CHAPTER 48

THE DEVELOPMENT OF COAST PROFILES ON A RECEDING COAST PROTECTED BY GROYNES

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This paper presents an analysis of the longshore sand transport by waves and current on natural coasts outside the breaker zone. A tentative expression for the transport capacity is established and applied to the problem of the effect of groynes on the development of the coast profiles. It is shown that the results are consistent with the observed development of the Danish North Sea Coast at Thyborøn, which has been protected by groynes and closely observed through the last 60 years.

INTRODUCTION

When a continuously receding sandy coast is protected by groynes the immediate result is a considerable reduction of the rate of recession of the coastline chiefly due to a reduction in the beach drift. This fact is generally accepted and has been confirmed empirically under prototype conditions.

However some disagreement still seems to exist regarding the long term effect of groynes under the conditions mentioned above. Clearly, the groynes do not directly affect the sand transport at some distance seaward of the groynes and therefore erosion seaward of the groynes will continue to occur after the construction of the groynes. Since the coastline and the depth contours must eventually attain the same rate of movement some coastal engineers have drawn the conclusion that the effect of groynes on a receding coast will be of a temporary character only.

This reasoning is obviously rather superficial. A better understanding of the manner in which the coast profile develops after the construction of groynes may be obtained by considering the fundamental physical factors involved in the sand transport outside the breaker zone (the offshore bar).

FUNDAMENTAL CONSIDERATIONS

The water movement - The water movement close to the bed outside the breaker zone consists of an oscillatory motion in the direction of propagation of the waves and a longshore current. The current component in the direction perpendicular to the shore is of second order only and may be disregarded in this connection.

The longshore current may be due to a slope of the water surface along the coast caused by astronomical and/or storm tides, or it may be due to a longshore component of the wind shear stress on the water surface. The waves do not contribute essentially to the longshore current on a straight coast outside the breaker zone.

Under storm conditions the longshore gradient caused by the wind shear stress will often be much more important than the tidal gradient at depths well above the breaker depth - except, of course, when the wind is blowing approximately at a right angle to the shoreline. This is simply due to the fact that the wind gradient increases inversely proportional to the depth, whereas the tidal gradient remains constant over the entire coast profile. This is the reason for which the direction of the current under storm conditions is often determined by the direction of the wind at considerable distances from the coast irrespective of the tidal currents at larger depths.

<u>The bed shear stresses</u>. The problem of the shear stresses in the combined motion of waves and current is very complicated and still remains largely unsolved, qualitatively as well as quantitatively. It is known, however, that the boundary layer in the wave motion is quite thin, and therefore the maximum bed shear stress τ_w caused by the wave motion may be expressed by

$$\tau_w = \lambda_w \tfrac{1}{2} \rho U^2 \tag{1}$$

in which U is the maximum orbital velocity at the bed as calculated by the irrotational theory. Little is known about the magnitude of the factor λ_w, but the available evidence indicates that it has a value of about 0,02.

The approximate value of 0,02 for λ_w implies that the shear stress exerted by a wave motion with the instantaneous bottom velocity U is several times greater than the shear stress exerted by a steady current with the mean velocity U.

The shear stress component due to the longshore current may be inferred directly from the tidal and wind gradients along the coast. At moderate depths this shear stress will usually be considerably smaller than the maximum wave shear stress under storm conditions.

The problem of a combination of waves and current has been analysed by professor H. Lundgren, chief of the Coastal Engineering Laboratory, Copenhagen, who found that the resulting maximum shear stresses may be found by superposition of the maximum wave shear stress and the constant longshore current shear stress. Qualitatively this superposition may be represented by fig. 1. The resulting maximum shear stress will only be slightly different from the maximum wave shear stress.

The direction of the maximum shear stress indicates the direction of the maximum particle velocity near the bed. This implies that for constant τ_w the velocity V of the longshore current is approximately proportional to the first power of the longshore current shear stress τ_c.

