fence that gathered material in the exit. Later a jetty had to be built to the north. If vector-polyons had been constructed before the southern jetty was built, the mistake probably could have been avoided.

Figure 23 shows the harbor of Libaus (German Liepaja), which at one time was the most important naval harbor of the Russians and its dimensions had therefore to be great. The velocity of the wind here is greater than at other places on the coast, and during gales a content of 3% sand in the water has been measured. The littoral drift is slight, but as the vector-polygon shows the bottom erosion is great.

The conditions at Windau are more difficult (Figure 24). The vector-polygon shows that the direction of the material-moving power is very oblique, and as a result a very strong one-sided deposition occurs. The conditions remind one very strongly of the harbor of Gilleleije, but they are much greater in magnitude. The coast line has moved seaward about 700 meters and there is now about 3 meters of high dry land where there was 4 meters deep water before. Windward of the head of the jetty there is a sand bank and 200,000 cubic meters are deposited annually in the exit.

Figure 25 shows the point and the sandbank at Kolkasrags. The vector-polygon shows a strong sand drift toward the point on the west side, whereas on the east side there seems to be a balance between the material drift in the two directions. Two surveys of the sandbanks, made 10 years apart, show that an average of 50,000 cubic meters of sand is deposited annually. This sand comes from the south. From this we can compute the constant, c, in the formula. As the projection of the material-moving power on the coast line is 7.4, we get

$$c = \frac{50000}{7.4} = 6800$$

If we now go back to Windau where the projection is measured at 18.0 the littoral drift from the south should be:

$$18.0 \times 6800 = 132000 \text{ cubic meters}$$

which corresponds quite well with the fact that each year about

200.00 cubic meters of sand is deposited in the harbor entrance, must assume here that some sand comes from the north.

Mr. Revelis concludes his thesis with the following statement:

"When determining the movement of sand on our coasts by Professor Munch-Petersen's formula, we found at all locations a good correspondence with the conditions of nature, as these have been observed or found through measurements. The vector-polygons constructed according to the formula, and the projection of these polygons on the coast line, give a clear picture of the directions of the material movement, and through this a criterion for the orientation of preventive projects for harbors on sandy coasts."

From this we can see that Professor Munch-Petersen's explanation of the problem of material drift has met with great interest and understanding abroad, and that the essential parts are accepted. However, it cannot be denied that the formula is too little varied and is still in fact, under development, but it is, in a way, the duty of technicians to continue the study of this problem. It is to be hoped that it will be possible to improve the formula so that the material drift can be determined not only qualitatively but also quantitatively.

In conclusion I will mention that at the hydrological conference in Berlin which ended last Sunday a resolution was agreed upon which calls on the governments of all the Baltic states to investigate the question of sand drift. The governments are asked to make maps of the deposits on the ocean bottom from the coast line out to great depths, then to measure the quantities of the drifting sand and try to find formulas that agree with what they have found.

* * * * *

ERRATA

All copies of the above Bulletin, published October 1950, should be marked to indicate the following correction.

FIGURE 3

In the illustration of the dependence of material movement on wind direction the figure should have shown α as the abscissa and cos α as the ordinate.

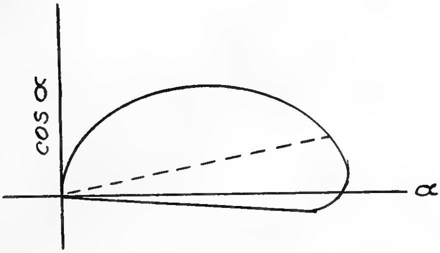


FIGURE 3

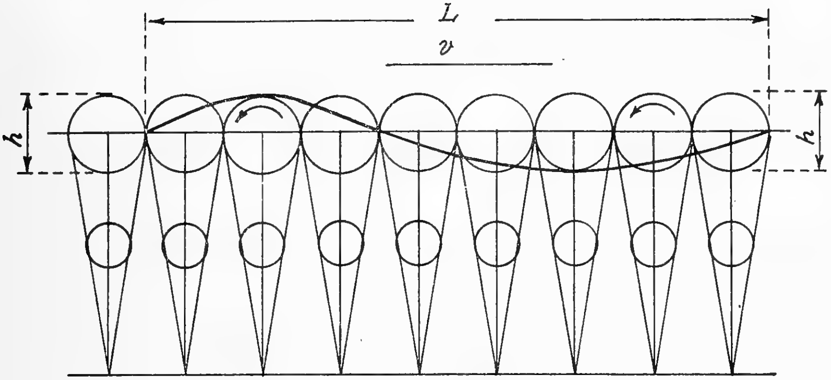


FIGURE 1. TROCHOIDAL WAVE.

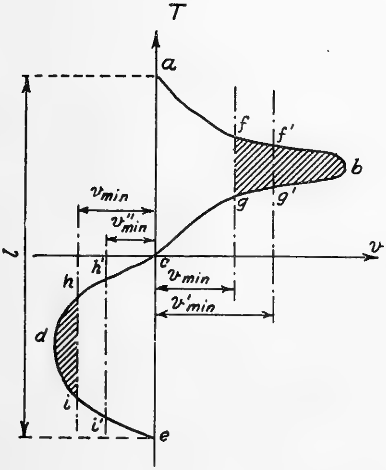


FIGURE 2. MOVEMENT AND SPEED OF WATER PARTICLES IN A WAVE.

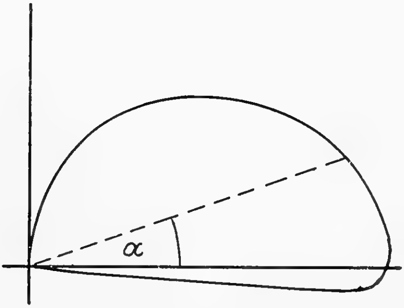


FIGURE 3. DEPENDENCE OF MATERIAL MOVEMENT ON WIND DIRECTION.

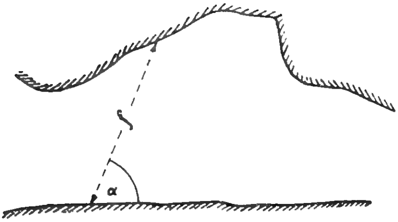


FIGURE 4. FETCH.

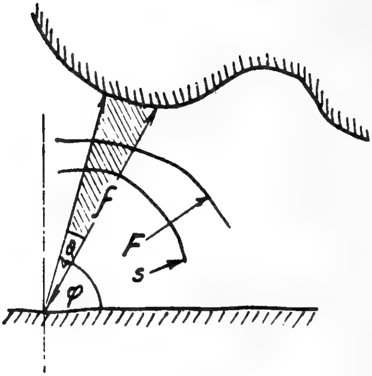


FIGURE 5. CURVES FOR FREQUENCY, F, AND SPEED, S, OF THE WIND.

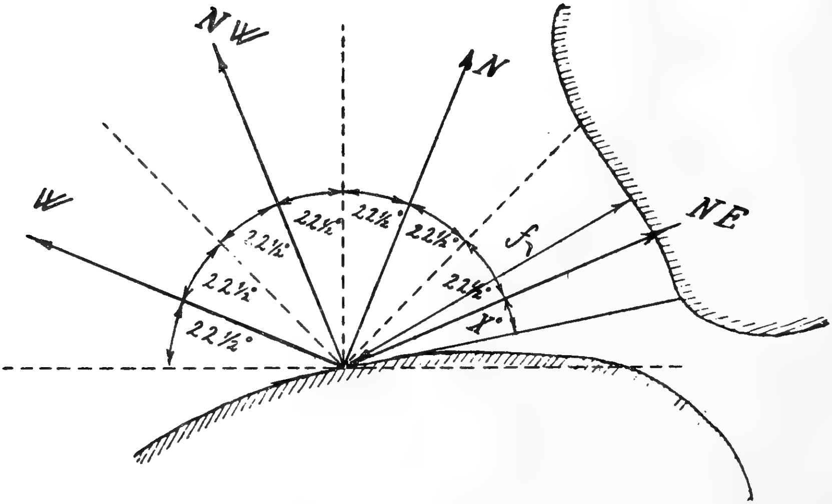


FIGURE 6. DIRECTIONAL WIND ROSE.

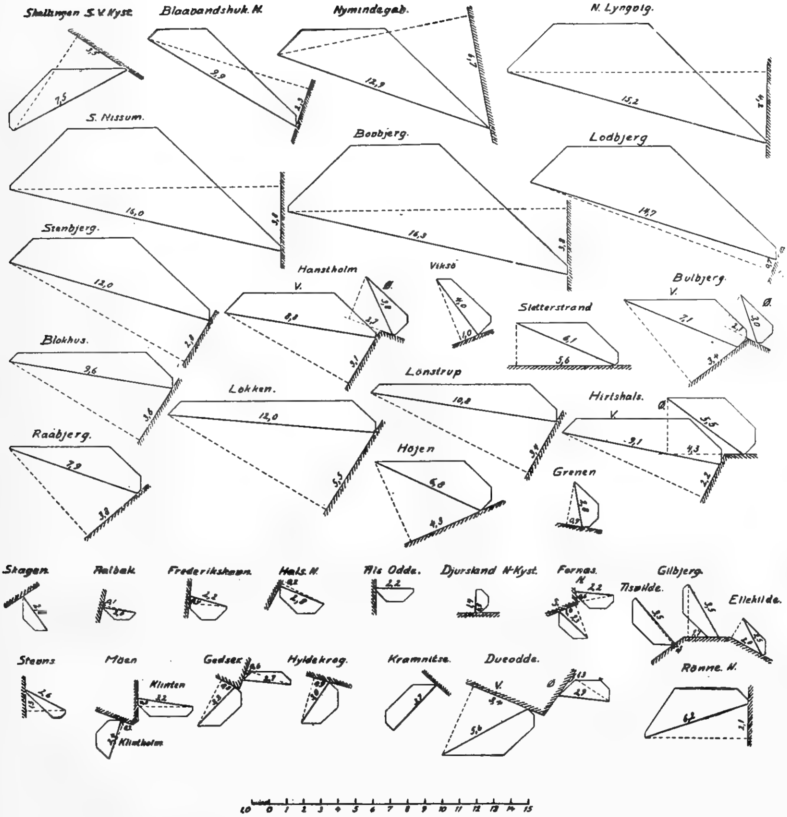


FIGURE 7. VECTOR POLYGONS AND MATERIAL MOVING POWER AT LOCATIONS ON THE DANISH COAST.

