CHAPTER 11

MEASURES AGAINST EROSION AT GROINS AND JETTIES

Technical University of Denmark
Copenhagen, Denmark
Per Brunn

Abstract. One of the difficult problems on a littoral drift coast is the erosion on the leeside of groins and jetties. This paper will deal with the problem giving special consideration to the conditions on the Danish North Sea coast where many interesting problems of littoral drift and coastal protection are found. They are discussed as an introduction to the main part of the paper which is principally concerned with leeside erosion and measures for its prevention.

A. THE DANISH NORTH SEA COAST

SITUATION

The Danish North Sea coast is the west coast of the peninsula Jutland, the Danish mainland. Fig. 1 shows the situation of this coast. From a point in the middle at Thyboroen lines are drawn NW, W and SW, and the distances to the respective coasts in England are indicated. It can be seen that there is free communication to the Atlantic Ocean from the northwest. The depths (metres) show that the North Sea is shallow; depths greater than 100 metres are found only in the northeast part of the Skager Rack, where there is a system of through-faults off the Norwegian coast.

GEOLOGY, WIND AND WAVES

The peninsula of Jutland is built of Pleistocene deposits, chiefly glacial drift originating from three different glaciations (boulder clay, meltwater-sand and clay), but in the northernmost part postglacial "marine-foreland" accumulations occur.

The west coast is shown in detail in Fig. 2. It is composed of weak material, mainly sand, and thus presents a smooth and plain shoreline, shaped by the action of the waves and currents. The most frequent and strongest winds are those from the western quadrant and they have consequently shaped the coast. Speaking of the southern part of the coast, a characteristic gale will start from the south-west with a force 4-6 Beaufort and in the course of 12 or 14 hours it will, with increasing force, 6-9 Beaufort, veer to the west or the northwest and continue there for two to three days or more. The water often begins to rise when the barometer falls, even before the gale has started because water from the English Channel is forced into the North Sea through the Straits of Dover. When the wind has turned to the north-west, the water falls. The tidal range at Esbjerg is about 4½-ft., at Hvide Sande (White Sands) about 2-ft., at Thyboroen about 16-in., and at the Scaw about 10-in. Heavy westerly gales may cause a high-water of 10 to 13-ft. at Esbjerg, 7 to 8-ft. at Hvide Sande, 5 to 6-ft. at Thyboroen and 3 to 4-ft. at the Scaw. The wave height is greatest at the North Sea coast,

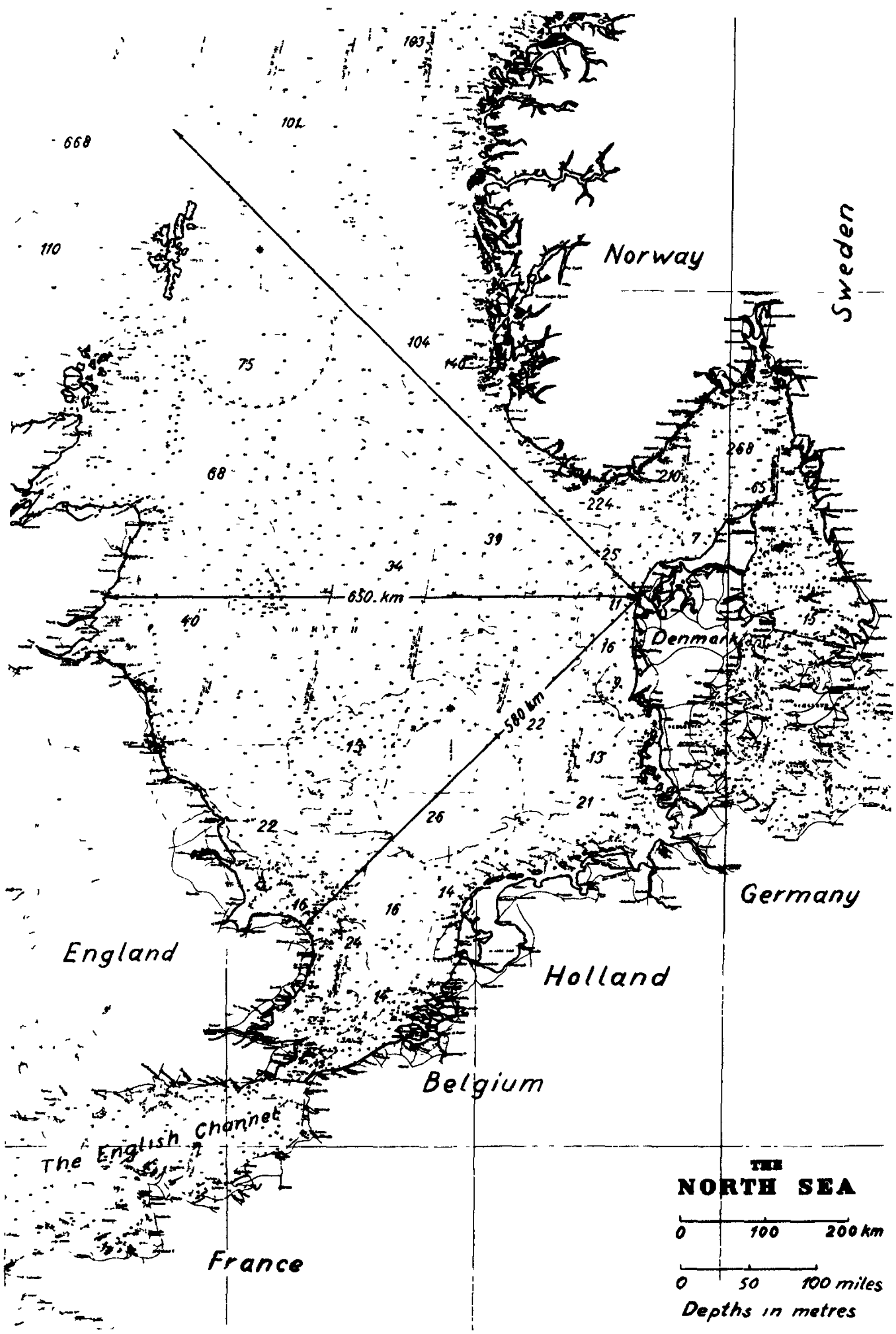

Fig. 1. The North Sea.

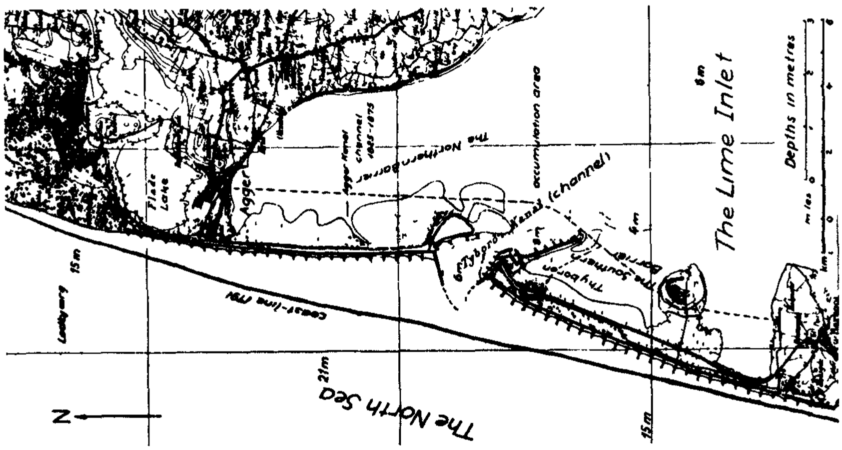

Fig. 3. The Lime Inlet Barriers.