The sand transport function. Very little definite knowledge exists concerning the transport capacity of a combined wave and current motion. Therefore, the only way in which it is possible at present to establish a reasonably sound hypothetical relationship is to utilize the existing knowledge of sand transport in uniform open channel flow.

Using the terminology of R.A.Bagnold (1957) we will define the bed load grains as that part of the moving grains whose submerged weight is transferred to the bed as a grain stress in the dispersion near the bed. The suspended load grains are the grains whose settling through the water is balanced by the turbulent diffusion.

In the case of uniform grains with the diameter D and the specific gravity s Bagnold found that, when the bed shear stress τ_0 is large in terms of the stress unit $(s - 1)\gamma D$, the bed load transport and the suspended load transport are both proportional to $\tau_0^{3/2}$. Since $\tau_0^{1/2}$ represents the velocity of the fluid this result may be interpreted in the way that the load (the submerged weight of the moving grains per unit area of the bed) is proportional to τ_0 and that it moves with a velocity proportional to the mean fluid velocity. As far as the bed load is concerned this interpretation appears to be physically correct. With regard to the suspended load the question of the physical validity of this interpretation is impossible to answer as long as the nature of the transition between the bed load and the suspended load (the boundary condition of the suspended load) is unknown.

There can be little doubt that with regard to the bed load Bagnold's results are directly applicable to the case of combinations of waves and current. The role of the dispersed grains near the bed is simply to provide a means of transferring the shear stress τ_0 to stationary grains of the bed, and there seems to be no reason why this mechanism should be essentially different because of the comparatively slow variations in magnitude and direction of τ_0 in the presence of waves.

As stated above under storm conditions the maximum wave shear stress τ_w at moderate depths will usually be considerably larger than the longshore current shear stress τ_c. Consequently the major part of the bed load transport will occur when the bottom velocity in the wave motion passes its maximum. In accordance with Bagnold's results it may be assumed that the amount of bed load grains (measured by their submerged weight per unit area of the bed) may be represented by τ_w and that the mean longshore velocity of the bed load grains is proportional to the velocity V of the longshore current. By (1) the following expression for the bed load transport Q_b per unit width outside the breaker zone is obtained

$$Q_b \sim U^2 V \tag{2}$$

The problem of suspended load transport in combinations of waves and current is considerably more complicated. Since the thickness of the boundary layer in a wave motion without a superposed current is only a small fraction of the water depth, the diffusion coefficient becomes very small at a short distance above the bed. Consequently the waves alone are unable to support any significant suspended load.

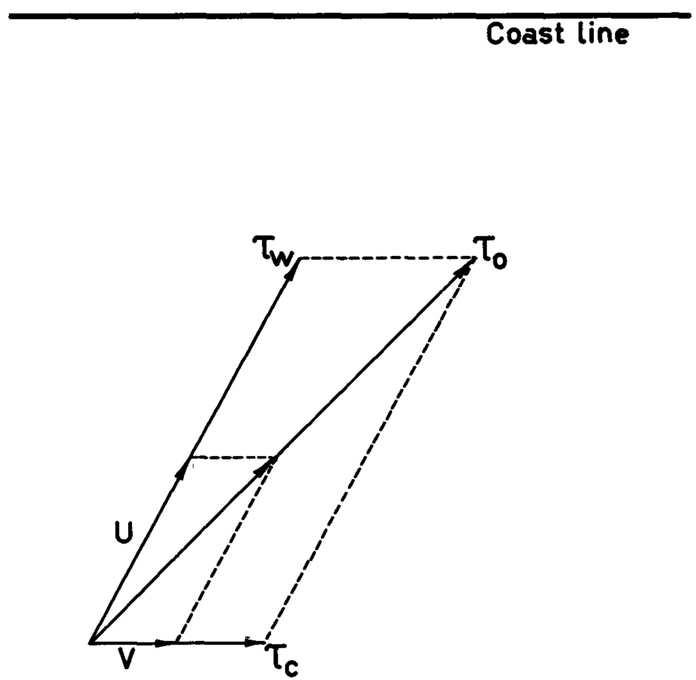

Fig. 1. Shear stresses in the combined motion of waves and current.