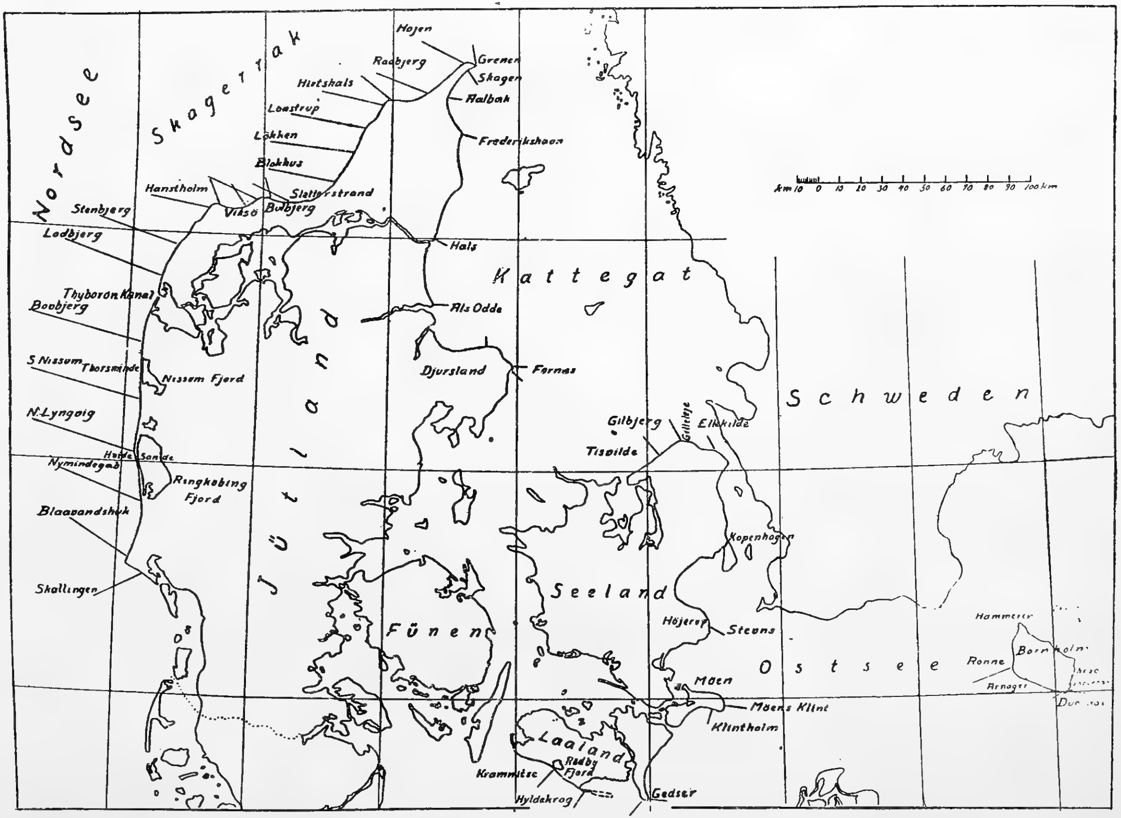


FIGURE 8. DIRECTION AND MAGNITUDE OF THE MATERIAL MOVING POWER ON THE DANISH COAST

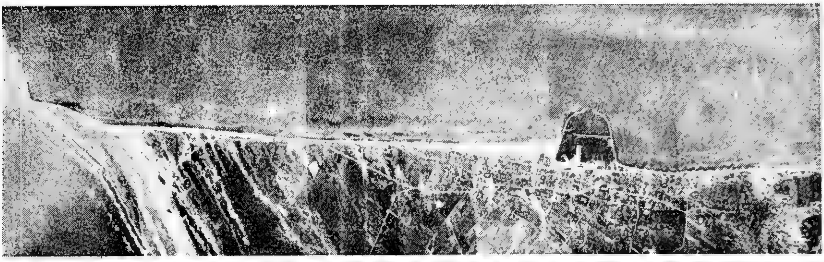


FIGURE 9. AERIAL PHOTO OF GRENEN AND SKAGEN.

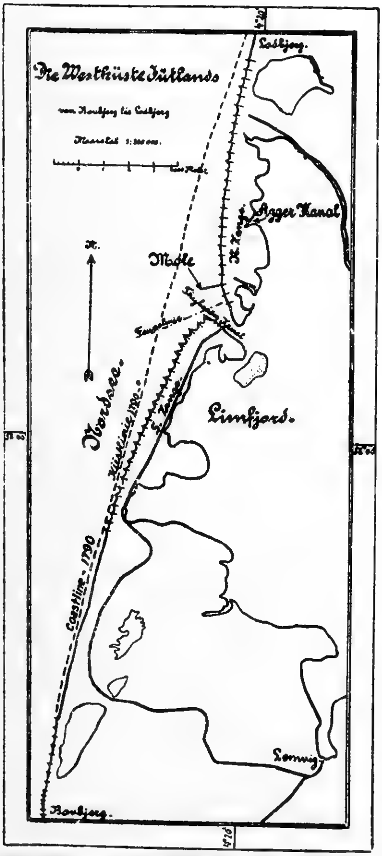


FIGURE 10. LIMFJORD TONGUES AT THYBORON.

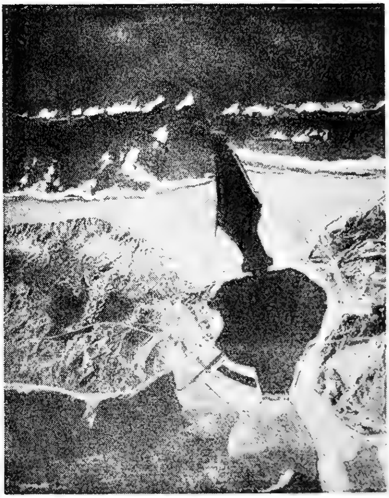


FIGURE 11. AERIAL PHOTO OF HVIDE SANDE.

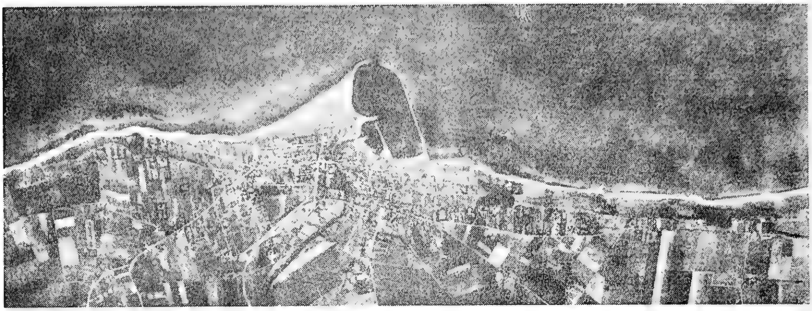


FIGURE 12. AERIAL PHOTO OF GILLELEJE HARBOR.

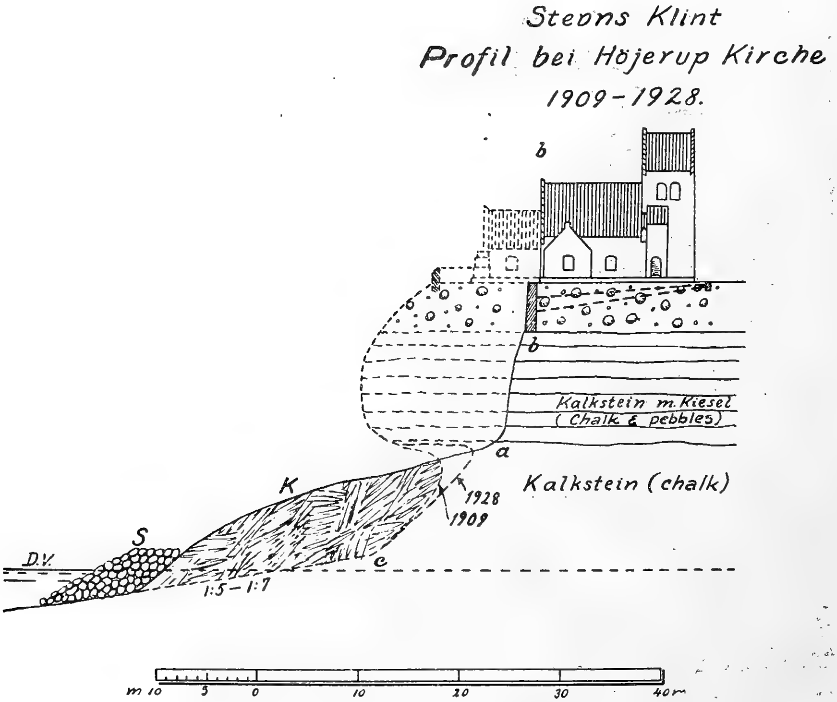


FIGURE 13. PROFILE OF STEVENS CLIFF AT HOJRUP CHURCH.

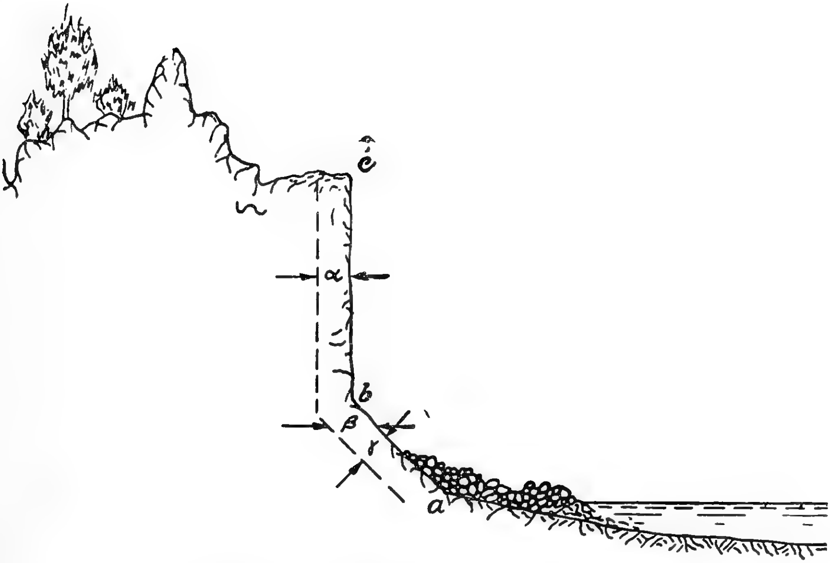


FIGURE 14. SCHEMATIC PROFILE OF MOEN CLIFF.

