# COASTAL ENGINEERING

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## COASTS

IN RECENT years International Conferences have been held on two branches of coastal science, Coastal Engineering and Coastal Geography (or Geology). The proceedings of these conferences are available—see Bibliography. Engineers concerned with coasts and estuaries would find much useful information in the geographic and geologic studies.

### TYPES OF COASTS

Coasts may be briefly characterized as follows:

*1* Hard (granite *etc*), medium hard (chalk, sandstone, limestone *etc*) and soft or loose (shingle, sand, clay). The soft and medium hard coasts give rise to difficulties.

*2* Young, middle aged and old (*Figure 1*). Hard coasts keep their young appearance (fjords), medium hard coasts develop spits, tomboli, cuspate forelands *etc* in their middle age, and later on become 'old' cliff coasts. Soft coasts turn old in a few centuries but this does not mean that an equilibrium is established.

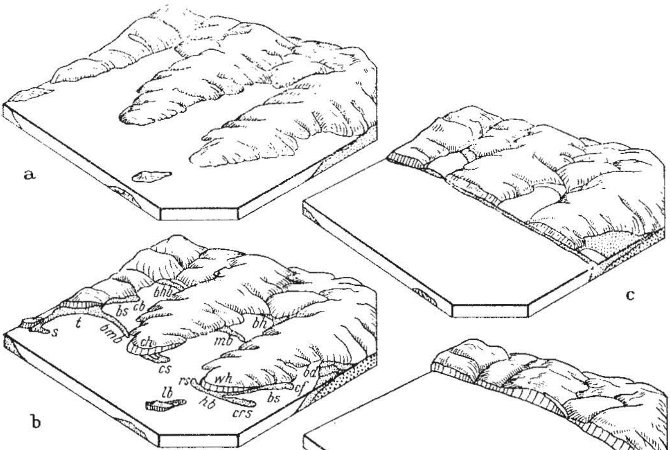



*Figure 1. Development of medium soft coasts* (D. W. Johnson) a *Initial stage* b *Youth* (bd *bay delta* bh *bayhead beach* bhb *bayhead bar* bmb *baymouth bar* bs *bayside beach* cb *cuspate bar* cf *cuspate foreland* ch *cliffed headland* crs *compound recurved spit* cs *complex spit* hb *headland beach* lb *looped bar* mb *midbay bar* rs *recurved spit* s *spit* t *tombolo* wh *winged headland*) c *Sub-maturity* d *Maturity*

*3* Shores of emergence and those of submergence. Owing to the general rise of the sea level relative to land levels by some 300 ft (100 m) or more, mainly as a result of the melting, due to climatic changes, of much polar ice during the holocene period, most coasts are of the submergence type. (The melting of the ice now existing would raise the sea level about 180 ft (54 m).) Coasts of emergence show eroded foreshores and ancient cliffs, or other former shore lines, above the present sea level.

*4* Coasts showing accretion and erosion. Coasts recede because of wave and current erosion; the eroded material (shingle, sand, clay) generally causes accretion in the neighbourhood.

*5* Hill land coasts. These have cliffs, the hardest parts of which form the capes, while the softer parts are modelled into coastal curves, which are 'suspended' between capes. 'Curves' are formed either by erosion, silting up of bays, or by the horizontal growth of a spit (*Figure 2*). If the curve is not wholly regular there must be a special reason for it. Sometimes erosion is too strong to form curves and the coast then may develop the appearance of the coast of *Figure 3.* Near such coasts there will be deep foreshores which could provide good harbour sites although the intense wave action may prove adverse.

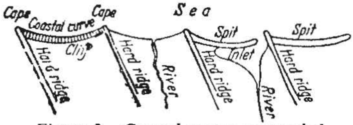



*Figure 2. Coastal curves suspended between capes*

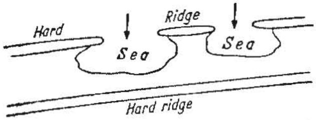



*Figure 3. Strong erosion of coastal ridge*

Spits and hooks are built up from the eroded material which waves tend to make into coastal curves; but these remain incomplete where there is not enough shingle or sand (*e.g.* German Bight), or they form anything else but a spit when there is no lee cape (*e.g.* the cape of Skagen, Denmark).