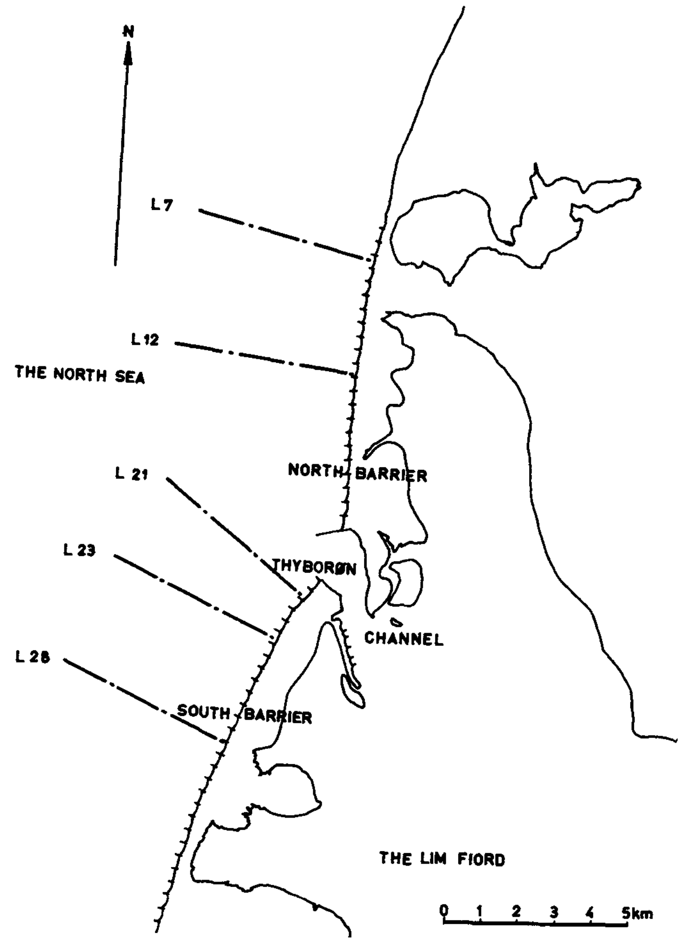

Fig. 2. Map of the Thyborøn Barriers.

The presence of the longshore current, however, implies that turbulent diffusion takes place over the entire depth and therefore suspended load can be maintained at any height over the bed.

According to the differential equation for the concentration of suspended grains the turbulence is able to carry any amount of suspend lead as long as the turbulence is not conceivably attenuated by the presence of suspended material.

In the case of a combination of waves and current the bed load and the turbulence near the bed is mainly determined by the wave motion. Consequently, the concentration of suspended grains near the bed and therefore the magnitude of the concentration at any level is determined essentially by the wave motion. Applying the above mentioned interpretation of Bagnold's results we arrive at the conclusion that the total load of suspended grains should be approximately proportional to the wave shear stress τ_w. It must, however, be expected that the ratio of current shear stress to wave shear stress τ_c/τ_w has some influence on the magnitude of the suspended load, but within the limits of interest in the present paper the influence of this ratio should be slight.

Since the mean longshore velocity of the suspended grains must be proportional to the longshore current velocity V, we obtain for the total transport rate Q_t of bed load and suspended load per unit width of the coast profile

$$Q_t \sim U^2 V \tag{3}$$

in which the factor of proportionality depends on the grain size D and the ratio τ_c/τ_w.

This relationship is a simple mathematical expression of the wel known fact that the waves put the sand into motion but the current determines the velocity and the direction of the transport.

The above expression (3) might, of course, have been given a dimensionless form by means of parameters similar to the ones used by Bagnold (1957). However, for the purposes of the present paper it is simpler to use the dimensional form (3).