FIGURE 15. JETTY AT THYBORON.

FIGURE 16. COAST EROSION LEEWARD OF GROIN AT BOVBJERG.

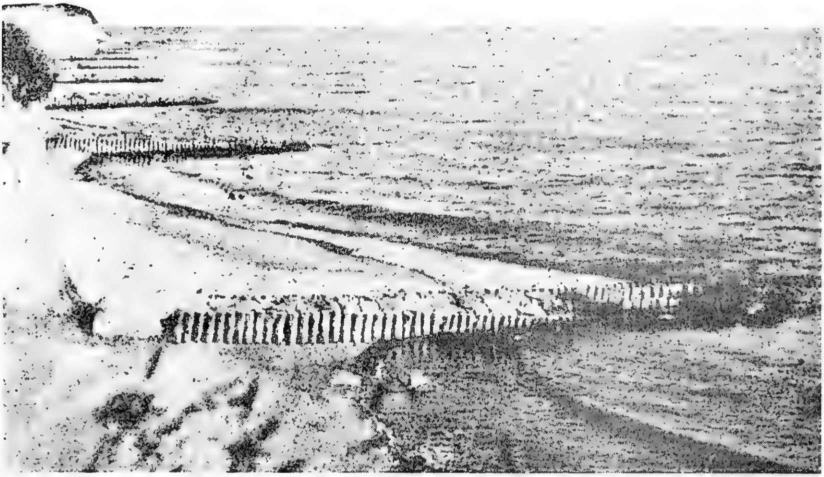


FIGURE 17. GROINS AT GEDSER.

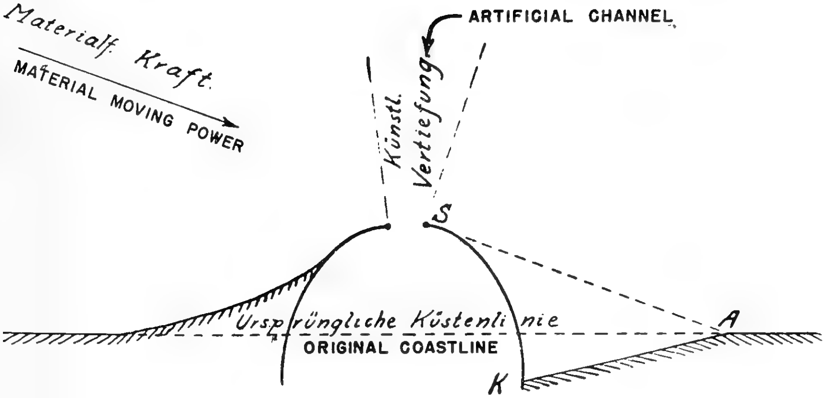
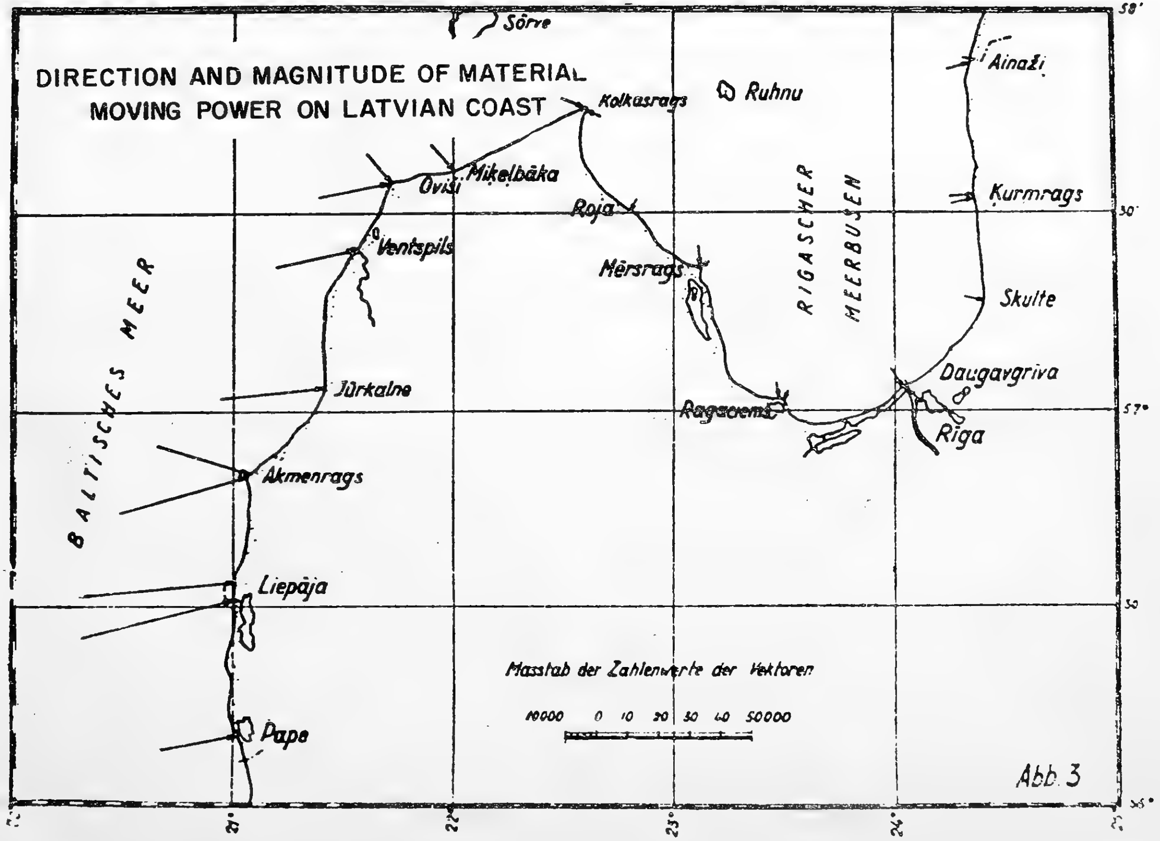