A cuspate foreland like Dungeness is an alluvial cape. It is a huge horizontal ripple obeying the general law of ripples and it is moving slowly eastward because of wave action (not current action) from the west. The shingle is eroded from the west bank and is carried around the top of the ripple to the east bank where it remains. The top of the ripple is the 'alluvial cape'. The lines of growth of shingle ridges on Dungeness show this. A tombola is a bar connecting an off-shore island with the mainland (*Figure 1*). Cuspate forelands, spits, hooks, tomboli *etc* are made up of eroded shore material.

*6* Lowland coasts (sand) are shallow coasts and may stretch monotonously over long distances (*e.g.* the east coast of North America, the coast of Guinea, the south east coast of the North Sea). Some small hills may have resulted in weak capes on such a coast and huge coastal curves may be 'suspended' between them. Other streamlined forms may also be present.

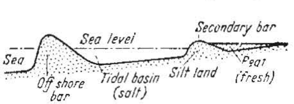



*Figure 4. Off shore bars*

Generally the original slope of the shore has been so small that off-shore bars have formed with shallow basins behind them. Such off-shore bars are formed principally in a vertical direction by wave action, *Figure 4*, but as soon as they have been formed horizontal growths such as spits come into existence. An off-shore bar often bears dunes. A low secondary bar may have formed because of wave action in the basin and behind this bar fresh water may have accumulated, which would cause fen land areas to come into existence. The secondary bar is the fertile silt area which shuts off the low fen district from the sea. The tidal (salt) basins may have partly silted up and in this way a lagoon coast may have formed. Because the tidal basin behind the off shore bar is filled and emptied by the tide, the off-shore bar often has openings at regular distances. Such a bar is transformed into a string of sand islands (*e.g.* Frisian islands).

The coast between Cap Blanc Nez (near Calais) and Denmark is formed essentially of an off-shore bar. In Flanders, that is south of the Scheldt, the original tidal flats behind this bar have since Roman times been wholly filled with sand and clay; but in Western Holland, where the Rhine and Maas provide fresh water, the flats could develop into huge fen districts. The tidal flats on the northern part of this coast are called *wadden* (*cf* ' to wade ').

## ESTUARIES

### TYPES OF ESTUARIES AND BARS

Estuaries are generally ' sunken ' valleys in which marine and river sand and mud have deposited. In these deposits the rivers and tides have scoured channels and creeks. Sometimes, in alluvial plains or in deltaic regions, an estuary has formed due to some low lying peat land becoming a tidal basin, or because some river mouth has become choked and a new mouth has developed. Such estuaries may follow the cycle, young⟶mature⟶old, as a result of silt movement along the coast or along the river.

The tidal rise and the area of the tidal basin are of primary importance for the estuary, because the currents which keep the channels in the estuary deep and wide are caused by the filling and emptying of that basin as the tides move in and out. The ' tidal basin ' is not, however, synonymous with tidal capacity because the tidal basin is the whole content of the estuary, whereas the tidal capacity is only that part of the estuary contained by the lines indicating the heights of slack water, *Figure 5*. The magnitude of tidal streams through a cross section of the estuary can thus be calculated.

When the estuary has the form of a wide and short basin (*e.g.* the Mersey basin), the tidal capacity will be almost as much as the total body of water contained in the basin between high water (h.w.) and low water (l.w.), because in such basins slack water generally occurs almost at h.w. and l.w.

When there are tidal streams in the estuary of about two or three knots at their maximum, which is generally the case because scouring and silting tend to establish that condition, the slack water will occur one or one and a half hours after h.w. and l.w.

When $P$ is the discharge of the river per tidal cycle and $f$ and $e$ are the flood and ebb discharges in the cross section considered, we have the simple relations:

$$Q = e + f \qquad \text{...........(1)}$$

$$P = e - f \qquad \text{...........(2)}$$

and

$$e = 0{\cdot}5\,(Q + P) \qquad \text{...........(3)}$$

$$f = 0{\cdot}5\,(Q - P) \qquad \text{...........(4)}$$

in which $Q$ is the total flow per cycle through the cross section.