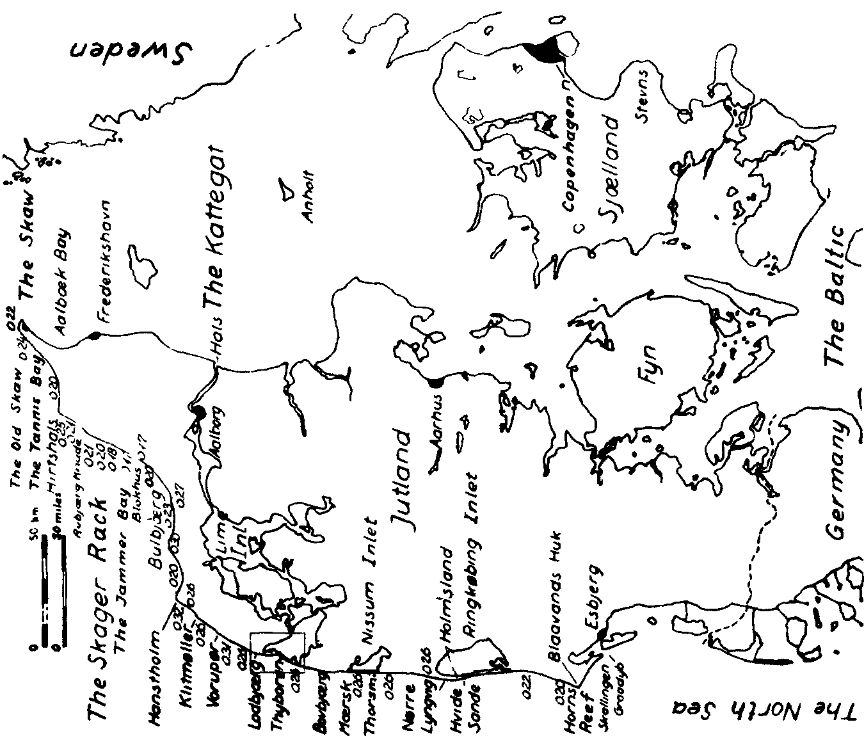

Fig. 2. Denmark.

about 10 to 12-ft. during heavy gales; the wave length is about 300-ft.

On that part of the coast between Blaavands Huk and Lodbjerg, which takes an almost north-south direction, we find the inlets closed by barriers, (the Ringkoebing Inlet, the Nissum Inlet and the Lime Inlet, cf. the New Jersey coast. Between Lodbjerg and the Scaw the coast is, as it were, suspended from hooks formed by headlands: Hanstholm (chalk and moraine, 160-ft), Bulbjerg (chalk, 100-ft), Hirtshals (Moraine, 100-ft.), and a few smaller headlands. Between these the coast is smooth and plain.

The height of the west coast is generally 10 to 20-ft. above mean water level, but the height of the barriers is only 3 to 6-ft., and, therefore, they must be protected from the sea either by dunes or by artificial dikes. Besides the headlands already mentioned considerable moraines are found at Bovbjerg (130-ft.), Lodbjerg (100-ft.), and Rubjerg (230-ft.).

It looks as if the near-shore drift along the coast, a result of the action of waves and currents, takes a northward direction from a point near Lodbjerg; whereas to the south of Lodbjerg, except for a short distance along the Southern Lime Inlet Barrier (see later), it takes a southward direction, i.e. towards Blaavands Huk. Lodbjerg is a neutral point for the near-shore littoral drift.

In Fig. 2 the average size of the sand for each locality is shown. The size is the average computed from 20 characteristic surface-samples, 10 of which were taken about May 1, 1951 and 10 about June 1, 1951 at the reference point (see (2)).

These investigations showed:

a. The average size of the sand ($d_{50\%}$) is greatest between the headlands I hjerg and Hanstholm. This is the part of the coast exposed to the most pow ful waves (see Fig. 1) and also the part nearest the neutral point. Becaus of refraction local maxima are found on the headlands Bulbjerg, Hirtshals and Hanstholm. The sand is largest where the coast retrogrades, or where the beach profile commonly is steepest.

b. The average size of the sand is smallest in the extreme areas, the Scaw and the Blaavands Huk, and at the slightly exposed coasts including the bays, and where progradation takes place, or where the beach profile is flat. The smallest grains appear at the bottom of the Jammer Bay (0.17 mm) This minimum size is also found on the beach of the Pacific Ocean (see (2) p. 869).

c. The size of the sand decreases southward from the point, supposed neutral, near Lodbjerg. The size also decreases northward, but not regular ly as local minima appear in the bays. It can be assumed, however, that this decrease can be attributed less to the wear of the material, than to a sorting out due to transportation (see (9) pp. 67-71).

d. The coefficient of uniformity ($d_{60\%}/d_{10\%}$) fluctuates between 1.2

and 1.9, and is generally highest for the largest average size.

COASTAL MORPHOLOGY

As mentioned the material is carried along the coast to the north from a point near Lodbjerg. By far the greater quantity is probably deposited north of the Scaw on the long reef which projects 2.5 miles into the sea. This reef consists of fine white sand. Consequently the spit is annually shifted 4 to 5 yards northward and about 1 mill. cubic yards are deposited there every year.

Between Hanstholm and the Scaw there are generally two off-shore bars; at the Scaw where the littoral drift is at a maximum there are even three or four bars.

With the exception of certain short stretches, especially to the north, the coast between Lodbjerg and the Scaw is fairly stable because the headlands lessen the possibility of changes in the coastline. As a result of the action to which they have been exposed, the headlands are almost identical in shape and position. Since the angle made by the shoreline is everywhere between 100 and 120 degrees the shape of the coast has a mature appearance.

We have seen earlier that the littoral drift south of Lodbjerg takes a southward direction, towards Blaavands Huk.

North of Blaavands Huk there are generally two off-shore bars, but between the Nissum Inlet and Hanstholm only one, and this is poorly developed along the Lime Inlet Barriers. It looks as if the number of bars increases with the intensity of the littoral drift, but the number is not indicative of the quantity of the littoral drift.

The beach profile is steepest at Lodbjerg where the 20-ft. depth contour is situated about 1000 feet from the shoreline, the 35-ft. depth contour about 2000 feet from the shoreline, and the 60-ft. depth contour about 9000 feet from the shoreline.

The shoreline has retired very considerably at the Lime Inlet Barriers about Thyboroen, where special conditions connected with the breach of the barrier prevail. Before the groins were built at Bovbjerg, the shoreline annually retired about 2 yards on an average, calculated over a considerable number of years. The erosion decreases towards the south until at the barriers by Ringkoebing Inlet it is zero. From this point towards Blaavands Huk, we find a growing tendency to accretion which makes the coastline turn slowly to the south-west. During the period 1870-1950, Blaavands Huk has thus been shifted about 1.200 yeads to NNW, or 15 yards a year. The movement of the coastline here must be considered from a geological point of view, according to which the 25 miles of Horns Reef, probably the remnants of a marginal moraine, must be supposed to play a great part as a sheltering and material-stopping wall (tombolo-development). Thus it looks as if great quantities of the sand eroded on the southern part of the North Sea coast are deposited at Horns Reef. Various circumstances, however, indicate that a considerable quantity of small grained sand is carried over the reef from which it drifts further to the south along the peninsula of Skallingen.

Here it contributes to the great difficulties of maintaining the fairway of Graadyb, which has a depth of 27 feet leading to the harbor of Esbjerg, the important outport for agricultural produce to England. About 1 million cubic yards are dredged every year.

Nothing is known about the littoral drift at greater depths, caused by the action of waves and especially by currents, but, because of the westerly winds, a drift of small-sized material is probably taking place from the North Sea to the deep water of the Skager Rack, where the material settles.

Beach profiles which retrograde and have only one bar follow roughly the equation $y^{3/2} = p \cdot x$ with $p = 0.03\text{-}0.05$ ($y =$ the water-depth, $x =$ distance from the shoreline to the point with the depth y) between 16-ft. depth and 45-ft. depth, or a distance of about 3-4000-ft. Yet near the shore and out over the 45-ft. depth contour the profile follows a 2° - parabola. More stable and flat profiles will follow the equation $y^2 = px$, $p =$ about 0.1. Provided storm-waves with $L_0 = 300$-ft., and constant shearing stress, i.e. that the average velocity of the oscillating wave-motion at the bottom is constant, and $dE/dx =$ constant, where E is the transported wave energy, a theoretical approach gives the equation $y^{3/2} = px$ valid for depth outside of the bar, 16-ft. to about 45-ft.