FIGURE 18. COASTLINE VARIATIONS AT A HARBOR ON A COAST WITH LITTORAL DRIFT

FIGURE 19. ARNAGER



DIRECTION AND MAGNITUDE OF MATERIAL MOVING POWER ON LATVIAN COAST

FIGURE 20

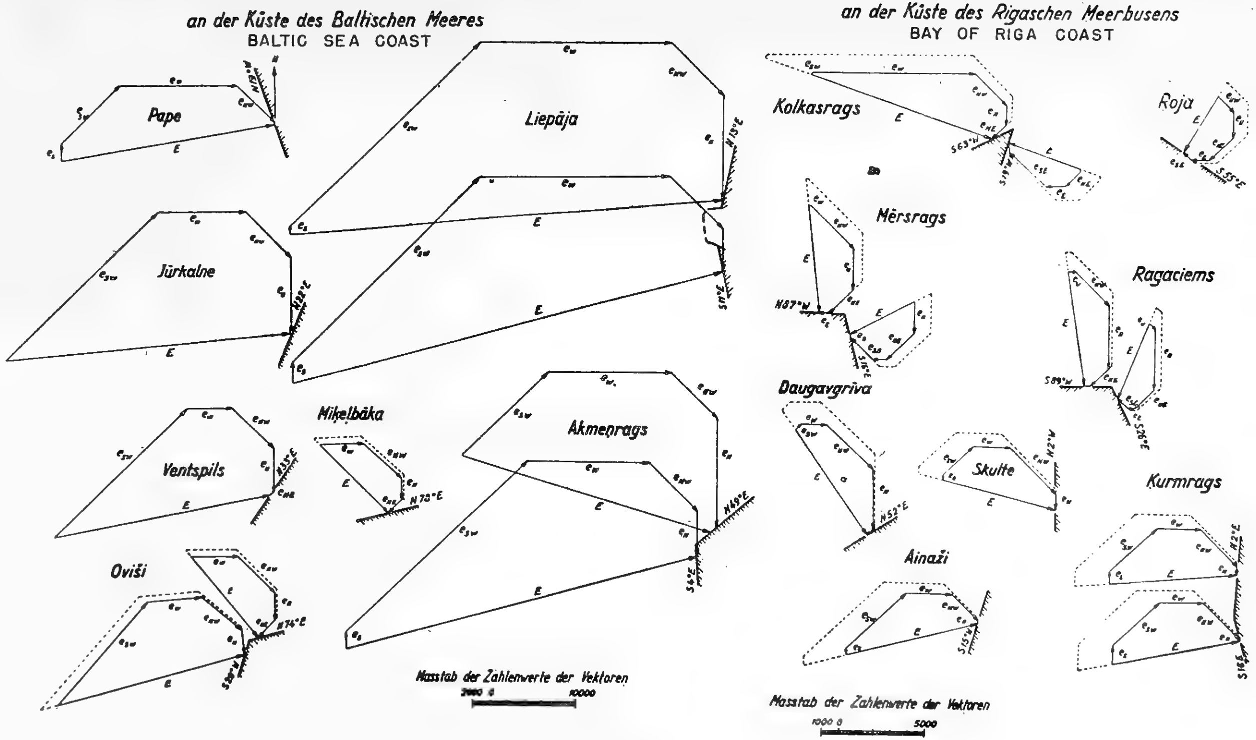


FIGURE 21. VECTOR POLYGONS AND MATERIAL MOVING POWER ON THE LATVIAN COAST

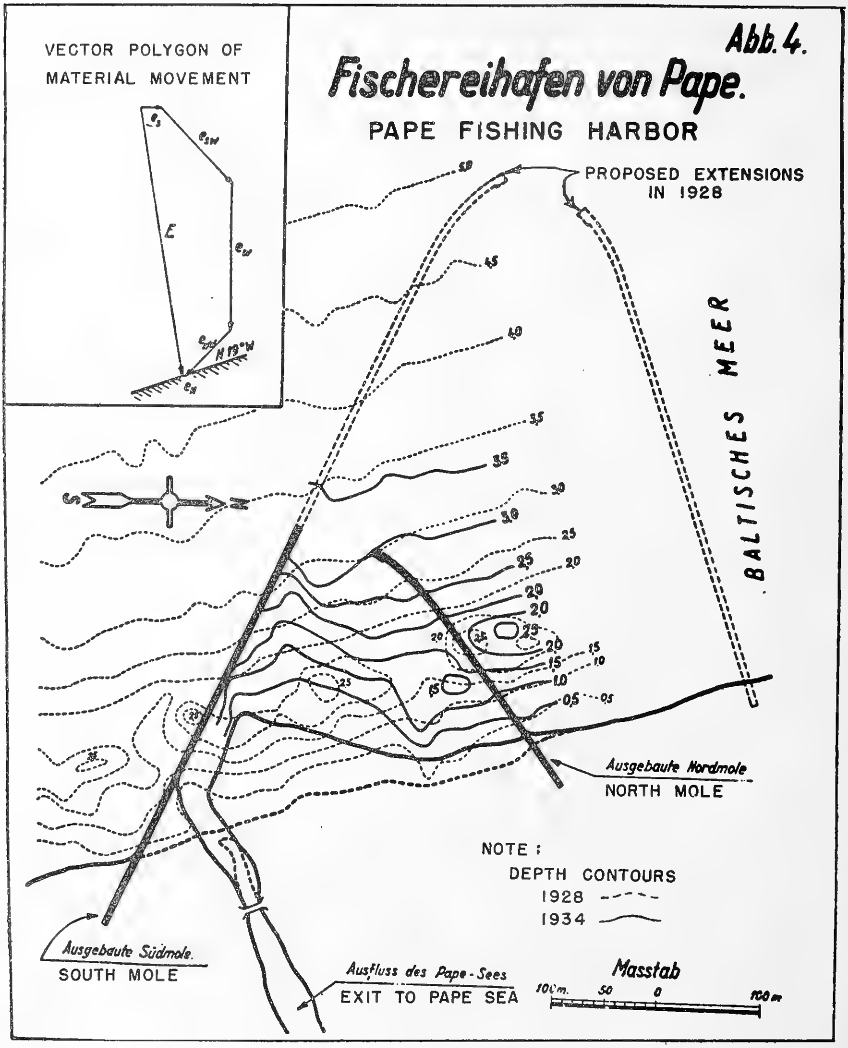

VECTOR POLYGON OF MATERIAL MOVEMENT
e_s
e_{sw}
E
e_w
e_{nw}
N 19° W
e_n
Abb. 4.
Fischereihafen von Pape.
PAPE FISHING HARBOR
PROPOSED EXTENSIONS IN 1928
BALTISCHES MEER
5.0
4.5
4.0
3.5
3.5
S
N
3.0
3.0
2.5
2.5
2.0
2.0
2.0
2.0
2.5
2.5
2.0
1.5
1.5
1.0
1.5
1.0
0.5
0.5
2.5
2.5
2.5
Ausgebaute Nordmole
NORTH MOLE
NOTE :
DEPTH CONTOURS
1928
1934
Ausgebaute Südmole.
SOUTH MOLE
Ausfluss des Pape-Sees
EXIT TO PAPE SEA
Masstab
100 m.
50
0
100 m

FIGURE 22

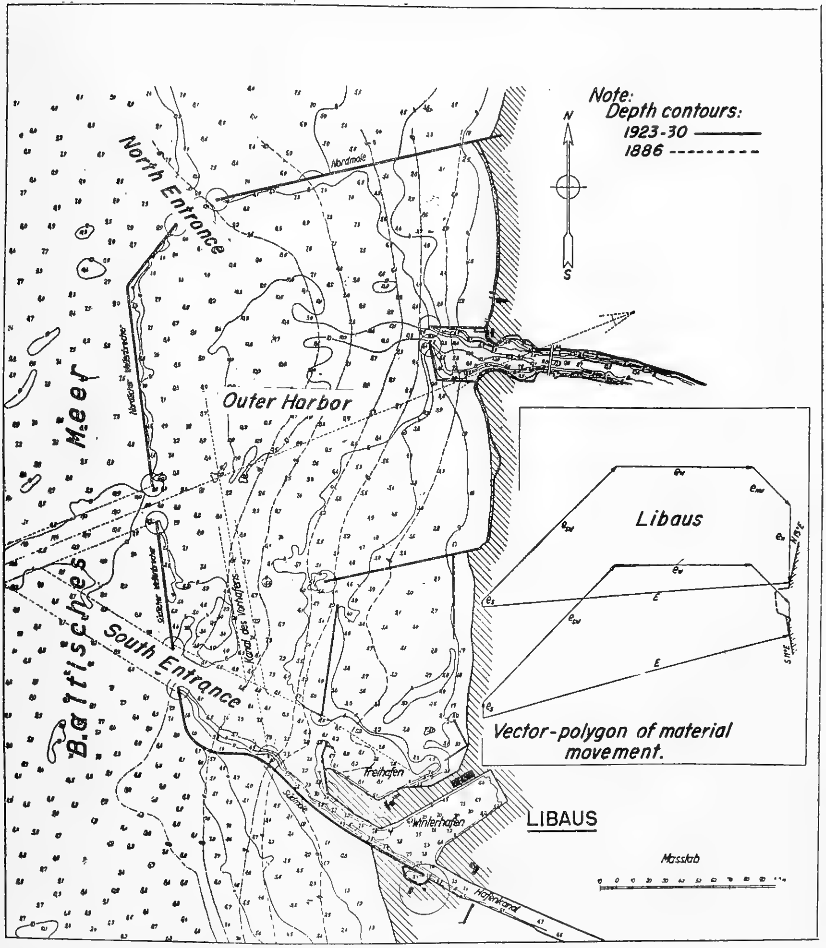


FIGURE 23. LIBAUS HARBOR.

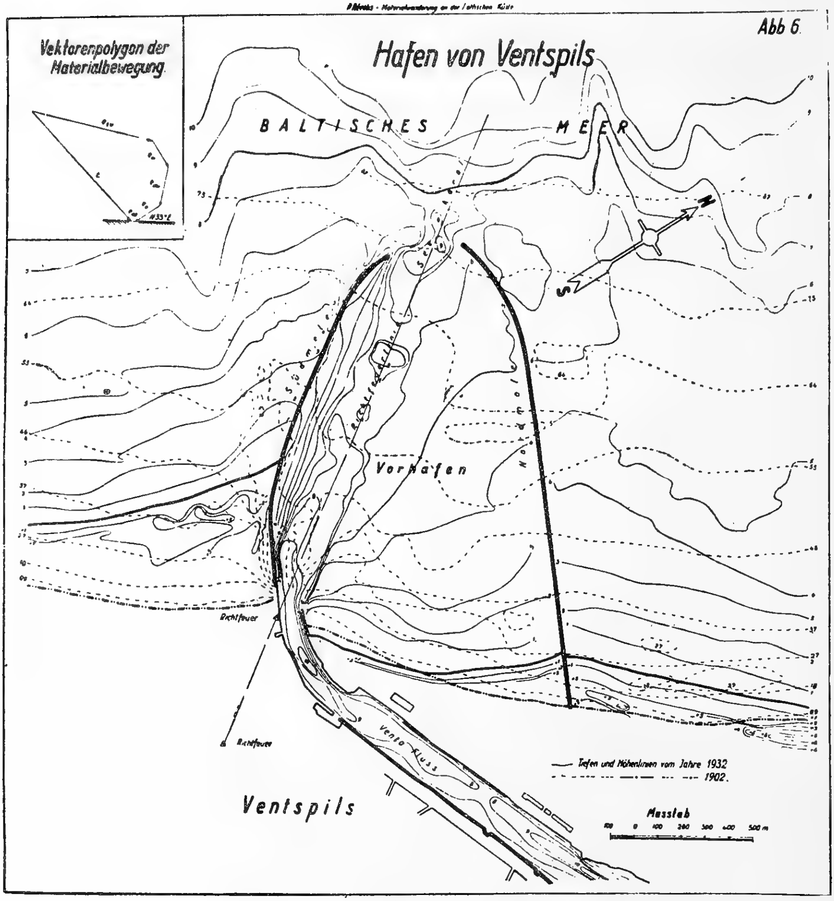


FIGURE 24. WINDAU HARBOR.