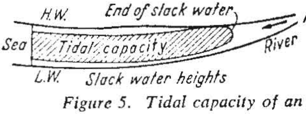



*Figure 5. Tidal capacity of an estuary*

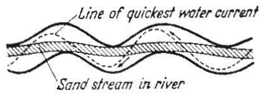



*Figure 6. Sand stream in meandering river*

As a result of the tidal fill and ebb, sand movements occur. We may introduce the term 'sand stream' here. In meandering non-tidal rivers, the sand stream tends to be straight, brushing the concave bends (*Figure 6*). The bulk of the sand moves near the bottom, the motive power being the current and the turbulence of the water. In bends there is a centrifugal movement at the top part and a centripetal movement near the bottom.

Generally two sand streams occur in estuaries and deltas, one coming down the river from the interior, the other travelling along the coast and often entering the estuary. The latter, called the coastal or littoral drift, can be mainly caused by waves. It may be much larger than the river sand stream. Both sand streams may meet in the estuary, or in front of its mouth. Of course, the sand streams are not continuous steady flows of sand; they are resultants of intricate movements over a long period. Ebb and flood move the sand to and fro in the estuary, and so do waves; but the important thing is that there are resultant sand streams often landward, or across the mouth, of the estuary. The resultant sand streams may not have the same direction as the resulting water streams near the surface. They may be opposed, or at different angles, to the main water streams.

Fine silt also may move differently, following the resultant currents which depend on the relative densities of fresh and salt water. Like salt, marine silt may move far inland. Where marine salt can go, fine marine silt can also go, and is likely to do so.

When there is any sand movement in a river mouth or estuary, either a terrestrial delta or a submarine delta will have formed. The river solids often create a delta inside the spit or offshore bar of the estuary (*e.g.* the Rhine). In quiet seas the delta may extend beyond the general coastline; in rough tidal seas a submarine delta is more likely. Though there are many estuaries on the coast between Calais and Jutland, no river, discharging at this coast, has carried enough material since the last ice period to build up a terrestrial delta in the ordinary sense of the word. The many submarine deltas of that coast consist of marine sands and the same can be said of the English rivers and coasts. There is very little soil erosion in western Europe except in Spain.

The simplest form of a sand bar is as indicated in *Figure 7*. When a river, carrying sand, flows into fresh water, the primitive form of such a bar is self evident; the cross section suddenly becomes very wide and therefore shallow. But when the river flows into the sea an additional factor affects the result because the fresh river water flows over the heavier salt water (see *Figure 20*). A primitive bar may develop into a delta or into a submarine delta. When there is coastal drift the form of the bar or delta will be asymmetrical. A tidal wave running along the coast also makes the delta asymmetrical (*Figure 38*).

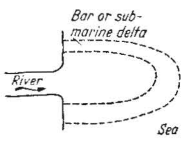



*Figure 7. Bar formed by river sand outside the river mouth*

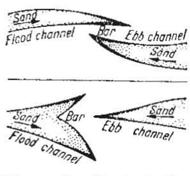



*Figure 8. Typical situation of flood and ebb channels*

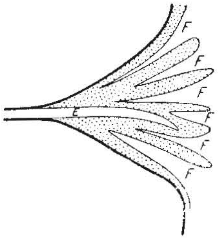



*Figure 9. Flood and ebb channels in a wide estuary* E *ebb channel* F *flood channel*

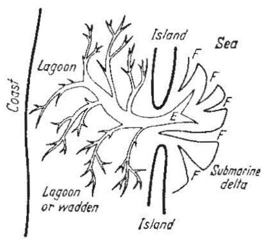
In tidal waters with sand bottoms the channels can be divided into flood channels and ebb channels: a flood channel is open to the flood and has a bar at the ebb end, an ebb channel is open to the ebb and has a bar at the flood end (*Figure 8*). Ebb channels and flood channels carrying sand will not follow the same course and shipping channels in estuaries often have one or more bars on which dredging must go on. Ebb channels have a tendency to take a different course from flood channels and *vice versa* (*Figure 8*). It is only when special works effect coincidence of these channels that a shipping channel without bars is formed. The reason why ebb channels and flood channels tend to evade each other is the action of sand streams which have a seaward direction in an ebb channel and a landward direction in a flood channel. Each stream deposits sand at its end and forms a bar.

*Figure 10. Flood and ebb channels in a narrow estuary—ideal poplar tree type (Scheldt)* E *ebb channel* F *flood channel*

When the estuary is wide and relatively short there are several flood channels and only one or two ebb channels (*Figure 9*). When the estuary is long and not too narrow the ideal form is like a poplar tree (*Figure 10*), whereas on a lagoon coast the creeks take a form resembling an apple tree (*Figure 11*).