COASTAL PROTECTION WORKS AND HARBORS

In 1949 six groins were built at the Old Scaw, cf. Fig. 1 and Fig. 18, 170-ft. in length and 270-ft. apart, consisting of a wall of wooden piling with rubble heaped along the sides, combined with a lateral work built of rubble and supported by wooden piling.

At Hirtshals a harbor, covering a water area of 46 acres, was finished in 1932. The harbor serves as a fishing-port and as terminal ferry-harbor to Norway (Kristianssand). The ferries require a depth of about 23-ft. at the entrance, but the maintenance of the depths has involved great difficulties owing to the strong north-easterly littoral drift, and it seems that these difficulties are likely to continue with the present dimensions of the jetties. At the headland of Hanstholm the construction of a harbor has been started. The western jetty has been built, but has caused great deposits on the leeside due to diffraction, cf. section D, the angular groin.

Very considerable works of coastal protection have been carried out from Lodbjerg to a point about 13 miles to the south, except for a distance of about 1/2 mile at Thyboroen Channel. Fig. 3 shows the cut indicated in Fig. 2. The figure comprises principally the two barriers (1/2 to 1 mile in width) which separate the North Sea from the Lime Inlet. The barriers are built up of sand to a level of about 5-ft., below this is a weak, inlet deposited, Litorina clay (level + 19-ft.). On the point of the Southern Barrier lies a fishing harbor, Thyboroen (about 2,000 inhabitants). In Fig. 3 is shown the position of the shoreline in 1791, when the barrier was unbroken, and that of the shoreline of to-day. The existing open channel was formed by a barrier-breach in 1862. Several channels existed before that time, f. inst. the Agger Channel, cf. Fig. 3, breached

1825, closed by nature in 1875. Historical accounts suggest that in the 11th century the Lime Inlet had an open and good connection with the sea, through which the Viking raids on England passed. On account of trading interests, fishing and shipping, the State has maintained the channel by extensive protective and regulating works, groins and dikes, cf. Fig. 3. The latest measures in this respect are embodied in the Act of August, 1946, which provided for the construction of two big jetties, one on each side of the channel, and a new solid dike about 1 1/2 miles from the sea. The dike will later be built across the channel as a dam with sluices. This new project, just commenced, is indicated by dotted lines in Fig. 3.

Immediately after the breach the barriers began curving inwards towards the channel, so that to-day the shoreline at Thyboroen is situated about 1 1/4 miles farther landwards than in 1791. The curving of the barriers is caused by the erosion in connection with the difference in water level (up to about 5-ft.) between the sea and the inlet prevailing during westerly gales, the result of which is that the water with its contents of suspended material is sucked into the inlet, where the solids are deposited in large shoals, cf. Fig. 3. At present about 1 million cubic yards of sand are deposited annually, whereas the annual average erosion of the barriers is 1 1/2 to 2 yards on the Southern Barrier and 2 to 3 yards on the Northern Barrier. During strong westerly gales the current in the channel may reach a speed of about 10-ft. per second. The mean depth of the channel has been stated in metres in Fig. 3.

Until now the coastal protection works, which are to be described in the following, have comprised the construction of dikes and groins. During the period 1875-1910, thirty groins were built on the Southern and twenty-five on the Northern Barrier, besides the big dikes (shown in Fig. 3) and the groins and dikes constructed along the channel. All these works, as the harhor at Thyboroen, are financed, built and maintained by the Danish State (the Ministry of Works), acting through The Board of Marine Works.

The dikes are to protect the barriers from wash-outs, and the groins are to check the littoral drift, which for a distance of 5 to 7 miles on both sides of the channel goes in the direction of the latter. The space between the groins is about 1.250 feet, and the length of the groins is 700 to 1.300 feet, generally increasing towards the channel. The last groins on both sides of the channel are reinforced and built out as jetties of 1.400 feet and 3.000 feet respectively, cf. Fig. 3. The groins are not maintained to their full length any more, for the continued erosion made them gradually become too expensive, and 200 to 400 feet of the end farthest from the coast have been abandoned.

The construction of the groins and the dikes has been gradually developed and improved. Fig. 4 shows a section of the costal protection of the Southern Barrier, which, like the Northern Barrier, has a "sea dike" and a "reserve dike" of the dimensions stated in the figure. The sand dikes are planted with marram-grass (16 tufts of three to four plants per square yard). They are built by excavators and bulldozers. The new dike is built by suction-dredgers. The figure shows a longitudinal section of a groin. The height of the outer end (4-ft.) has been chosen for constructional reasons.

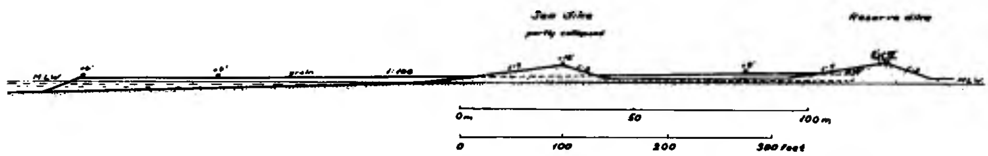

Fig. 4. Coastal protection, the Lime Inlet Barriers.

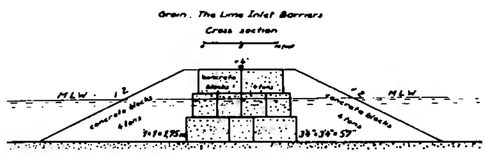

Fig. 5. Cross section of groin, the Lime Inlet Barriers.

Fig. 6. The crane at work, the Lime Inlet Barriers, 1948.

Fig. 7. Groin K, leeside-erosion, 1949.

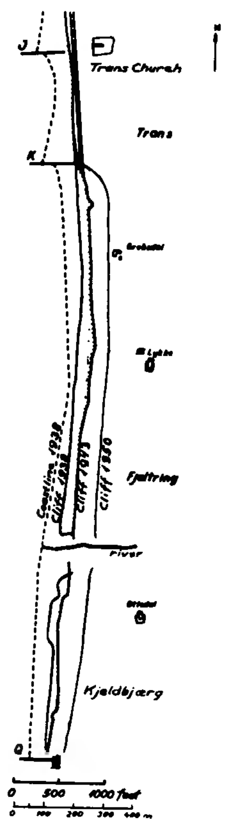

Fig. 8. The coast between groins J-K and Q.

Fig. 9. Erosion on the leeside of groin I, Bovbjerg, 1895.

Fig. 5 shows a cross section. The groin is built of a core of piled-up concrete blocks - the "crown" - with concrete blocks or rubble heaped along the sides. The weight of a block is 4 tons, the volume 62 cubic feet, and dimensions 3-ft. 4-in. x 3-ft. 4-in. x 5-ft. 9-in. Each block contains 8-cwt. of cement, 53 cubic feet of gravel (taken from the foreshore), 28 cubic feet of sand (from the foreshore or screened from a gravel pit), a filler, and 50 gallons of water. The blocks are cast by means of a concrete-mixer in a working place nearby and take 6 to 8 man-hours. They are rammed or vibrated carefully and are kept wet after the casting. The block is cast with a hooked iron bar in it, which is used for slinging when the block is being placed in the groin. The cement used is a sea-water cement specially produced by the Danish cement factories. This "sea-water cement" is a type of Portland cement specially manufactured to withstand the influences to which it is exposed in sea-water, particularly the deteriorating effect of sulphates. Experiments on air-entrainment and asphalt-compounds for surface-treatment are being carried out.