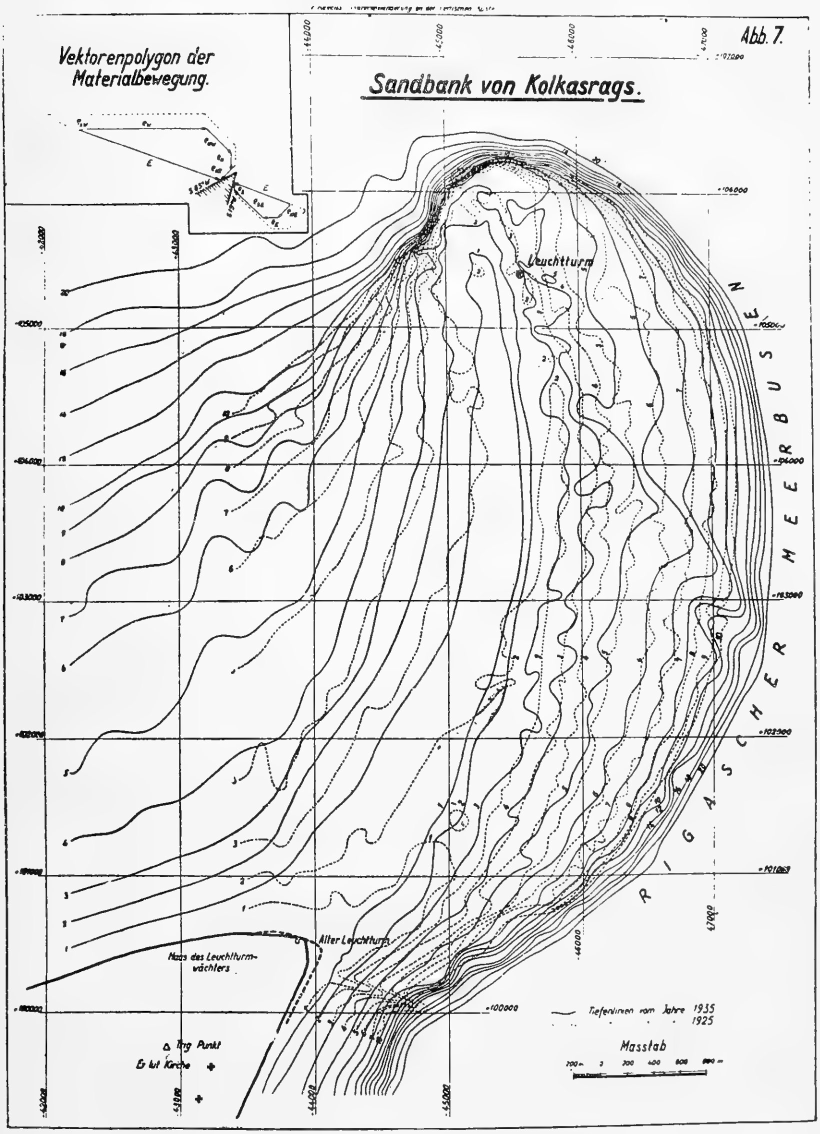


FIGURE 25. KOLKASRAGS SAND BANK

SURGING IN DEPOE BAY, OREGON

FOREWORD

The following description of surging in Depoe Bay first appeared in limited issue as Field Report No. 2, October 1947, Waves Project, University of California, Berkeley. The report was prepared by Mr. Willard Bascom for use by Waves Project personnel and would not ordinarily be available for public distribution. In view of increasing recognition of surging as an important harbor problem (e.g. Monterey, Grand Marais, Terminal Island) this description is now published with the permission of the University of California for the use of harbor engineers who encounter such problems.

Depoe Bay is an unusual little harbor on the rough Oregon coast about 90 miles south of the Columbia River. It is completely natural and easily accessible by highway. On a coast whose principal harbors are noted for bars which are impassable in heavy weather, Depoe Bay affords an all-weather small-craft shelter. Inside the bay, the shelter is complete and except for rare instances, like the occasion herein described, the surface shows only ripples. The entrance to this quiet harbor is through a short but torturous and narrow channel less than 40 feet wide at the entrance. Beyond the opening there is an outer bay bounded by two small headlands and somewhat protected by an underwater reef. This outer bay is surrounded by steep rocky walls from which the surf reflects. The bottom of the bay is covered with jagged rocks (indicated by irregular kelp beds). It offers no protection for boats but does assist in sheltering the channel slightly. The entrance looks suicidal small from the sea to those who are inexperienced and many a boat has headed back out after a quick look at the opening. No boats have ever been lost in attempting this entrance although here have been some narrow escapes, and each passage in heavy weather brings a gallery to the bridge above. At night this entrance is brilliantly lighted by floodlights. In the daytime the high arch bridge above offers a good landmark.

There is about 4 acres of water in Depoe Bay at full tide. The eastern shore of the bay is a gently shelving sandstone dip slope. On the western side the water is deep next to the shore. Most of the boats at Depoe Bay are commercial fishing boats less than 40 feet in length. Also, there are about eight sport fishing and tourist boats and a Coast Guard life boat.

From October 27 to October 31, 1947 an unusual surging condition existed at Depoe Bay. A general storm condition outside had caused about 30 small craft to seek shelter in the Bay. These boats were tied up about six deep along the southwest floating dock. Two Coast Guard boats were moored at the Coast Guard dock opposite the bay opening. One of these craft, on a rescue mission from Newport, was unable to return there because of the impassable condition of the Yawuina Bay bar. The seas outside (as obtained from the Heceta Head wave recorder) were as follows:

			Upper	
	Time	Period	H30%	H10%
10-27-47	0043	11.75"	4.7	6.2
	1234	12.5"	6.4	8.2
10-28-47	0038	15.0"	10.7	13.1
	0634	16.5	13.0	15.0
	1347	14.5	9.7	12.3
	1957	16.0	11.1	13.4
10-29-47	0046	15.0	8.5	10.7
10-29-47 to 10-30-47	0800 to 1200	Recorder unit taken to Depoe Bay and used as surge recorder.		
10-31-47	0945	9.5	10.2	13.1
	2133	10.5	6.5	8.1

Some slight surging is not unusual in Depoe Bay and on the morning of the 27th the boat movement was not considered to be exceptional. However, as the day progressed, the surge increased in intensity and by late afternoon extra bumpers and lines had been added to most of the craft. Three boats were moored on long lines near the center of the bay. During the evening many lines were parted, the dock ladders were smashed and light fishing gear was damaged. Flotsam in the bay entrance was carried back and forth by the surge and the larger pieces caused considerable anxiety among the boat owners until they were beached. It became increasingly evident that lines on the outer boat and on boats at critical points would not hold; the owners of these craft, therefore kept a full time watch for the next 48 hours. Engines were kept running; as each surg-front reached the boat they would run at full speed ahead for a few seconds to take the strain off of the lines. The two Coast Guard boats were in a particularly critical position at the entrance to the channel and on the larger surges they would ride up as much as two and one-half feet on the wave front.

At about 1600 on October 28, 1947, the field party of the Waves Project arrived at Depoe Bay and observed the surging. At intervals of 10 to 20 minutes a series of 3 to 5 waves (often with a definite front) about 40 seconds apart would come through the narrow opening into the bay. The larger of these wave fronts would actually be spilling and floating debris would surfboard on the crest. After passing the end of the channel, these waves would diffract into the bay losing most of their amplitude as they spread; however, enough of the horizontal component of movement remained to move the boats about and part mooring lines.

It was decided to try a spare Mark III pressure head (with the Heceta Head shore recorder) as a surge recorder. The normal felt damping on the air chamber of the Mark III was replaced with a single thickness of felt and some washers which cut the effective opening to about 3/16 inches. As the pressure head was to be placed in less than four feet of water (below MLLW) this was necessary so that the instrument would center and yet not follow the tides. It must be remembered that only the surge came through the bay opening and that the short period waves were mechanically damped out by the nature of the entrance. The head was placed at the mouth of the bay (as shown on the sketch map) at the point of maximum surge amplitude and conveniently located with respect to the recorder shack and power supply. It operated from about 1600 to 2200 on October 29 and from 0930 to 1200 on October 30. The installation was hastily put together and could admittedly be improved upon; however, it did give a record of the surge which had only been recorded visually before. The records and observations seem to indicate that (1) certain locations such as Depoe Bay may make ideal places for the installations of long period wave recorders because of their natural ability to damp out short period waves; (2) there is enough vertical movement in some surging to allow a vertical (pressure) type instrument to make a record; (3) surging and long period waves may be related to large local storms as well as to more distant storms; and (4) records of long period waves are much like those of short period waves--they seem to have maximum arrivals of 3-5 waves at correspondingly longer time intervals.

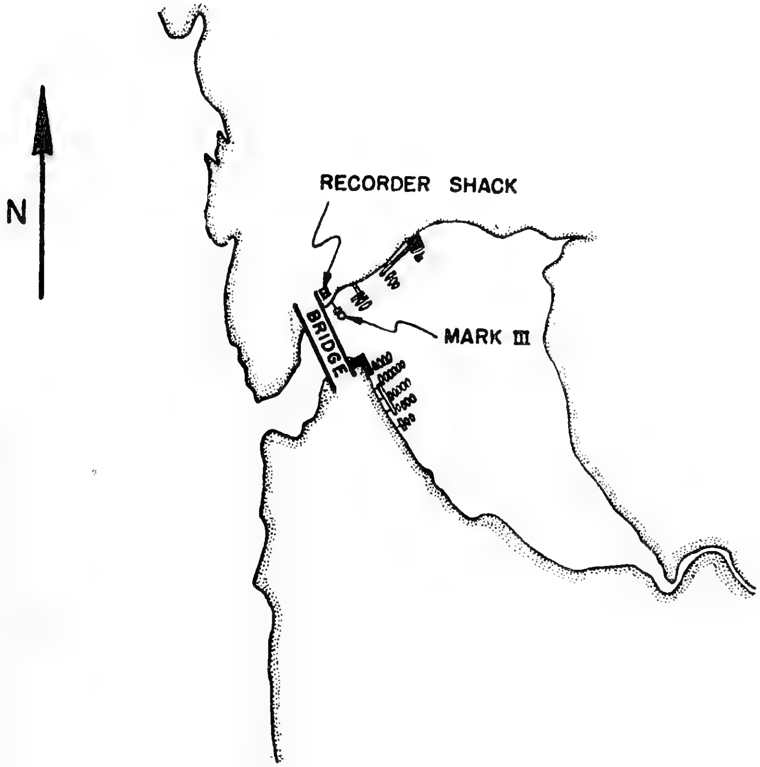
The results are inconclusive for the following reasons: (1) Since only one recorder unit was available there was no simultaneous record of ocean swell. (2) The maximum surging had died down before the recorder was operating. (3) A somewhat different type of instrument might have given a better response (by measuring the more intense horizontal component).