The ideal 'poplar' type very seldom occurs. When it does occur, as in the estuary of the Scheldt, the 'trunk', or ebb channel, provides a good fairway for ships. The shores of the estuary are responsible for this ideal state; they have been fixed at the right places. In all other instances the

*Figure 11. Flood and ebb channels in a short, wide lagoon—apple tree form*



'trunk' is nearly always broken more than once (bars occurring in the main ebb channel). We may call this the 'wild type': with this type of estuary bars occur at both ends of the channels. If the sea bar is higher than the inland bar, we may still call the channel an ebb channel, but sometimes both bars are equally high. A clear picture of an estuary is obtained by showing ebb channels in blue and flood channels in red, schematizing the channels while doing so and increasing the strength of the colour towards the bar.

Cutting off of tidal meanders sometimes occurs in a natural way in an estuary, but generally the initial stage of the cut remains a common flood channel.

Wild types may change their channels by meandering, but more often the depth of their bars, so that shipping has to follow different courses from time to time, *Figure 12*.

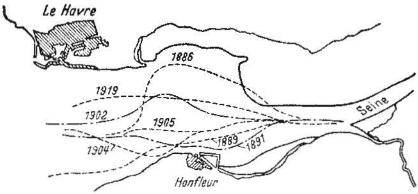



*Figure 12. Variations in shipping channel at the mouth of the Seine*

The erosive action of the flow of water at bends is the main cause of changes in the ebb and flood channels, a phenomenon we shall call bend action; it is the result of the centrifugal force of the water.

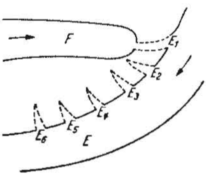



*Figure 13. Movement of small ebb channels showing a cycle of change* E= *ebb channel* F=*flood channel. The start is at* $E_1$

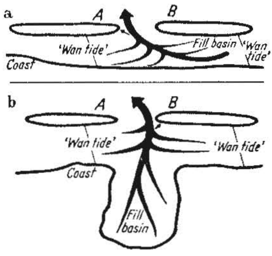



*Figure 14.* a, b *influence of situation and form of fill basin*

There are sometimes secondary ebb channels, originating near a bar at the end of a flood channel, and then shifting after some years due to bend action, as indicated in *Figure 13*. Such secondary ebb channels should not be trusted. When new ($E_1$) they may be fairly good shipping channels but their life is short, as ebb channels and flood channels tend to follow different courses. During successive stages the secondary ebb channel will show a movement from $E_1$ to $E_6$ (*Figure 13*) and after this a new cycle will start over again. The bend which the ebb-water has to follow to reach $F$ becomes more and more sharp, thus causing more and more bend action.

The geographical shape of the tidal basin may influence the place of erosion of the shores of a bottleneck; when the left part of the basin is the larger the right hand island is attacked by the tidal streams and *vice versa*

(*Figure 14*). The action is caused by the centrifugal force of water flowing in a curve. The largest body of water goes with the ebb from the largest fill area and determines the left or right curve.

In the northern hemisphere streams tend to the right shore because of the rotation of the earth, in the southern hemisphere to the left shore; this is of practical importance where the streams are more than about a mile wide.

The wind may displace a river or channel slowly in its most active direction due to wave action on the shore.

## COAST AND ESTUARY RESEARCH

The study of the behaviour of coastal waters and estuaries serves important economic interests. They include the saving of dredging expenses, the opening up of harbour and river mouths, the avoidance of land losses by erosion, the gaining of new agricultural land or industrial sites, and a saving on shore defences.

Four different lines of research are required: *1* geological and historical research, *2* research on the site to ascertain the currents and sand streams, *3* mathematical research and *4* research in hydraulic laboratories.

### GEOLOGICAL AND HISTORICAL RESEARCH

The general geology of our coasts and estuaries should be known. Borings can be made in the water covered areas and the study of all available historical data should not be neglected. Among the many questions to which answers are needed are the following. How much does the coast recede in a century and what are the fluctuations in this recession? What quantity of material is added annually to the coastal drift because of coastal recession or river discharge, neither clay layers nor mere chalk producing much coastal drift? Does the coastal drift protect the shore? In what direction do the shingle and sand travel ? How much is being lost into the deeper parts of the sea ? Is there any cycle in the changes of the channels of an estuary? Does the estuary deepen or does it silt up as a whole, and at what secular rate? See Proceedings of Conferences on Coastal Geography.