THE INFLUENCE OF GROYNES ON THE COAST PROFILES

The significance of the longshore transport. Most of the previo work on coast profiles, whether in the laboratory or in the field, has been concerned mainly with the role of the transverse transport (onsho and offshore) in the shaping of the profiles. This transverse transpo has been shown to depend on the steepness of the attacking waves throu which it has been possible to explain the seasonal fluctuations of the profile shape, and it has even been possible to correlate profile fluctuations over periods of several years with variations in the frequency of strong onshore winds, Bruun (1954).

THE DEVELOPMENT OF COAST PROFILES ON A RECEDING COAST PROTECTED BY GROYNES

When groynes are built on a long, continuously receding sandy coast the recession of the coastline is immediately reduced and the coast profiles become steeper. Since the primary cause of the recession of the coast almost invariably is an increasing longshore transport capacity along the coast, it must quite obviously be expected that the long term development of the coast profiles will depend mainly on the manner in which the increasing steepness influences the longshore transport.

If it is assumed that no change in the meteorological conditions takes place the only change in the wave conditions outside the breaker zone due to an increase in the steepness of the coast profiles will be that the damping of the waves by bed friction during the travel from deep water to the breaker zone is reduced. Consequently, the average wave height just outside the breaker zone will be somewhat higher in the steeper profile so that the longshore transport capacity will be increased.

On the other hand the waves do not contribute materially to the longshore current which is caused almost exclusively by the longshore tidal and wind gradients. If the conditions at a certain depth before and after the increase in steepness are compared, the longshore gradients will be identical in the two cases. By fig.1 it may be seen that the longshore current velocity V caused by a certain longshore gradient τ_c depends on the wave shear stress τ_w in the following manner:

$$V \sim \frac{\tau_c}{\tau_w} \cdot \sqrt{\tau_\circ} \sim \frac{\tau_c}{\sqrt{\tau_w}} \sim \frac{\tau_c}{U} \tag{4}$$

Thus, if the wave height is increased the longshore current velocity decreases.

The resulting relative increase in the longshore transport capacity by (3) becomes identical with the relative increase in U, which is the same as the relative increase in the wave height H.

Since the width of that part of the coast profile in which the steepness increases is usually rather small (a few kilometres) the increase in the average wave height and transport capacity corresponding to a substantial increase in the slope of the bed will normally be in the order of a few per cents only.

If we consider two coast profiles a unit length apart the annual depth increase at a certain depth d due to the difference ΔQ_t in transport capacity per unit width per year between the two profiles will equal ΔQ_t. When the steepness increases, ΔQ_t must obviously increase in the same rate as Qt, that is, much more slowly than the steepness.

The rate of movement of the d m depth contour will be equal to $\Delta Q_t/\tan\alpha$, where $\tan\alpha$ is the slope of the bed at the depth d meters. It is evident from the above that this expression decreases with increasing steepness.

Thus, we are led to the conclusion that the effect of the groynes on the profile outside the breaker zone will be that the rate of movement of the depth contours will decrease, until it eventually becomes equal to the annual recession of the coastline.

The increasing steepness of the coast profile must, of course, be expected to influence the magnitude of the annual recession of the coastline. First, the average wave height will be greater in the steeper profile. Since the beach drift is probably proportional to about the 3rd power of the wave height an increase in the wave height of a few per cents may increase the coastline recession with 10-20%.

Second, the equilibrium between onshore and offshore sand movement, which might have existed before the construction of the groynes, will probably be disturbed by the increased steepness. There seems to be no way in which the importance of this factor can be evaluated theoretically. However, empirical evidence seems to indicate that the transverse transport is on the whole of very little importance with regard to the coastal erosion, and therefore this factor may generally be expected to be rather unimportant.

In conclusion it may be said that the effect of construction of groynes on a continuously receding sandy coast will be a permanent reduction of the rate of movement of the coastline. When the steeper equilibrium profiles of the protected coast have been reached, the annual recession of the coastline will probably be a little greater than shortly after the installment of the groynes, but still considerably less than that of the unprotected coast, depending on the efficiency of the groynes.