The 4 tons blocks are taken to the groin on trolleys and put in place by means of specially designed self-propelled cranes running on 100 lb. rails laid out on sleepers attached to the block-hooks. The cranes are designed to carry 10 tons, so that they may also be used for handling 8 tons blocks, which are used only in the exposed places of the groin. Fig. 6 shows the crane in function. The 'land-ends' of the groins consist of three 'crown-blocks' only, and the block is often cast in the groin itself.

The type of groin used is called an 'after-filling groin'. The material required for the construction of a groin 700-ft. long, about half of which is situated within the coastline, consists of approximately 3,000 4 tons blocks, and at the present time costs 150,000 dollars. The weakness of this type of groin is that it gradually sinks and must be re-heightened, generally about every 10 years. This consists in redressing the crown and supplementing the concrete blocks or the rubble along the sides.

A stepped revetment of reinforced concrete, slope 1 in 2, has been built on the outer slope of the dike north of Agger (the Northern Barrier, cf. Fig. 3) for a distance of about 1 mile off Flade lake and for a distance of about 1200-ft. at Thyboroen (the Southern Barrier). In places the design has not proved very durable, partly because the sheet-piling was not tight, and partly because the waves swept over the construction and washed away sand behind and under the revetment. A flexible type would have been better, but to a coastline subject to continual erosion like the Lime Inlet Barriers this design offers an adequate protection (see (11) pp. 163-167).

The groin construction described has also been used at Bovbjerg where 23 groins 500 to 700-ft. long, spaced about 1250-ft. apart, were built during the period 1875-1937. The coast erosion, which immediately before the groin-building at Bovbjerg was about 10-ft. a year, is now less than 3-ft. The soil is moraine clay and is classed with the best arable land in Denmark. On the leeside of the group of groins (the South side) a severe erosion, which will be described later, has taken place in the 30 to 40-ft. high, rather sandy coast.

South of Bovbjerg are two small groups of five groins each. Here a block-construction with a central wooden sheet pile wall has been tried, but so far this type does not seem to be an improvement on the pure block-construction.

To protect the sand barrier in front of Nissum Inlet from overtopping, a dike has been constructed 300 yards from the shoreline which retrogrades nearly 2 yards a year. The upper level and width are 16-ft. 6-in. and 6-ft. 6-in., the slope towards the sea is 1 in 7, and the slope towards the land 1 in 3. The littoral drift is to the south. At Thorsminde the outflow from the inlet is covered by two jetties built of concrete blocks, 500-ft. and 700-ft. in length respectively, and by four groins, two of which (650-ft. long) are situated north of the outflow and two (350-ft. long) south of the outflow. The outflow is provided with a sluice, first built in 1868-1870 during an attempt to dry up part of the inlet. There is also a fishing harbor navigable for boats up to 10 G.R. tons.

At Husby, south of the Nissum Inlet, there is a group of 12 smaller groins built of concrete blocks. The sand barrier in front of Ringkoebing Inlet is unprotected, as the coastline seems to be in a state of equilibrium. The outflow at Hvide Sande is protected by two jetties, 850-ft. long, built of concrete blocks. The outflow is provided with sluices, and there is a fishing harbor for boats of 10-20 G.R. tons.

Between Hvide Sande and Blaavands Huk there is no coastal protection work as the coast is either in a state of equilibrium or advancing. To the south-east of Blaavands Huk on the peninsula of Skallingen, where the shoreline is retiring, some smaller groins of wooden sheet piling have been built.

South of Blaavands Huk are the islands of Fanoe, Manoe and Roemoe; between them and the mainland is the Danish marsh-sea of a nature similar to that of the adjacent German and Friesian coasts.

B. EROSION ON THE LEESIDE OF JETTIES AND GROUPS OF GROINS

THE PROBLEM EXPLAINED WITH AN EXAMPLE

We have heard earlier of the very severe erosion on the leeside of the groins at Bovbjerg, cf. Fig. 2. Erosion on the leeside of jetties and groins is without doubt due to the fact that the beach drift on the luffside changes, past the groin, into suspended-load and bed-load, while at the same time the ratio H_0/L_0 is lowered in consequence of the wave diffraction, by which the beach drift on the leeside is possibly increased (see (28) pp. 558-562).

Since the groin breaks off the beach drift from the up-drift side, the result must be erosion on the leeside. In Fig. 7 is shown the groin K, photographed from the leeside. This groin is the last on the leeside of a group consisting of 5 groins constructed in 1933-1937 south of the already existing groins at Bovbjerg, to protect among other things the old church at Trans, a typical Danish village church in Roman style, built of granite probably in the 12th century, though the tower is not so old, cf. Fig. 7. The tower is now situated 270-ft. from the top of the cliff. Immediately after the construction of groin K (1937) a very severe erosion started on the leeside. Fig. 8 shows the rather sandy coast, 30 to 40-ft. high, between the groins J-K and Q, the former at Trans church, the latter at the clay-hill of Kjeldbjerg, about 1 mile to the south. The upper edge of the slope in 1938-1943-1950 and the shoreline in 1938 is shown. The average width of the beach is about 170-ft. - more in the summer and less in the winter.

The shoreline has retired 20 to 25-ft. each year for the past 10 years. It has, therefore, been constantly necessary to lengthen the land-end of groin K. The groin was in 1937 465-ft. long, in 1950 650-ft., which means it has had to be lengthened 185-ft. in only 13 years.

The beach profile is about 1300 feet from the shoreline to the 20-ft. depth contour and 2600 feet to the 30-ft. depth contour. The erosion on the leeside has in this, as well as in many other cases, especially effected a retrogradation of the shoreline, but not corresponding retrogradations of the depth contours in deeper water, because the 0 to 20-ft. area has been widened both inward and outward, the latter probably by deposits of eroded material from the cliff.

The development at groin K is probably the most severe in Denmark. A corresponding development has taken place at Maersk, cf. Fig. 10, and at the Old Scaw, cf. Fig. 18. In technical litterature "the leeside erosion" has been described several times, f. inst. in (3) chapter 6/35, (4), (5), (21), and (22) pp. 103-110 and pp. 192-212.

In (5) the chapter called "Federal Responsibilities in Shore Protection" deals with the problem from a legal point of view. Neither has any court in Denmark up to 1952 awarded the injured on the leeside any compensation for loss of area from such groin-building and the consequent leeside-erosion.

C. MEASURES AGAINST EROSION ON THE LEESIDE OF JETTIES AND GROUPS OF GROINS: OLDER PRINCIPLES

A LATERAL WORK ON THE LEESIDE

This measure is the most primitive, but it is often used, and it is effective when the coast retrogradation is not so strong that the shoreline moves quickly behind the end of the lateral work. Fig. 9 shows the lateral work of concrete blocks at groin 1 at Bovbjerg, photographed in 1895.

The method is expensive and not correspondingly effective. As a rule one may, therefore, say that lateral work on the leeside is a rather passive arrangement, as the work in many cases will, sooner or later, be cut off at the end of the lateral work, cf. Fig. 19. The lateral work ought under all circumstances to be built so that it gives as little reflection as possible, because the littoral drift as bed-load seems to depend on the shearing stress raised to the 2.5 power (see (27) p. 799) and, as a consequence of this, is approximately proportional to the average water-velocity, raised to the 5 power.

CORNER-GROINS

Fig. 10 shows the coastal area at groin V in Maersk north of the Nissum Inlet. Groin V is the most southerly groin in the group I - V, built in 1931-1932. Included in the figure are the shorelines in 1938 and 1948, and one can see that the shoreline during these 10 years has retired about 20-ft. a year. Actually, the retrogradation has mainly taken place in the period 1946-1948. The groin is the end-point to the reserve dike on the North Thorsminde barrier, which was built 1941-1949 and carried out to the groin in a great circle. It became clear, when in 1946-1947 the erosion south of the groin group began seriously, cf. Fig. 11, that the dike ought to have been connected to a groin further north or should have been carried due north into the high-lying land north of Maersk. The construction of the dike-section in the circle was, however, very much advanoed, and it was, therefore, decided to secure the corner at groin V, first building a corner-groin, and then a dike-reinforcement, between groin IV and groin V. In order to increase the effect of the corner-groin, the land-end of groin V was enlarged, and the groin was built as shown in Fig. 10. Fig. 12 shows the groin in action during the severe gale in October 1948. Only a little of the old sea dike was left after the storm, cf. Fig. 13. Some German pill-boxes, built in 1944 into the dike, can still be seen far out on the beaoh. The January gale in 1949 demolished the rest of the dike (Fig. 14), but the reserve dike, which was nearly completed, stood. Now the reserve dike is extended northward into the high-lying land north of Maersk.