Sediment petrology is a branch of geology which studies the sand grains heavier than bromide (specific gravity$=$2). The origin and deposits of these materials can thus be established as well as the course of the sand and mud streams. Diatoms and foraminiferae may also give some useful information. There are distinct salt, brackish and fresh water diatoms. Geologists often want undisturbed boring samples and borings should reach to the rock bottom, or to a depth of about 120 ft (36 m), which is the depth dredgers can reach.

### RESEARCH ON CURRENTS, SAND STREAMS AND WATER LEVELS

Because shore processes are slow the average rate of change can only be decided where exact data are available for a long time. Where such information is lacking, concrete poles should be placed now along receding coasts in order to be able to measure their future annual recession. These poles should be placed every mile or half mile and taken as fixed points on the national triangulation net. The height of the beach should also be measured annually, and more often (monthly or weekly) when the height fluctuations of the beach are wanted. Those fluctuations may be up to three feet or more.

The foreshore should be surveyed periodically and the work can be greatly facilitated by the use of modern measuring techniques, *e.g.* echo sounding, measuring distances by tellurometer (see chapter on Surveying, vol. 1), by making use of portable radio *etc.* Bottom charts can then be prepared, showing the different materials (rock, clay, sand, shingle *etc*). These charts may show the places where silting and scouring occur; the size of the grains of sand must be determined as this gives an indication of the strength of the bottom currents. The engineer in charge of estuaries or shores should have complete records of the nature of the bottom of the whole area in his charge.

The currents and sand movements can be measured from the surface to the bottom under different conditions of wind, tide and river discharge. Different kinds of instruments can be used. The instruments necessary are an echo sounder, a current meter, a bottom sampler, a sand grain meter, salinity meters *etc.*

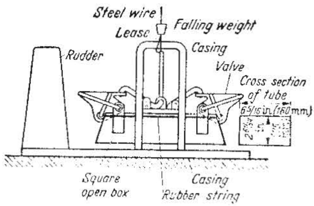



*Figure 15. Water and silt sampler*

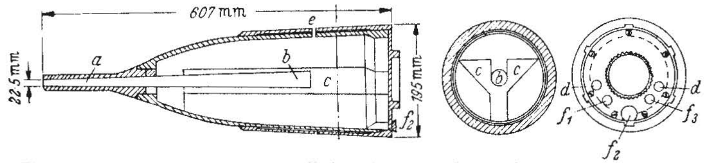



*Figure 16. Sand-transport meter (called 'Delft jar') a, b, nozzle for letting in water. c, room between plates. d, water-release openings. e, air-release opening. $f_1$, $f_2$ and $f_3$, plugged openings to remove the materials, deposited in the side chambers*

There are two main types of sand catchers, one measuring the sand content of the water, the other measuring the sand transported per minute. For sand content measurement the open tube is placed with its axis in the direction of the current, *Figure 15*. By means of a small weight sliding down the wire suspending the instrument two valves are released which shut simultaneously, actuated by a strong rubber attachment. The content of the tube may be five litres.

The sand transported can be measured in a vessel having a small opening at the front, through which the current flows without any deflection. This can be obtained by means of suction at the back. The idea is that as the flow expands inside the instrument it drops its sand, *Figure 16*.

The volume of sand streams, measured by means of sample takers or sand transport meters, can be checked by comparing the volume of material moved, as taken from the charts. Volumetric comparison of old and recent sounding charts is most useful. If the places where scour has occurred are shown in blue and the silted parts in yellow a good picture is obtained. The scouring and silting quantities must balance each other after geological subsidence has been taken into account. Hydrographic charts show principally shallow spots and relatively few deep figures but engineers need more detail than hydrographers, especially near shores and on sand banks. For volumetric comparison of the channels use should be made of cross sections sounded with an echo sounder. Charts based on lead soundings and on echo soundings may differ; the echo sounder generally gives more detailed results. Sand bottoms, which commonly have huge bed dunes, and also liquid mud bottoms, show considerable differences in depth when sounded by echo and by lead.

At a sand coast it is important to know at what distance the four or five fathom (7 or 9 m) depth line lies from the shore. If this line is moving close inshore the coast will recede after a few years.