It is interesting to note that since the width of the coast profile decreases much more that the transport capacity increases when the steepness is increased, the total longshore transport will be less in the steeper profile. Thus, the groynes will reduce the longshore movement of sand over the entire coast profile, not only on the beach.

These results are confirmed conclusively by the development of the groyne protected North Sea coast of the Thyborøn Barriers in Denmark, which will be described briefly below.

COAST DEVELOPMENT ON THE THYBORØN BARRIERS

A detailed account of the coast development on the Thyborøn Barriers has been given by Bruun (1954).

The Thyborøn Barriers are located on the northern part of the Danish North Sea coast. A map showing the present shape of the coastline is given in fig. 2.

The Thyborøn Channel, which separates the North and South Barriers, connects the Limfjord, which has water surface of some 1200 km^2, with the North Sea. This channel was formed in 1862 during a severe gale. Since the tidal range at Thyborøn is very small - about 25 cm - the cross section of the channel is determined by the flow under storm tide conditions. With strong westerly gales storm tides of more than 2 meters above MSL may occur accompanied by discharges of up to about 13.000 m^3/s in the channel.

The direction of the littoral drift on about 10 km of coastline on each side of the channel is towards the channel. Since the current in the channel during strong onshore winds is invariably ingoing, all the sand - about 800.000 m^3 per year - eroded on these 20 km of coast is carried through the channel to the shoals in the Limfjord.

The formation of the channel caused a strong erosion of the coast of the barries, which led to the construction of a system of heavy concrete groynes on these coasts around 1900. Since then the Board of Maritime Works has kept the development under close control by frequent soundings and measurements of the location of the coastline.

Fig.s 3 and 4 show some results of these observations for a typical stretch of the North and the South Barrier, respectively, at some distance from the channel. Similarly, fig. 5 represents the coast development off Thyborøn town on the northern end of the South Barrier. The location of these stretches is shown on fig. 2. The curves on fig.s 3, 4 and 5 represent the averages of the results of all measurements on the considered stretches. The results of a survey made in 1874 have been included to show the effects of the groynes on the coastline recession.

The dashed line in these figures is a plot of the location of the coastline as measured from the coastline in 1874. This shows that while the unprotected coast receded at a rate of about 10 meters per year, the rate of recession after the construction of groynes has been only about 2 meters per year. Although the measurements of the location of the coastline - which are very numerous - have been smoothed considerably before plotting, the movement of the coastline is still somewhat irregular. It is not possible in the later years to detect any tendency towards a general acceleration of the coast recession that may be distinguished from the irregular variations that have previously occured.

The full line are plots of the distances from the coastline at the time of the sounding to the 6, 8 and 10 meter depth contours. Thus, the vertical distances between these lines directly represent the reciprocal value of the slope of the bed.

The slope of the bed at the 8 m depth contour has now increased to about twice the original value or more since the construction of the groynes about 1900. This has been accompanied by a very marked stabilization of the distance to the 6 m depth contour, and the figures also show a more or less clear tendency towards a general reduction in the rate of movement of the 8 m contour relative to the coastline. On the whole, there seems to be no doubt that the profiles are now approaching their equilibrium shape up to depths of 9 to 10 meters.

A calculation of the wave attenuation by bed friction according to (1) for a 3 meter high wave with a period of 8 seconds and an angle of incidence of 45° has been made to illustrate the influence of the profile development on the wave heights. The result was, that while this wave, which is quite representative of a medium strong gale at Thyborøn, would in 1900 lose 11% of its height travelling from a depth of 20 meters to the 6 meter contour, it would between the same depth contours in 1950 lose only 6%.