The corner-groin hindered the erosion on the leeside from running in directly along the main-groin; this method was expensive, however, and the effect was limited to a very small area. Also an unfortunate effect was that the uprush and the wind were pressed together between the main groin and the corner-groin. Corner-groins are especially not a good measure when the coast is under continuous erosion.

THE SHORTENING OF GROINS ON THE LEESIDE

I do not know when the principle of shortening was used for the first time, but Kressner's interesting thesis was published in 1928 (see (21)). At the Technioal University of Danzig Kressner carried out model-experiments, concerning the space between groins and the problem of the leeside-end of a group of groins. A short summary of Kressner's investigations is given below.

The investigations, concerning the space between groins, were first carried out as sheer current experiments with a velocity of 0.25 m/sec. These investigations proved that the largest space allowed between groins was 5 x the groin-length outside the shoreline; if more, there was at onoe a decrease of material from the area between the groins, as this no longer

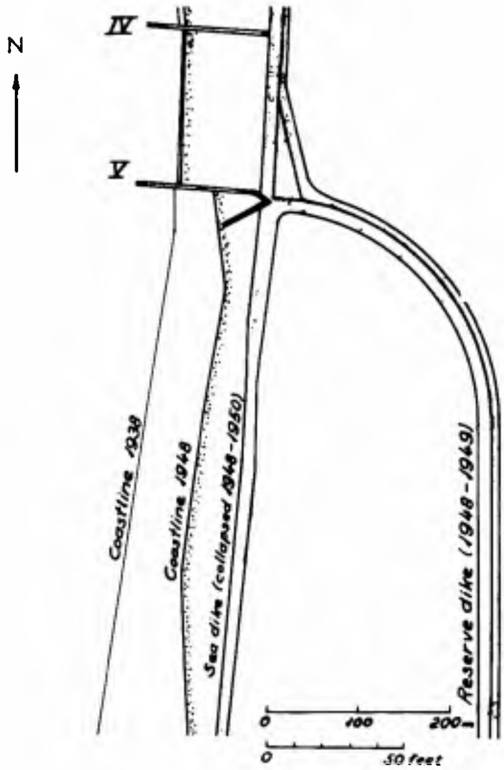

Fig. 10. The coast at Maersk.

Fig. 12. Groin V, October 1948.

Fig. 13. Groin V, October 1948.

Fig. 11. Groin V, April 1948.

Fig. 14. The coast south of groin V, January 1949.

was filled with eddies, and the longshore current penetrated the area between the groins and removed material.

A similar result was achieved in experiments with spurs in rivers, carried out in Poona (Pakistan). The experiments are described in (23). The spurs were supplied with a short T-formed head. The erosion between the groins started when the space between the groins was between 5 and 8 x their length in the water.

Later on Kressner carried out experiments with waves about 1 1/2 in. high, and a current 1/2-ft. per sec. These investigations proved that the shoreline between the groins could only be kept in a straight position, when the space between the groins was not more than 2-3 x the length in the water. If the space were greater, the shore would get a saw-tooth form as material was still accumulated on the up-drift side.

After this Kressner carried out experiments concerning the erosion on the leeside.

The experiments showed that erosion could be avoided by shortening the groins on the leeside; the angle of shortening being about 6 degrees, cf. Fig. 15. By doing this the longshore current ran smoothly along the shore and the groins, i.e. the drifting material was not pushed away from the beach.

The principle of shortening which is also mentioned in (29) pp.11-12 is now extensively used. Fig. 16, taken from Thierry's and van der Burgt's report to the XVIIth International Navigation Congress in Lissabon, 1949 (see (30) pp. 135-156), shows schematically this principle as regards the common Dutch 'Strandhoofden' (or beach groins) and the so-called V-groins; the latter being small headlands which probably can be built with double the normal space (see (30) pp. 154-156). Besides, these V-groins may prevent leeside-erosion better. Fig. 17 shows the groins at Scheveningen, Holland, where the principle has been successfully employed. In accordance with the shortening the space should be decreased so that the normal ratio between the groin-length and the space is maintained.

The shortening is generally carried out at about 6 degrees. In the successful case at Scheveningen the angle is about 5 degrees.

The principle of shortening has not been employed on the Danish North Sea coast, but has on the coast of Zeeland (Sjaelland), the largest of the Danish islands. The results here are not very convincing, however, but the shortening-angle is $<$ 10-15 degrees, i.e. very steep. I believe that the shortening should begin far in the group. If the group consists only of a few groins the shortening should start after the first groin on the up-drift side. If the group consists of several groins the shortening should probably be carried out on the up-drift side also, to ensure a smooth passage to the unprotected coast, cf. Fig. 35.

D. MEASURES AGAINST EROSION ON THE LEESIDE: NEWER PRINCIPLES

THE BREAKWATER GROIN

In a report to the XVth International Navigation Congress in 1931, Pala and d'Arrigo write about a so-called 'Bayonet-groin' (see (24) pp. 6-7) as follows:

"There is a special type of groins which must be particularly taken into consideration, especially when there is not a large flow of matter towards the beach: it is what we might call the "bayonet" type. It is formed by two successive broken stretches, the second stretch being practically at about right angles to the direction of the prevailing waves. In the construction of a certain number of these groins for the protection of a long stretch of coast, the head of each groin must mask for a certain distance, in the direction of the prevailing waves, the point of juncture between the first and second stretches of the neighbouring groin downstream.

What distinguishes this second type of groin is that the second section has as its function the breaking of the most violent waves, which it thus prevents from flinging themselves on to the shore and causing erosion.

In addition, seeing that in rough weather the waves which pass over the tops of the groins carry, more or less, materials torn up from the bottom of the sea, it happens that such sediment, poured into the space protected by the groin, deposits there and thus forms the reconstitution of the coast.

This phenomenon also occurs when the filling-materials do not arrive on the beach in sufficient quantity. It is for this reason that this kind of groins may be efficacious where the others, transversal and aligned end to end, would give no result or only have a limited result."

I am, however, inclined to believe that the explanation given of the effect of the Bayonet-groin is not quite satisfactory, and I believe that the groin probably worked as an angular groin too, see below.

Use of breakwaters as coastal protection is fairly common in Italy, see f.inst. (33).

The Italian breakwaters are often joined to the coast, among other things for maintenance-reasons, but this practice has often been necessary to achieve a successful effect from the total construction (see (33) p. 123).

Vera, Isla and Acena write in (32) p. 27 that "l'erosion adjacente" can be avoided partly by joining the groin-group to solid cliff, and partly by building a breakwater in connection with the groin, i.e. some sort of a "Bayonet-groin". No explanation, however, has been given of the effect of these breakwaters. In a new passage in the same report, called "Etude Theorique Des Transports De Sable Causes Par La Houle" ((32) pp. 36-44) computations are made of the coastal current outside the breaker-zone, on the basis of Iribarren's theory which only considers the static pressure differences arising from the refraction etc. The currents are particularly strong in places where the coastline bends or where there is a headland.

I shall not go further into Iribarren's theory nor into the descripti given by Vera, Isla and Acena, concerning the development of the shoreline behind a curved jetty which, according to the figure, gives an erosion abo 10 x as big as the deposit. For this one reason the theory cannot be satis- factory. Iribarren does not go into wave diffraction which gives the real explanation of the current on the leeside of the jetty, cf. (15).