Wind velocities and directions are usually recorded at inland stations but they are not much recorded on coasts. Land breaks the force of the wind, so coasts influence rainfall and sunshine to a marked degree; even low coasts have a considerable effect when there are dunes, houses or trees.

The influence of wind on the water causes waves, currents and abnormal water levels. 'Wind effect' is the raising or lowering of the mean sea level because of the direct drag of the wind upon the surface of the water. Shallow waters show high wind effects, deep waters small ones; the effect is given by the following expression

$$Z = 0{\cdot}036\, l \frac{v^2}{h}$$

where $Z$ = wind effect in cm
$l$ = fetch in km
$h$ = depth in m
$v$ = wind velocity in m/sec

A 'storm surge' is an exceedingly long wave produced by a depression or by wind elsewhere and it has a propagation of its own. It is important that the tide gauge records should be kept to the exact time, because the slope of the surface level between two stations is largely dependent on time differences (see p 483 *et seq*). One basic level only should be used for all gauges and the heights of the water level at the recording gauges should be frequently checked with the non-automatic ones placed near them. Moreover, in order to learn the variation of the mean sea level, there should be a few unalterable, totally stable, mean sea level recorders, which should be quite proof against any human attempt to alter or correct them.

The height of waves before they are reflected by shoals can be recorded on poles placed at 10 m depth.

An empirical formula for the influence of wind on natural wave height cannot easily be obtained. Modern wave-recorders show much wider

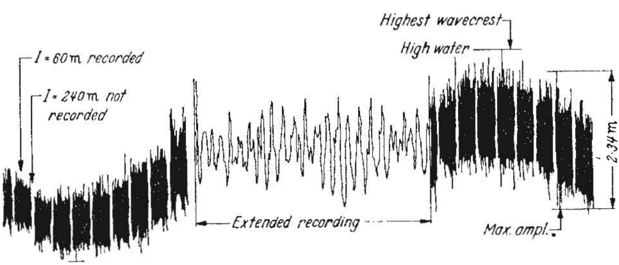



*Figure 17. Fragment of a diagram of a wave recorder. The motive power of the recorder is obtained from the waves themselves. The instrument works intermittently: 60 m amplitudes recorded, 240 m not recorded*

fluctuations of natural wave heights (*Figure 17*) than those obtained in a wind tunnel. When a wave reaches an embankment the extent of the uprush is determined by the form, slope and roughness of the sea face: embankments are made to such a height that say only 2 per cent of the storm waves will overtop them. Laboratory tests with the natural wave-pattern, or with the so-called significant wave, might give the amount of the uprush for a given cross-section of the embankment. At storm tide level consideration must also be given to the fluctuations of the storm flood level due to short surges which may last about $\frac{1}{4}$ to 1 hour and raise the flood 1 to 2 ft higher than the 'smoothed-out' level that is often called the storm flood level. The storm flood record is generally far from smooth and the top of the peaks that record these surges should be taken as the storm flood level. These peak levels could be responsible for many breaks in embankments where the free board was not very great; *e.g.* those facing east. Embankments facing west have been built for large uprushes of water and could often withstand these brief fluctuations. The height of the wrack of floating weeds *etc* left on an embankment or shore should be measured after each storm. In the Thames estuary waves can surge about 10 ft (3 m) higher than the storm h.w. level, but on many coasts it can be still higher. The new embankment at Veere (Zeeland) has a maximum height of 13·5 m (44·3 ft) above mean sea level, made up of 5·5 m (18 ft) for a flood with a frequency of 1 : 10,000 per year and 8 m (26·3 ft) for the expected wave uprush. The embankment does not face the open sea; it has shallows in front of it.

Among the lessons learned from the 1953 floods were: (*a*) the inner slope of embankment should not be steeper than 1:2$\frac{1}{2}$; (*b*) an embankment of clayey material may be stable so long as the material is neither too wet nor too dry. If the clay is a shrinkable one, large cracks will occur if it dries out and will reduce the stability of the bank; storm water may find its way into the bank by way of such cracks or by mole tracks, again weakening the embankment. An embankment of cohesionless material like sand, covered with a layer of clay that has dried out and cracked may also fail if it becomes saturated. As twin or triple storm floods often occur, the time between each storm being only 2 or 3 days, the risk of saturation of embankments becomes greater the longer the storm period. Only a cover of asphalt or a layer of very good non-shrinkable clay will keep the body of the embankment in good condition; (*c*) the toe of an embankment protecting land lower than high water should be strong enough to prevent the scouring tides running daily in and out after a break. In 1953 there were 67 such tidal gaps in the Netherlands and they were very difficult to close.