According to the previous analysis a change in the wave height of this magnitude should involve an increase in the average annual erosion of 5%. Since the slope of the bed has been doubled in the same period, the (absolute) rate of movement of the 6 meter contour

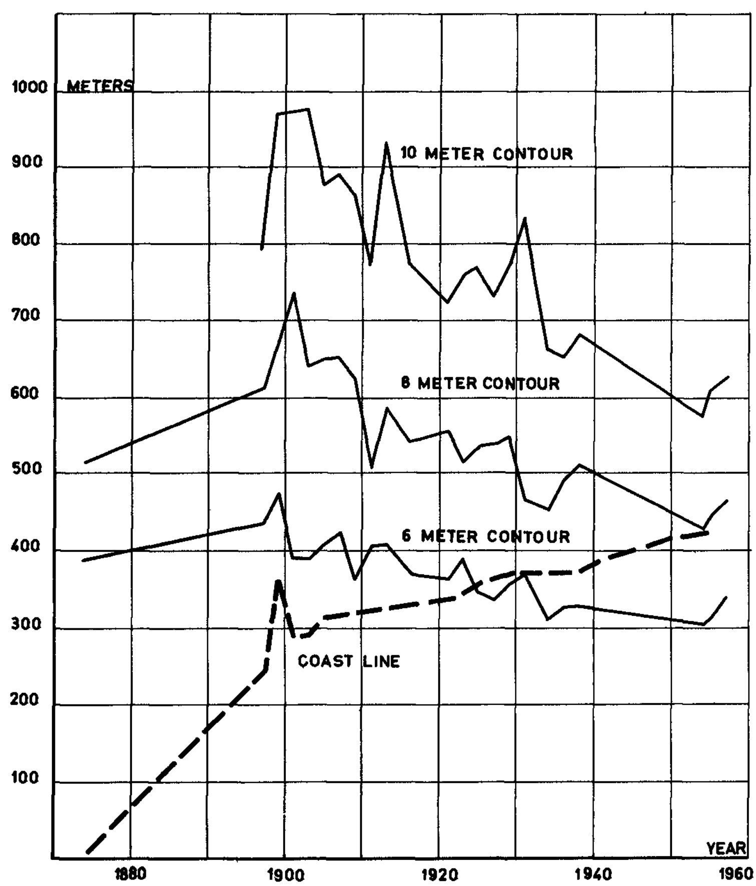

Fig. 3. Coast development on the North Barrier between L 12. Full lines show variation of distances from the coastline to various depth contours. Dashed line is a plot of the distance from the coastline to the original coastline in 1874.

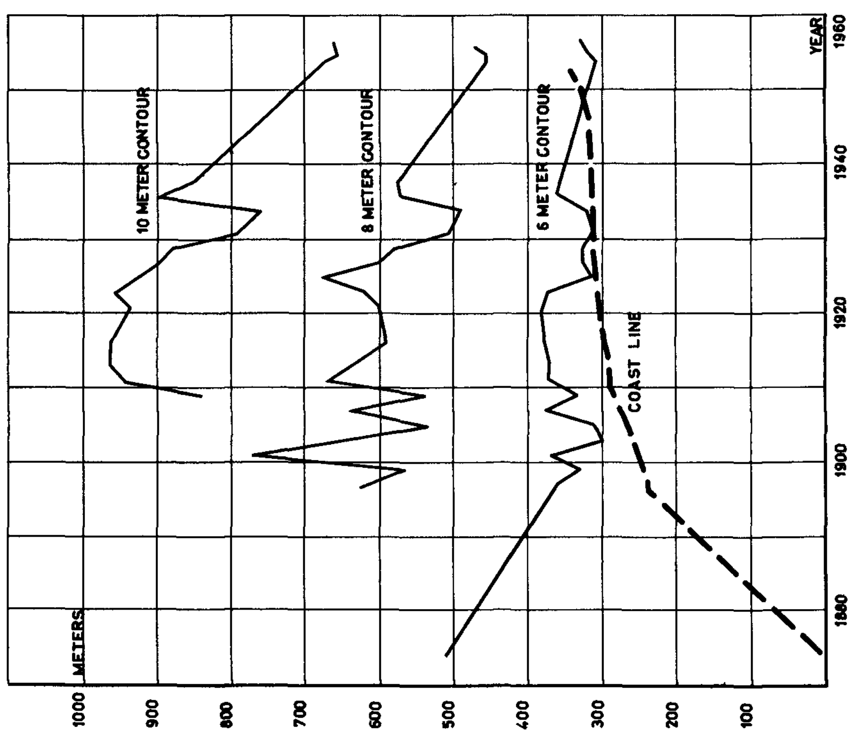

Fig. 4. Coast development on the South Barrier between L 23 and L 28.