THE T-GROIN

In his report to the XVIIth International Navigation Congress in 1949, Col. Frech writes about the T-groins, built at Asbury Park in New Jersey as follows (see (14) p. 52): "Several of these groins have been experimentally supplemented by breakwater members extending 100 to 150 feet at right angles at their outer ends forming a T. It is too early to judge the results produced by these structures, but the following obser- vations may be made: certainly, further erosion of the bluff has been stopped; the groins not having the breakwater feature at their outer ends have not accumulated much sand, if any, but those with the breakwater ad- dition (known now as T-groins) have had a paradoxical effect, sand having accumulated along both sides of the stem of the T, but with deposits on the down-drift side exceeding considerably the accumulation on the up-drift side".

The T-groin has, however, been used before. Matthews wrote in 1934 (see (22) p. 218): "If, on the other hand, there is a sufficient travel of material, the protection of the coast can be assured by groynes alone. If the supply is insufficient, or there is a reason to fear that storm- waves may strike the coast in a direction parallel with that of the groyne so producing an excessive thinning of the beach, the protective works should comprise in addition to groynes a longitudinal structure. Special types of groynes, in a bent line, T-shaped or crusiform, designed for this purpose, have not yet received the sanction of experience".

The successful effect of the T-groin is explained by the theory of tl angular groin (see below).

INCLINED GROINS

Fig. 18 shows the groin-group at the Old Skaw, cf. Fig. 2. It is buil mainly in 1949, and the groins are constructed with slanting landends, particularly advantageous at the last groin in the group, because, when it is so built, the erosion on the leeside does not move close to the lee- side, but the construction of the last groin as a short angular groin probably would have been more advantageous and will now be carried out (sh with dotted lines).

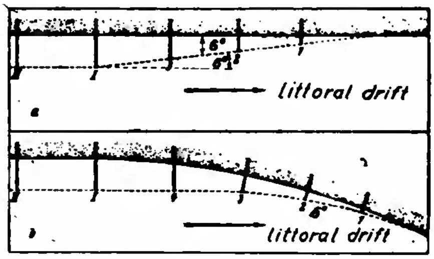

Fig. 15. The principle of shortening: Kressner.

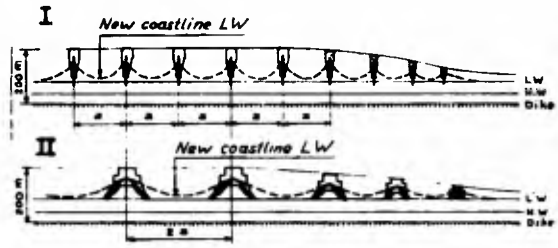

Fig. 16. The principle of shortening: Thierry and van der Burgt.

Fig. 17. The principle of shortening, Scheveningen, Holland: Thierry and van der Burgt.

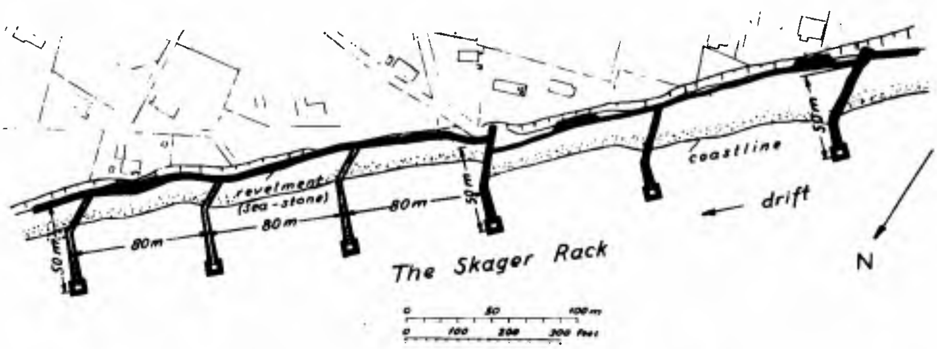

Fig. 18. The groins at the Old Scaw.

Fig. 19. The leeside-groin at the Old Scaw.

THE ANGULAR GROIN

In order that deposits may take place on the side of a groin, there must be:

a. Littoral drift towards the groin, and
b. the material must be thrown ashore.

a. Since the littoral drift moves towards the groin on the up-drift side and off the groin on the down-drift, it is, if deposits shall take place on the leeside, necessary to turn the littoral drift. This might take place in a limited area on the leeside, if the groin is equipped with a short lateral work, an "angle".

Fig. 20 shows an angular groin. The wave propagation is as in the figure. A cylinder-wave is caused by the diffraction at the corner a. The wave-action at an arbitrary point x.y can be calculated (see (19) and (25)). In the figure dotted lines are drawn through points with the same diffraction-coefficient provided there is a constant depth behind the angle, complete absorption at the stem of the groin (length 2 x L where L = wave length) and no friction-loss at the bottom.

As a consequence of the diffraction a littoral drift is produced from the leeside, towards the groin.

b. The mere transport of material towards the groin is, however, not sufficient. The strong gales certainly supply the leeside of the groin with considerable material, but investigations with beach profiles at the laboratory (see (10) Beach Erosion Board, (17) Waters, and (28) Thorndike Saville, and Fig. 22, experiments in Copenhagen 1949), as well as experiments with actual beach profiles (see (7)) and investigations on the Danish West coast have proved that waves with a large steepness-ratio will erode the beach making the profile flatter, cf. Fig. 22 B, b, bar profile, whereas waves with a small steepness-ratio build up the beach and make the profile steeper, cf. Fig. 22 D, d, and C, c, beach ridge profiles. (The small letters indicate similar results with tests in scale 1:2).

Storm-waves will often strike the stem of the groin at a greater angle, in consequence of which the steepness-ratio is increased along the stem, and, therefore, erosion will occur. This is particularly so, if the stem gives rise to a strong reflection, or in some other way causes an increase of the turbulence, cf. Fig. 23, which shows seasonal fluctuations of the shoreline of the up-drift side of a groin on the Lime Inlet Barriers. Even if the littoral drift towards the groin is much stronger in the winter than in the summer the beach will be eroded in the winter. The steepness-ratio is, however, lowered behind the angle. The lowering is considerable (Fig. 20), and consequently the waves will quickly change into a constructive type; cf. Fig. 22 D, d, and C, c.

The total effect of the circumstances mentioned in a and b is that a beach is built up behind the angle. Provided that no reflection from the stem of the groin takes place, the shoreline will, as a consequence of diffraction-currents, bend further out rather than follow that circle centered at the end of the angle.

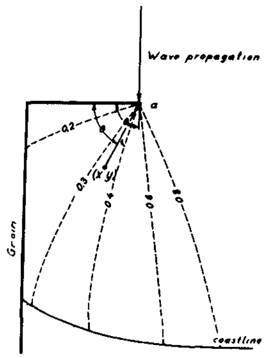

Fig. 20. An angular groin, diffraction.

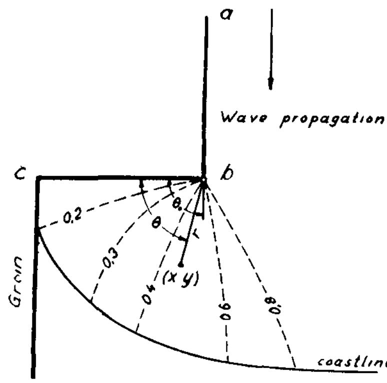

Fig. 21. A Z-groin, diffraction.