* * * * *

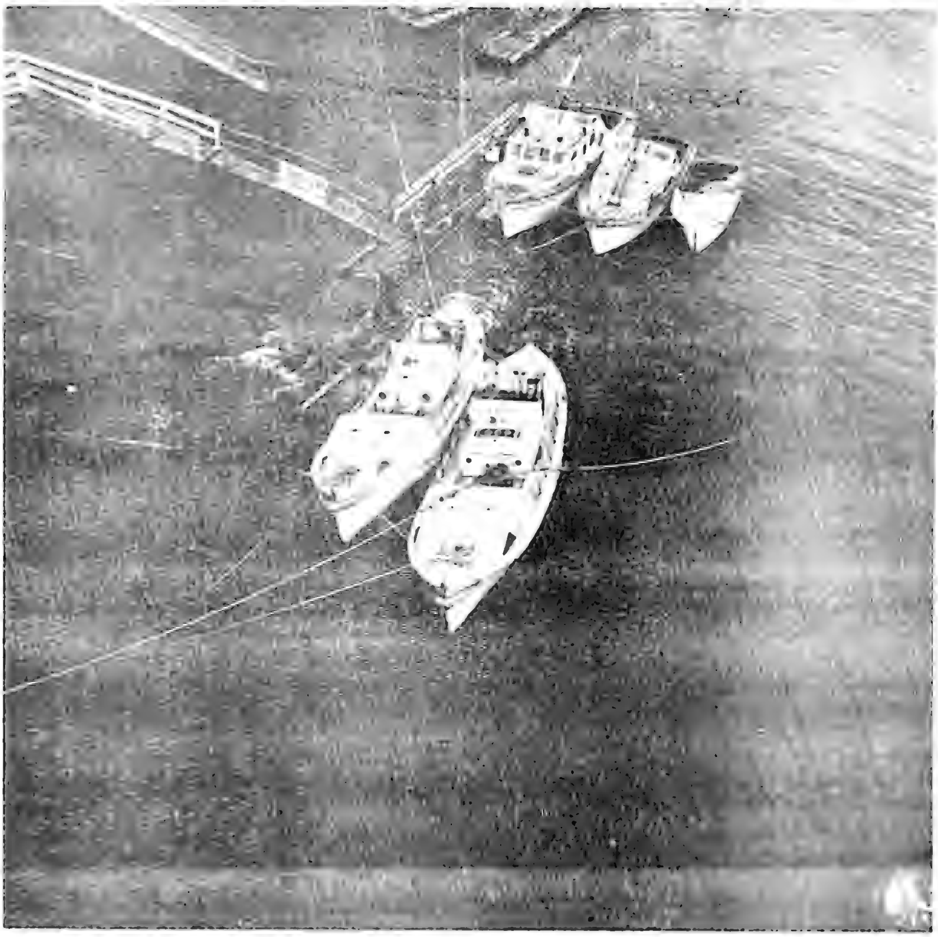
DEPOE BAY, OREGON

OCT. 29, 1947

DISPOSITION OF BOATS IN BAY



SCALE - ABOUT 250' = 1"
HYD. 3514 - 116 - 00

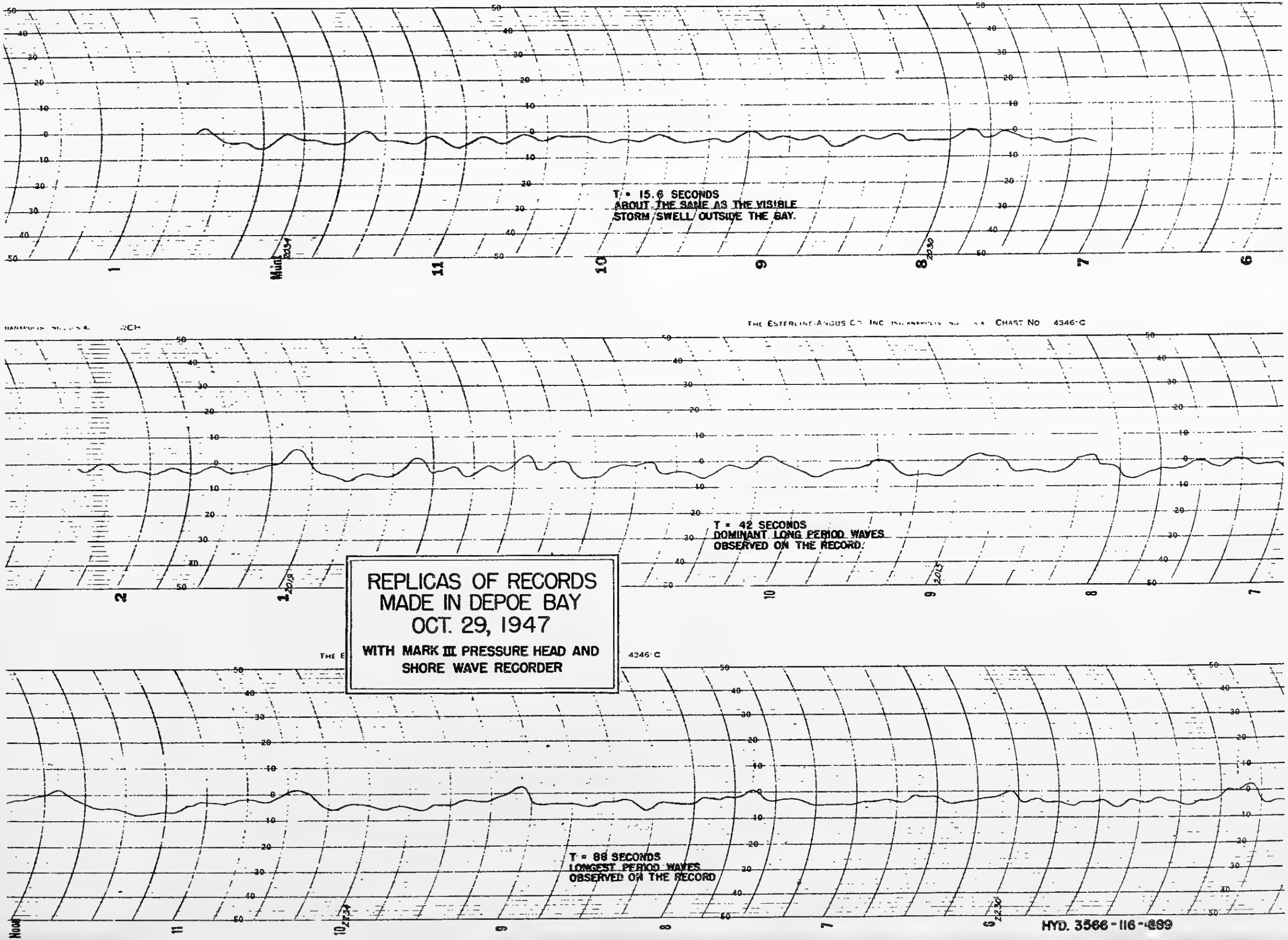


October 28,1947 Depoe Bay, Oregon 1600

During the worst of the surging it was necessary for the boats to be manned 48 hours continuously. Note the men at the wheels, the wake of the idling engines, the extra mooring lines, and the flotsam on the docks. On a maximum surge, these boats would ride up as much as two and one half feet.

Oct. 28, 1947

Large seas (estimated to be 20 feet high) breaking off Heceta Head Light. This shows the general appearance of the ocean at the time of maximum surging in Depoe Bay.



REPLICAS OF RECORDS
MADE IN DEPOE BAY
OCT. 29, 1947

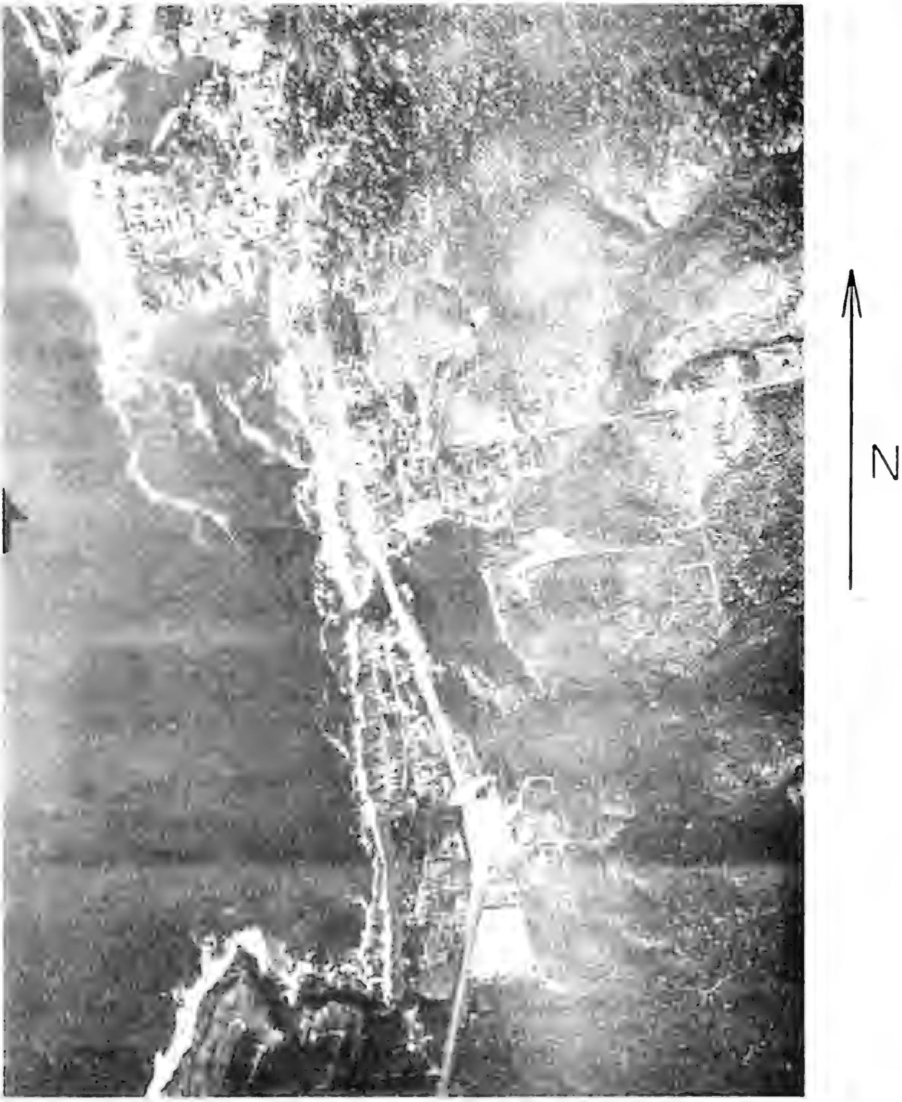
WITH MARK III PRESSURE HEAD AND
SHORE WAVE RECORDER

T = 15.6 SECONDS
ABOUT THE SAME AS THE VISIBLE
STORM SWELL OUTSIDE THE BAY.

T = 42 SECONDS
DOMINANT LONG PERIOD WAVES
OBSERVED ON THE RECORD.