In estuaries the tidal currents generally are stronger than on the coasts, whereas the waves are less powerful. These are the characteristic differences between estuary coasts and sea coasts.

The h.w. water level at the upper end of the estuary (*Figure 18*) may not reach the heights of h.w. attained nearer to the sea. This we will call the flood tide depression. It results from either too large a tidal capacity or too shallow and small a bottleneck in the estuary, or both. On the south eastern shores of the North Sea such flood tide depressions occur south of Antwerp, east of Rotterdam *etc* and also formerly in the Zuider Zee and south of Emden. Such areas involve danger when work or dredging is in progress in the bottleneck, because the storm tides will reach much higher h.w.'s in the flood tide depression area. Such estuaries should be studied with great care. The Zuider Zee flood tide depression vanished when the enclosure dam was made. The h.w.'s came up to 3 ft higher, velocities increased by 20 per cent.

One method of dealing with tidal creeks, tidal rivers, and tidal tributaries is to dam them off, a lock being added for shipping. Such dams often cause higher sea-floods and to prevent this occurring basins with low

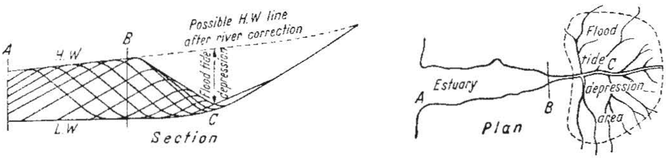



*Figure 18. Illustration of the term 'flood tide depression'*

embankments are sometimes provided into which the sea flood may spill. Wide tidal rivers need large basins to lower the storm floods. This method is not very satisfactory because such a basin is not habitable and raising the embankments is often the better method.

In order to retain a flood-tide depression area, a weir may be provided to close the river over, say, 90 per cent of the width: such a weir would not cause very high floods on the seaward side.

When a weir is closed while the flood is already coming in, translation-waves must be expected on both sides of the weir. The quicker the closing and the faster the currents, the higher and more dangerous are the translation-waves for anchored or berthed ships.

When studying coasts, rivers, and estuaries, sand movement is often found to be the most important factor. Erosion causes an increase in the sand stream, silting means a decrease. Scouring also means that sand deposits elsewhere, often where it is undesirable. Strong currents cause damage to the shore and also much sand displacement resulting in unstable channels and bars; against these, dredging may be of little avail. Small currents of less than half a knot at 3 ft (1 m) above the bottom may allow the fine silt to settle. Medium currents of one half to one knot at 3 ft height may give stable conditions and an estuary in which dredging is required only at long intervals.

In estuaries where there is an excessive amount of sand movement, the sand will flow up the flood channels and down the ebb channels as indicated in *Figure 19*. There may be many circular sand streams. Excessive sand movements indicate that Nature, not man, is the master: but shore defence and estuary training can reduce scour and thus reduce the sand movements and bars. Sometimes when such a bar is dredged the dredgings are dumped in a circular sand stream, thus making the dredging of little avail. (Actually the movement of a single sand grain is not 'circular' but is much more complex because of the ebb and flood streams; however, we may call these sand streams 'circular' to indicate that the same sand may return to the same spot again.)

There are also the non-circular sand streams mentioned on p 474 the magnitude of which can be learned by comparing the amount of material moved, as found from old and recent sounding charts. These non-circular sand and silt movements over a long period sometimes make the landward end of an estuary silt up while its seaward end deepens; sometimes the whole estuary may silt up when the coastal drift or the river itself provides much material. It is of importance to know these slow geological processes when a new harbour is planned.

Clay settles more quickly in salt water than in fresh water, because of coagulation (ionization): when water from a silt laden river flows into the sea this effect may be of great importance. Temperature has also a noticeable effect upon the settling of silt.

The difference in specific gravity of the fresh river water and the salt sea water may cause resultant bottom currents which move sea sand in a landward direction (*Figure 20*). In deep river mouths of depth 30-40 ft (9-12 m) these currents can be strong and they may tend to cause a bar inside the river mouth which has to be continuously dredged.