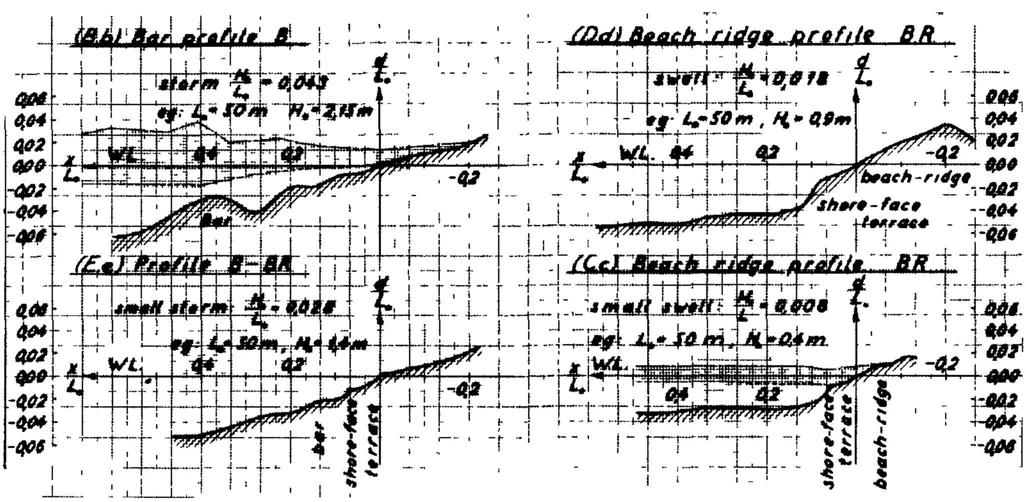

Fig. 22. Beach profiles. Laboratory experiments, Copenhagen 1949.

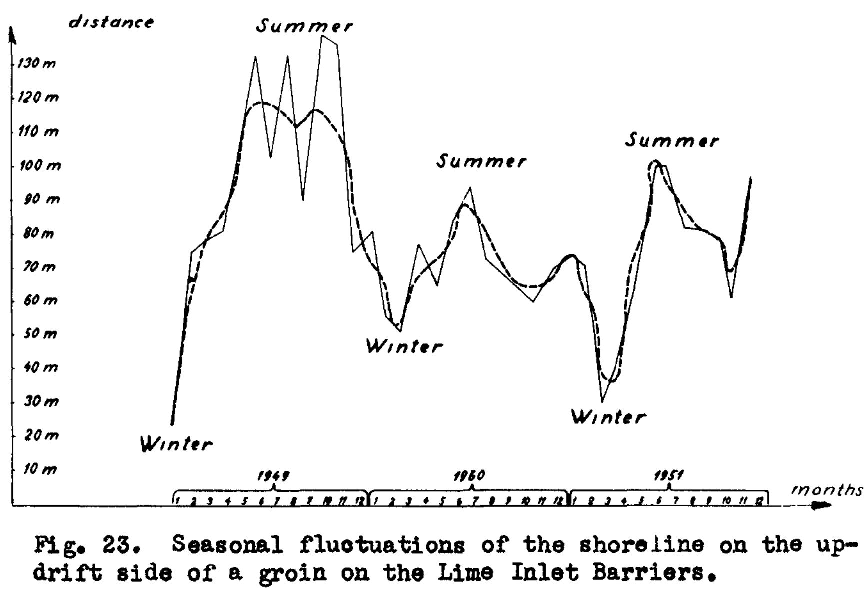

Fig. 23. Seasonal fluctuations of the shoreline on the up-drift side of a groin on the Lime Inlet Barriers.

It is, therefore, of great importance that the energy-absorption of the stem is increased.

Laboratory investigations with an angular groin. - The investigations were carried out in the Hydraulic Laboratories in Copenhagen (1951). The length of the tank was 44-ft., water depth = 1-ft., wave length L_o = 5 1/2-ft., wave height H_o = 3-in., i.e. H_o/L_o = 0.045 (storm-wave) and wave period = 1.05 sec. Sand with an average size of 0.22 mm, representing shingle, was used. The coefficient of uniformity ($d60\%/d_{10\%}$) was 2.

In the tank an experimental groin consisting of plates was erected. The angle between the wave direction and that of the groin was 15°. The length of the groin outside the shoreline was 4-ft. Before the tests a beach profile with a slope of 1:10 was constructed.

Fig. 24 shows the normal influence of a groin, accumulation on the up-drift side and erosion on the down-drift side. In Fig. 25 the groin is provided with an angle of 2-ft. as well as a rubble mound, and it can be seen that the shoreline has prograded on the leeside. Fig. 26 shows the groin with a 6-in. angle, and here the shoreline has almost the same position on both sides of the groin.

Development of the angular groin in detail.- There was, however, a decided defect in the structure, as considerable erosion repeatedly appeared at the bottom of the end of the angle. The erosion indicated that there was an increase in the shearing stress, which is of course disadvantageous, and the erosion so influenced the beach profile that its stability was reduced and the shoreline retrograded. Furthermore, the erosion is undesirable for the construction, since it may cause the rubble mound or other constructive elements to give way, which will make its maintenance expensive.

The erosion is due to a submergence of trajectories, caused by their bending around the end of the angle, while at the same time the velocity of the water particles is greater at the surface than at the bottom. This is explained in detail by Professor Tison in Gent, Belgium, who has worked out a theory about erosion at bridge-piers (see (31) pp. 3-5).

The erosion is avoided by turning the angle-end outward, so that the trajectories actually move upwards, cf. Fig. 27. It is also important that reflection from the outside of the angle is reduced as much as possible.

Fig. 28 shows a groin with its angle-end turned outward, radius 5-in.; when the angle-end is made in this way, no erosion will occur at the bottom. But if the angle is turned so that the end bends inward, erosion will start at once.

There was another weak point. A strong retrogradation of the shoreline appeared on the up-drift side right along the stem of the groin. This is due to a concentration of wave-energy along the stem, because the waves arrive slantwise, and, therefore, the wave height and the steepness-ratio is increased which causes the beach to be lowered. This is also known

Fig. 24. Laboratory experiment, normal groin, erosion on the lee-side.

Fig. 25. Laboratory experiment, angular groin, 24-in. angle.

Fig. 26. Laboratory experiment, angular groin, 6-in. angle.

Fig. 27. Laboratory experiment, angular groin, inward-turned groin-head.

Fig. 28. Laboratory experiment, angular groin, the angle-end turned inward.

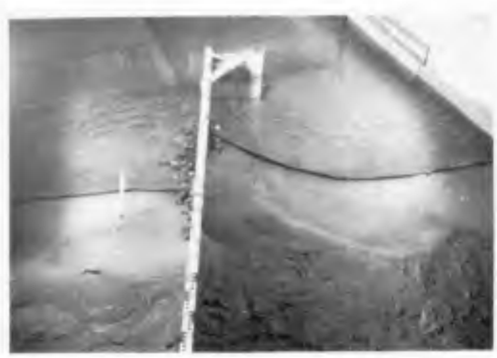

Fig. 29. Laboratory experiment, angular groin with a rubble mound along the stem.

in practice where a smooth stem often has bad results, while a stem roughened with inclined piles works better.

In order to neutralize the tendency of retrogradation along the stem of the groin, the up-drift side and part of the leeside, cf. Fig. 29, are supplied with a rubble mound 1-2 in., which is especially satisfactory on the up-drift side.

From investigations concerning the construction of lateral works it appeared that horizontal sleepers provided particularly well the uneveness needed to reduce the wave-energy (see (13)). When the interstices in a rubble mound are filled with water, it works by its roughness alone and is in this respect not very suitable. An uneveness achieved by piles will work in the same way. In a supplementary investigation this was shown in the following manner:

I built a canal 5-ft. wide, which in a distance of 12-ft. was equipped on both sides with 3/4 x 2-in. piles and at intervals of 16-in. The water depth was 10-in., and a wave was lead through the canal, (H_o = 4-in., L_o = 10-ft., H_o/L_o = 0.033 representing a moderate storm-wave). It was found by measuring the wave height before and after the passage past the piles that the height was reduced 30%, i.e. a 50% loss of energy. This is probably due to the eddies between the piles. A rubble mound 1-ft. tall, with a slope of 1 in 1 on both sides of the canal, was thrown up in the same section as the piles, and the rubble mound of 1 to 2-in. shingle rose 2-in. above the water level. The experiment was repeated and showed that the energy-loss was about 50%, although the decrease of the cross-section of the canal in this case was greater than with the piles.