T = 88 SECONDS
LONGEST PERIOD WAVES
OBSERVED ON THE RECORD

HYD. 3566-116-889



DEPOE BAY, OREGON K 17 - 12" 1 - 15 - 48

STEREOPHOTOGRAMMETRIC WAVE MEASUREMENT

FOREWORD

The following article was prepared for the Beach Erosion Board as Technical Report No. 5, Photogrammetric Division, Army Map Service, by Mr. Lewis A. Dickerson. The test was suggested in part by the work of Schumacher on the German "Meteor" Expedition, who, it is believed, was the first to demonstrate the possibilities of stereophotography in wave measurement. The work reported herein was performed in connection with a study of wave gauges which appeared as Technical Memorandum No. 6, Beach Erosion Board.

Purpose

This report covers the investigations and experiments conducted by this organization to determine the feasibility of measuring the heights of ocean waves by photogrammetric means. This work was undertaken upon the request of the Beach Erosion Board, Corps of Engineers.

Factual Data

Location of Test Area - The test area, which was set by the Beach Erosion Board, was that portion of the Atlantic Ocean off the end of the Steel Pier at Atlantic City, New Jersey. The end of the pier was used as the base from which to perform the photographic work. The photogrammetric instrument work was performed at the Army Map Service.

First Test

The first test photography was performed by the Beach Erosion Board. Photography was accomplished during the period 4-6 August 1947. Two Fairchild F-56 aerial cameras were used for the photography. These cameras had a focal length of 8½ inches (nominal) and exposed a film negative 7 x 7 inches. These cameras were not of a precision photogrammetric type.

One camera was mounted rigidly on each corner of the end of the pavilion on the Steel Pier as shown in Figure 1. The distance between the cameras was 99 feet. The cameras were pointed seaward with their optical axes approximately horizontal, parallel, and normal to the base line between them. The elevation of the cameras was not determined. The shutters of the two cameras were connected electrically so as to be tripped simultaneously. The exposures were made on Kodak Aerographic film using a shutter speed of 1/75 second and an aperture of F 4.5 with a yellow filter. Several exposures were made and checked for quality and image movement. From a qualitative standpoint, all were found satisfactory. The direction of travel of the waves was toward the cameras and approximately parallel to their optical axes. The overlapping photographic coverage of the area was triangular in shape as outlined in Figure 2, and contained a usable area of approximately 15,000 square feet.

From the overlapping film negatives described in the preceding paragraph, positives on glass plates were prepared by contact printing. These positives were used in a Zeiss stereoplanigraph equipped with normal angle, 21 cm. plotting cameras. Due to lack of precision in the taking cameras, lack of precise exterior orientation data, and lack of distinctive images in the overlapping photographs, relative orientation was found to be very difficult and absolute orientation was impossible. Although a stereoscopic model entirely free of significant parallax could not be obtained, it was evident that wave formations could be observed stereoscopically and that measurements could be carried out on these formations.

Second Test

Based upon the results of the first test described above, a second test was arranged by the Beach Erosion Board with a representative of the Army Map Service assisting in the photography. The photography for the second test was carried out at Atlantic City on 2 September 1947.

The cameras for the second test were two Zeiss P-21 precision aerial cameras having focal lengths of 204 mm. and exposing negatives 19 x 19 cm. The shutters were arranged for simultaneous tripping by electrical means and tested by photography of moving objects. The film magazines were removed from the cameras and replaced with special glass plate holders. The plates used were Eastman lantern slides, contrast emulsion, having a speed of approximately 10 Weston. The exposure time used was 1/75 second at an aperture of F 4.5, no filters being used.

The same general arrangement as in the first test was used in mounting the cameras on the Steel Pier but more precision was used in all settings. The two cameras were rigidly mounted 41.5 feet apart. The centers of the lenses were at the same elevation and 1.51 feet above the deck of the pier. The height of the pier deck was 20.0 feet above mean low water. Tide level at 11:15 A.M. on 2 September 1947, the time of the test exposures, was 2.0 feet above mean low water. The two cameras were pointed seaward with their optical axes parallel, horizontal, and perpendicular to the base line between them. This condition was obtained by sighting along the focal planes of the two cameras with a transit and by viewing the position of the horizon image on a ground glass in the focal plane. The horizon image passed through two opposite fiducial markers of each camera. To provide more definite images for relative orientation, three boats were maneuvered into the overlap area of the fields of view. The direction of travel of the wave fronts was toward the cameras and approximately parallel to their optical axes. The stereoscopic overlap from the two cameras was triangular in shape as shown in Figure 2 and provided a workable area of approximately 30,000 square feet.

The Zeiss stereoplanigraph was used again with the second test photography. It was equipped with plotting cameras set to a focal length of 204 mm. and matching the aerial cameras used for the photography. The original glass negatives which were exposed in the aerial cameras were oriented in the stereoplanigraph plotting cameras, no prints being made. Using the exterior orientation data obtained at the time of photography, the overlapping exposures were oriented in the instrument to form a stereoscopic model. As a result of the methods used in the photography, it was found that a stereoscopic model resulted without undue difficulty and only very slight residual parallaxes were encountered. The photographic quality of the model was good and confirmed the result of the first test, that wave formations could be observed and measurements could be made thereon. For work in the near part of stereoscopic model, a stereoplanigraph and coordinatograph scale of 1:100 was used. For the more distant parts of the model, a scale of 1:200 was used for the stereoplanigraph and the scale of 1:100 was retained for the coordinatograph.

Following orientation of the stereoscopic model, an attempt was made to "contour" the wave formations which was the result originally contemplated. Contouring was found to be extremely slow and difficult and of little value once obtained due to the irregular nature of the wave formations.

After the attempt at "contouring" the wave formations, a method of measuring spot elevations was adopted. Elevations were measured throughout the area of the usable overlap of the exposures, these measurements being taken at arbitrary locations and at horizontal intervals of approximately eight feet. The elevation values were measured to 0.1 foot and were referred to the tide level at the time of photography as a zero datum. The results of these measurements are as shown in Figure 2. No difficulty was encountered in making these measurements and it is felt that they are accurate to within 0.1 foot although no check of this accuracy was possible.

Discussion

An examination of the measurements recorded in Figure 2 shows that some 90% are positive values, that is higher than tide level at the time of photography, and that the values range between -1.2 feet and + 3.4 feet. These results tend to indicate that measurements were not secured in the bottom of the troughs. It is believed that this is the case and that it is due to "masking" of the troughs by the crests of the waves due to the very oblique angle at which they were photographed. This condition was noted during the attempt at contouring and is believed to be part of the reason for the complications encountered. As a result, measurements were not secured in the troughs and thus the wave heights could be determined only when data are available to determine the height of the cameras above tide level at the time of photography and the relationship between troughs, crests, and tide level. This would not be likely in any application of the method.

Although the method tested, and as described above, did not permit the determination of wave heights, it is still possible that this can be done photogrammetrically. Two alternatives present themselves. The first is an arrangement similar to the one described in the above tests but arranged so that the camera axes are pointed in a direction of travel of the waves. This should permit measurements in the bottom of the troughs and on the crests of the waves. It should be noted, however, that in this system the mounting of the cameras must be such that they retain a fixed and known relationship to each other. For example, they could not be mounted on a floating vessel unless attached to a rigid framework which in turn is not rigidly attached to the vessel. The second alternative is the taking of vertical photographs much in the same manner as for topographic mapping. Due to the low altitudes involved, a lighter than air craft or a helicopter would be necessary for this purpose in order to secure the slow air speeds necessary. Two cameras would have to be mounted so as to expose simultaneous and overlapping photographs. The mountings of the cameras would not require extreme rigidity although it would be necessary to know the distance between cameras to an accuracy of about 0.5 inch. The flying height could be between 100 and 500 feet, depending upon what distance the cameras are mounted apart.

Conclusions

From the tests described above and the brief discussion, it is concluded that:

With the methods used in the test it is not possible to determine the heights of ocean waves.

Photographs of wave formations can be made so that measurements of sufficient precision can be made by photogrammetric means.

To be of value for wave height determination, the photographs must be exposed so as to record both the bottoms of the troughs as well as the crests of the waves.

That "contouring" of wave formations is extremely difficult and of little value.

FIGURE I. CAMERA INSTALLATION.