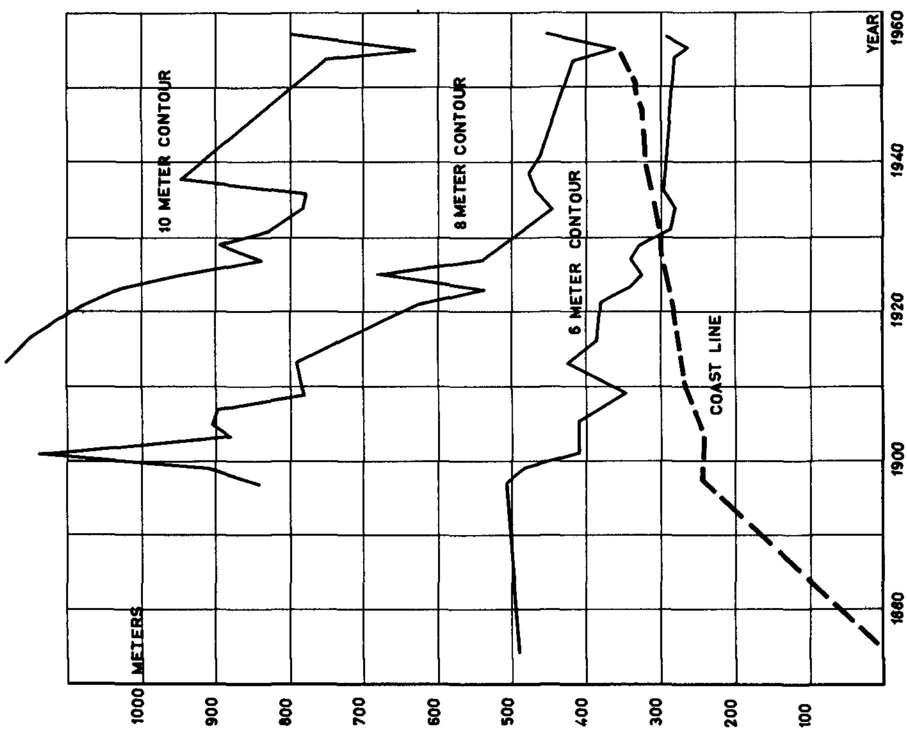

Fig. 5. Coast development on the South Barrier between L 21 and L 23.

should be expected to have been reduced by a little less than half of its original value. Because of the fact that the coastline also recedes,the reduction in the annual recession of the 6 m contour relative to the coastline should be considerably larger, which has, in fact, also been the case.

It is remarkable that the increase in steepness of the coast profiles has not caused any conceivable acceleration of the movement of the coastline. This may possibly be due to the fact that, as the coast recedes, the groynes are becoming longer, although the outer ends of the groynes are now submerged.

MODEL TESTS

The problem of the coast development on the Thyborøn Barriers has been investigated in a scale model at the Waterloopkundig Laboratorium De Voorst, Holland, for the Danish Board of Maritime Works. The results of this investigation has been that the coast recession would in the future be reduced to a lower value than the present one. In all probability, however, this result must be attributed to the fact that in the model the outer ends of the groynes were maintained in their original position, so that the coast protection in the model was more effective than in the prototype.

The main point is that the model gives no indication of any significant future increase in the coast recession, in which it agrees completely with the results of the analysis in this paper.

CONCLUSION

The construction of groynes on a continuously receding sandy coast will cause a permanent reduction of the rate of recession of the coastline. The groynes reduce the longshore sand transport not only on the beach, but also, indirectly, over the entire coast profiles. The shape of the equilibrium profile of the protected coast is determined almost exclusively by the longshore transport and the efficiency of the groynes.

ACKNOWLEDGMENTS

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