The energy-loss mainly caused by eddies between the piles is comparable with the friction-loss on a sand bottom corrugated by ripple marks, cf. Bagnolds experiments (see (1) and (18)).

THE Z-GROIN

The Z-groin is an angular groin where the angle is a part of the stem giving the groin a Z-form. It has all the properties of the angular groin. In Fig. 21 a Z-groin is shown schematically. One will see that the groin is produced by shifting the angle into the middle of the stem, which means that the Z-groin for that reason alone is going to be cheaper than the corresponding angular groin. The wave action at an arbitrary point, x.y, can be calculated in the same way as with the angular groin. In the figure lines are drawn through points with the same diffraction-coefficient, with the assumption that the depth is constant, that there is complete absorption at the groin (the length of the stem between the initial coastline and the coast-parallel part of the groin is L), and that there is no friction-loss at the bottom. As one will see a "double" diffraction will occur at the groin, as soon as the waves arrive slantwise from the up-drift side, first at point a and later at point b, although the former is fairly unimportant. The form of the Z-groin will cause the shoreline to be drawn further out on its leeside than will the corresponding angular groin; thus the land-end is better protected. With the Z-groin there is, furthermore, a possibility of making the section a-b of the stem rough so that the effectiveness of the groin, for that reason also, is increased.

At the same time the section b-c is very much effected, but if the waves do not break exactly at b-c, the force cannot be much different from the force in the angular groin, as the angle that the wave crest makes with the stem of the groin hardly ever will be less than about 60°.

The Z-groin is, as the angular groin, rounded at the angle-end b in order to reduce erosion of the bottom. The corner c ought to be sharp, or, if not, bent outward in the same way as b with the stem of the groin moved some distance towards the middle of the groin.

The rubble mound at b-c decreases the reflection, and it is not necessary that the wall be absolutely tight; but the waves passing through the structure must not interfere with the diffracted waves so that waves with a steepness-ratio greater than that of the constructive type are produced.

Laboratory-investigations with a Z-groin. - Fig. 30 shows an experiment with a Z-groin. Similar experiments with the corresponding angular groin proved that the Z-groin in conformity with the diffraction accumulates better than the angular groin on the leeside, and the danger of erosion on the up-drift side is less than with a smooth-stemmed angular groin, as part of the wave-energy otherwise running along the groin, is now destroyed by the part parallel with the coast. In Fig. 31 the Z-groin is made rough by the use of piles; (1 x 1-in., space 4-in) this proved to be effective.

SUMMARY, LABORATORY EXPERIMENTS

The experiments proved:

a. that the angular groin caused the shoreline to prograde both on the up-drift as well as the down-drift side. This fact allows an increase of space between the groins. Consequently, the head of the groins must be placed on the leeside, where the ice from the windward cannot be destructive;

b. that erosion at the angle-end can be limited by suitable rounding;

c. that a rubble mound probably may be replaced by uneveness along the stem, but in that case there ought to be a bottom protection;

d. that the Z-groin accumulates better right along the land-end than the corresponding angular groin.

EXPERIMENTS IN NATURE

Fig. 32 shows a small angular groin built by the Board of Marine Works in the Nissum Inlet, cf. Fig. 2. This groin is 50-ft. long, the length of the angle 7-ft. including the rounding at the angle-end, radius 1-ft. The wave height and wave length in heavy gales are about 1-ft. and 9-ft. respectively. The up-drift side of the groin is to the left, and

Fig. 30. Laboratory experiment, Z-groin, smooth.

Fig. 31. Laboratory experiment, Z-groin, rough.

Fig. 32. Practical experiment, angular groin, Thorsminde.

Fig. 33. Practical experiment, groin with an angle, the Scaw.

Fig. 34. Practical experiment, angular groin at Belle-Vue Beach, Copenhagen.

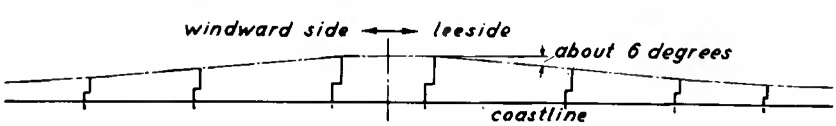

Fig. 35. Schematic group of Z-groins, arranged on the principle of shortening.

materials (sand 0.2 mm) are accumulated on the down-drift side quite as in the laboratory. The picture shows the groin at low water, but levellings on both sides of the groin show the greatest deposit on the leeside. Fig. 33 shows an angle on a groin at the Scaw, cf. Fig. 2.

Fig. 34 shows an angular groin constructed at Belle-Vue Beach, the famous seaside-resort near Copenhagen. The stem of the groin is 80-ft., the length of the angle 33-ft. It was built by Gentofte municipality.

One can observe many instances of effects similar to those of this groin, just discussed, f.inst. the deposits behind the Santa Monica breakwater in California (see (8) p. 5 and (20) p. 258).

PRACTICAL CONSTRUCTION OF ANGULAR AND Z-GROINS

Only a few practical experiments are known, f.inst. the breakwater groins in Italy and Spain and the T-groins in New Jersey.

The length of the angle should correspond to the dimensions of the groin. The ratio between the length of the angle and the length of the stem, provided that the gales are normal, cannot be given in general, as it depends on the intensity of the littoral drift, the angle of the waves with the shoreline, the beach profile, the size of the material, and the construction of the groin. Before more data are available for fixing a suitable ratio, the ratio 1/3-1/4 is practicable for most sand-beaches. In cases of ample littoral drift, the ratio may be reduced; for the contrary it ought to be increased, especially for places where an ordinary retrogradation of the shoreline takes place.

The angle may be a wall of sheet piling, supported by sloping piles on the inside and provided with a rubble mound in front, cf. Fig. 25; it may also consist of two rows of scattered piles with rubble. In the latter case one must make sure, by computation or experiment (see (6)) that the waves passing through the construction do not interfere with the diffracted waves so that they will be of the destructive type. The steepness ratio, therefore, must be $<$ about 0.02. In the usual groin-heads, built of piles with rubble, the loss of energy is, however, generally so great that one may completely disregard the wave-energy penetrating the construction.

The angle-end ought to be rounded outwards in order to decrease the possibility of erosion of the bottom at the angle-end. Practical experiences, as f.inst. an experimental construction at the coast-section concerned, should be used as a guide. The stem of the groin ought to be made uneven, f.inst. with the use of rammed coupled piles. In this case also, practical experience, on the basis of experimental constructions, should be the deciding factor in the type of construction.

CRITICISM

It could be maintained that the angular groin is generally more expensive than an ordinary groin. When T-groins and breakwater groins have, nevertheless, been built, it is because a beach must be produced.

Angular and Z-groins are particularly euited to the leeside-end of a group of groins and they will, therefore, probably be much cheaper than ordinary groins. All over the world one will find numeroue instances of the necessity for making expensive extensions of the land-ends becauee of eroeion on the leeside, ae we saw in Fig. 8. Theee lengtheninge of a land-end can be avoided by the use of angular groins or Z-groine.

It might be maintained that the angular groin producee merely a different distribution of the material in the group of groins. Thie is incorrect. When a groin does not accumulate any more material on the updrift side, it is among other things due to the fact that the eteepnese ratio of the waves is so great that the material is drawn out beyond the outer end of the groin and ie thus lost for the coaet. On the other hand material can accumulate on the leeside, if the groin is either an angular or a Z-groin.

CONCLUSION

On the basis of these hydraulic and practical experiments I believe that the most satisfactory group of groins ought to be conetructed as is shown schematically in Fig. 35 which illuetrates the uee of the principle of shortening with Z-groins. The coast is in thie way divided into small headlands.

The height of the groins outside the ehoreline must be fixed according to practical conditions (see (20) pp. 246-253); but the land-end must be as low as possible so that it starte functioning only under extraordinary depletions of the beach (eee (30) p. 155).

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