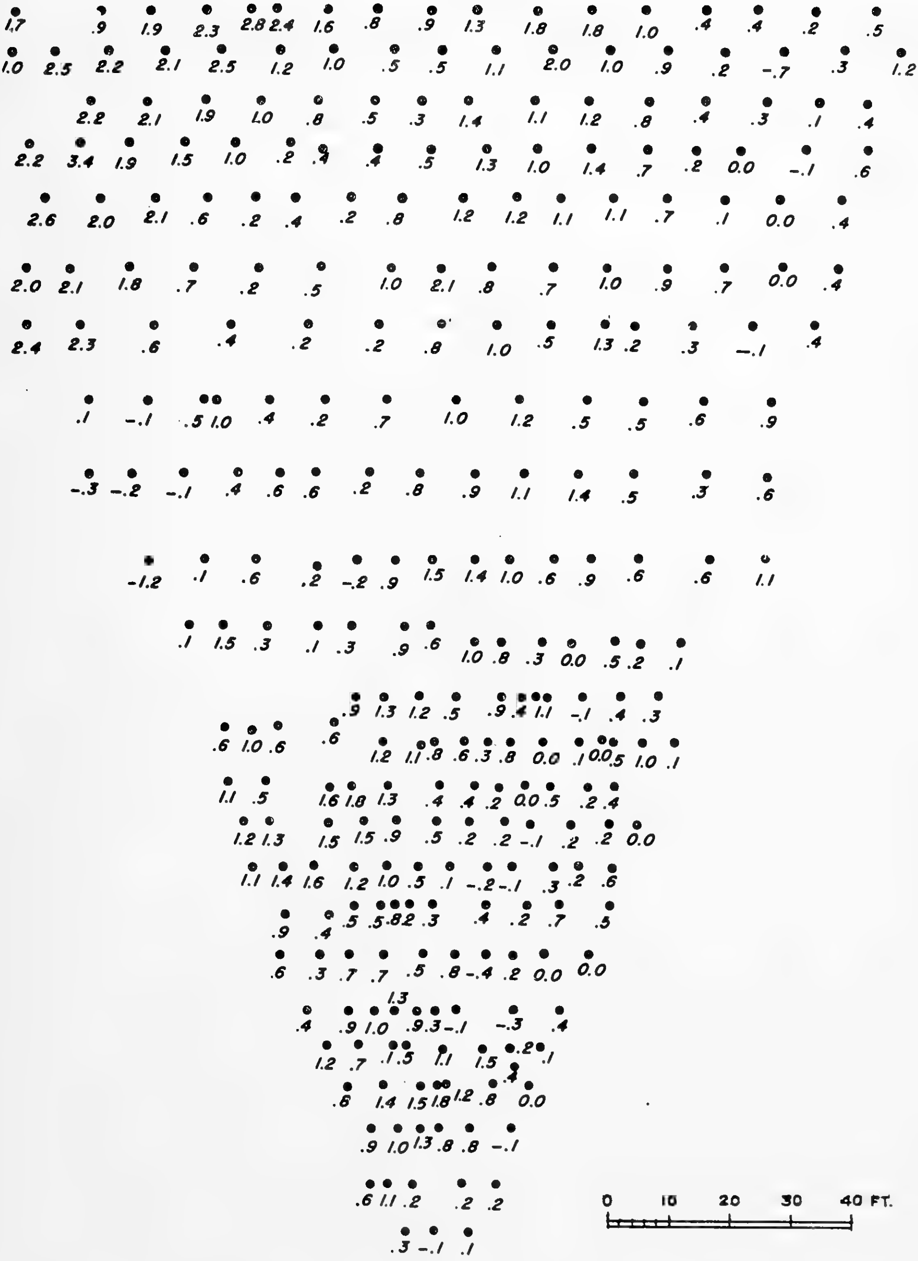


FIGURE 2. PLOT SHOWING LOCATION AND ELEVATION OF WATER SURFACE AT TIME OF PHOTOGRAPH IN FEET ABOVE TIDE LEVEL.

BEACH EROSION STUDIES

The principal types of beach erosion reports of studies at specific localities are the following:

a. Cooperative studies (authorization by the Chief of Engineers in accordance with Section 2, River and Harbor Act approved on 3 July 1930).

b. Preliminary examinations and surveys (Congressional authorization by reference to locality by name).

c. Reports on shore line changes which may result from improvements of the entrances at the mouths of rivers and inlets (Section 5, Public Law No. 409, 74th Congress).

d. Reports on shore protection of Federal property (authorization by the Chief of Engineers).

Of these types of studies, cooperative beach erosion studies are the type most frequently made when a community desires investigation of its particular problem. As these studies have, consequently greater general interest, information concerning studies of specific localities contained in these quarterly bulletins will be confined to cooperative studies. Information about other types of studies can be obtained upon inquiry to this office.

Cooperative studies of beach erosion are studies made by the Corps of Engineers in cooperation with appropriate agencies of the various States by authority of Section 2, of the River and Harbor Act approved 3 July 1930. By executive ruling the cost of these studies is divided equally between the United States and the cooperating agency. Information concerning the initiation of a cooperative study may be obtained from any District Engineer of the Corps of Engineers. After a report on a cooperative study has been transmitted to Congress, a summary thereof is included in the next issue of this bulletin. A list of cooperative studies now in progress follows:

COOPERATIVE BEACH EROSION STUDIES IN PROGRESS

NEW HAMPSHIRE

HAMPTON BEACH. Cooperative Agency: New Hampshire Shore and Beach Preservation and Development Commission.

Problem: To determine the best method of preventing further erosion and of stabilizing and restoring the beaches, also to determine the extent of Federal aid in any proposed plans of protection and improvement.

MASSACHUSETTS

PEMBERTON POINT TO GURNET POINT. Cooperating Agency: Department of Public Works, Commonwealth of Massachusetts.

Problem: To determine the best methods of shore protection, prevention of further erosion and improvement of beaches, and specifically to develop plans for protection of Crescent Beach, The Glades, North Scituate Beach and Brant Rock.

CONNECTICUT

STATE OF CONNECTICUT. Cooperating Agency: State of Connecticut (Acting through the Flood Control and Water Policy Commission).

Problem: To determine the most suitable methods of stabilizing and improving the shore line. Sections of the coast will be studied in order of priority as requested by the cooperating agency until the entire coast is included.

NEW YORK

JONES BEACH. Cooperating Agency: Long Island State Parks Commission

Problem: To determine behavior of the shore during a 12-month cycle, including study of littoral drift, wave refraction and movement of artificial sand supply between Fire Island and Jones Inlets.

NEW JERSEY

OCEAN CITY. Cooperating Agency: City of Ocean City.

Problem: To determine the causes of erosion or accretion and the effect of previously constructed groins and structures, and to recommend remedial measures to prevent further erosion and to restore the beaches.

VIRGINIA

VIRGINIA BEACH. Cooperating Agency: Town of Virginia Beach.

Problem: To determine the methods for the improvement and protection of the beach and existing concrete sea wall.

SOUTH CAROLINA

STATE OF SOUTH CAROLINA. Cooperating Agency: State Highway Department.

Problem: To determine the best method of preventing erosion, stabilizing and improving the beaches.

FLORIDA

PINELLAS COUNTY. Cooperating Agency: Board of County Commissioners.

Problem: To determine the best methods of preventing further recession of the gulf shore line, stabilizing the gulf shores of certain passes, and widening certain beaches within the study area.

LOUISIANA

LAKE PONTCHARTRAIN. Cooperating Agency: Board of Levee Commissioners, Orleans Levee District.

Problem: To determine the best method of effecting necessary repairs to the existing sea wall and the desirability of building an artificial beach to provide protection to the wall and also to provide additional recreational beach area.

TEXAS

GALVESTON COUNTY. Cooperating Agency: County Commissioners Court of Galveston County.

Problem: To determine the best method of providing a permanent beach and the necessity for further protection or extending the sea wall within the area bounded by the Galveston South Jetty and Eight Mile Road.

To determine the most practicable and economical method of preventing or retarding bank recession on the shore of Galveston Bay between April Fool Point and Kemah.

CALIFORNIA

STATE OF CALIFORNIA. Cooperating Agency: Division of Beaches and Parks, State of California.

Problem: To conduct a study of the problems of beach erosion and shore protection along the entire coast of California. The initial studies are to be made in the Ventura-Port Huneme area, the Santa Monica area and the Santa Cruz area.

WISCONSIN

RACINE COUNTY. Cooperating Agency: Racine County.

Problem: To prevent erosion by waves and currents, and to determine the most suitable methods for protection, restoration and development of beaches.

KENOSHA. Cooperating Agency: City of Kenosha.

Problem: To determine the best method of shore protection and beach erosion control.

OHIO

STATE OF OHIO. Cooperating Agency: State of Ohio (Acting through the Superintendent of Public Works).

Problem: To determine the best method of preventing further erosion of and stabilizing existing beaches, of restoring and creating new beaches, and appropriate locations for the development of recreational facilities by the State along the Lake Erie shore line.

TERRITORY OF HAWAII

WAIKIKI BEACH;)
WAIMEA & HANAPEPE, KAUAI.) Cooperating Agency: Board of Harbor Commissioners, Territory of Hawaii.

Problem: To determine the most suitable method of preventing erosion, and of increasing the usable recreationsl beach area, and to determine the extent of Federal aid in effecting the desired improvement.

* * * * * *

BEACH EROSION LITERATURE

There are listed below some recent acquisitions to the Board's library which are considered to be of general interest. Copies of these publications can be obtained on 30-day loan by interested official agencies.

"An Instrument for Recording Continuously the Salinity, Temperature, and Depth of Sea Water," A. W. Jacobson, AIEE Transactions, 1948.

This paper describes a practical salinity and temperature recording instrument. This instrument has been operated successfully in recording hydrographic data. It has been applied particularly for inshore surveys in shoal water and in ocean areas where its accuracy of 0.2 degrees Fahrenheit and $0.3^{o}/00$ is adequate. Its time constant of one-half second permits continuous records of temperature and salinity to be made from a moving vessel, or while measuring elements are being lowered vertically.

"Tourmaline Pressure Gauges," Clifford Frondel, American Mineralogist, Vol. 33, Jan-Feb. 1948.

This paper describes in detail the design and construction of the gauges. The gauges comprise thin-discs of tourmaline from ½-inch up to several inches in diameter cut perpendicular to the c axis and used in singly or in stacks. The piezoelectric response of the tourmaline is amplified and recorded on associated electronic equipment and both the magnitude of the peak pressure and the wave form deduced thereby. The supply, price and factors determining the usability of raw tourmaline for the purpose is also discussed.

"International Hydrographic Review," Vol. XXVI, No. 2, November 1949.

This publication presents status of several radio, navigation, and positioning systems as developed in the United States and foreign countries.

"An Instrument for Recording Ultra Low Frequency Ocean Waves," W. H. Munk, October 1948.

This article discusses an instrument designed to measure low amplitude waves whose frequencies fall between those of the wind-generated ocean swell and those of the astronomic tides.

"Water Waves Over A Sloping Bottom," E. Isaacson, Communications on Pure and Applied Mathematics, March 1950.

This paper presents a mathematical study of progressing gravity waves traveling over a plane sloping bottom with crests parallel to the bottom contours. The derivation handles a wide range of bottom slopes.

"Production and Study of Ocean Waves in the Laboratory, F. J. Sines, The Dock and Harbour Authority, Jan. 1950.

The article gives a brief description of a new type wave machine, constructed at the University of Washington which produces waves that are of true form as they leave the source. By setting the machine to conform with theoretical wave properties, the height, length, and orbital particle movement are controlled. The new wave machine duplicates these theoretical wave properties with a flexible stainless-steel plate perpendicular to the direction of travel. As particle rotation is introduced at the source, the wave attains its true form as it leaves the machine.

"An Electrical Method for Measuring Air Concentration in Flowing Air-Water Mixtures, Owen P. Lanb and John M. Killen, March 1950.

An electrical measurement of air concentration was chosen after examining possible mechanical, chemical, and magnetic methods. The method consists basically of a measurement of the difference between the conductivity of a mixture of air and water and conductivity of water alone.