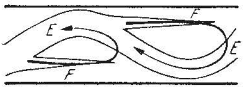



*Figure 19. Plan showing circular sand streams in tidal estuary; up in flood channels, down in ebb channels, but not quick and smooth movement. E ebb-channel F flood-channel*

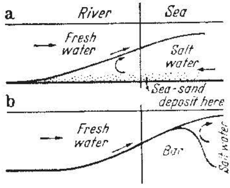



*Figure 20.* a, b *Reaction when fresh water flows into salt water*

Bars are of particular interest for engineers. They may grow higher even though strong bottom currents exist above them, silting being a question of the sand stream losing part of its sand. The growth of a ripple in a vertical direction may be akin to the growth of a bar, but there are also other factors.

In horticultural and agricultural districts the salinity of the estuary water is of great importance. The limit for fine fruit is 300 mg of chlorine per litre; for cows, horses *etc* about 1,200 mg per litre.

## MATHEMATICAL RESEARCH

The data gathered by means of site observations have to be analysed. Many hydraulic problems can be made clear and solved to a high degree of accuracy by mathematics and statistics. Tidal flow and tidal curves in new channels can be calculated accurately in this way, and sand movements to some degree. The height of embankments and the frequency of storm floods and abnormally low water levels, the mixing of salt and fresh water and many other problems can be approximately solved.

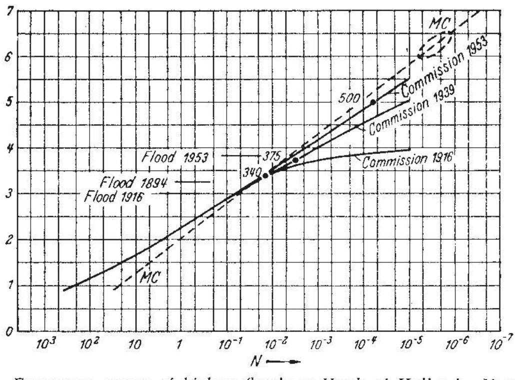



*Figure 21. Frequency curves of highest floods at Hook of Holland. Note that the steepness of these curves has increased since the study of flood occurrences started. The Mathematical Centre (MC) and the Meteorological Office of the Netherlands are of the opinion that only the most dangerous depressions may be used. The three highest floods occurred in 1916, 1894 and 1935*

Frequency curves of floods often assume the form of asymmetrical probability curves (*Figure 21*); when these are drawn on semi-logarithmic paper they produce approximately straight lines. Data collected during excessive storms only should be taken, according to Dutch meteorologists, oceanographers and mathematicians. Far steeper lines have thus been obtained than were accepted in former years (*Figure 21*).

### LABORATORY RESEARCH

This kind of research has become a special branch of hydraulic science and is dealt with briefly in the chapters on Mechanics of Fluids, vol. 1, and Hydraulics of Canals and Rivers of Mobile Boundary.

## TIDAL ACTION

Engineers dealing with coasts and estuaries should know the principles of tides, but they may find it difficult to master the mathematical details. The principles of tides can best be learned by studying an elementary book on alternating electrical currents. In the Netherlands three different methods are being used to calculate the tides for new schemes: the mathematical method is basic but slowest when no electronic computer is used. The hydraulic laboratory method is quick and can be made reliable, though it should be controlled by mathematics. The analogue computer is handy, especially for mass-computations, such as frequency problems for new schemes. The differences in tidal height found by the three methods will be small.

General analogy between tides and alternating currents:

| *Electrical current* | *Tides* |
|---|---|
| direct current | stream in ordinary river |
| alternating current | streams in tidal channel |
| mixed current | streams in tidal inlet with river discharge |
| conductivity | conductivity $= \Sigma b h^{3/2}$ (*Figure 22*) |
| resistance | resistance $= \Sigma 1/c b h^{3/2}$ |
| voltage | head |
| electromotive force | slope, gradient |
| capacitance | tidal capacity of basin |
| condenser | open harbour, tidal basin |
| self induction | inertia |
| angle of lag $\phi$ | angle of lag $\phi$ |
| conductor with varying capacitance | tidal channel or tidal river |
| Ohm's law | Chézy's law: $Q = c b_1 h_1^{3/2} \alpha^{1/2}$ |
| First law of Kirchhoff | $Q_1 = Q_2 + Q_3$ (at a knot of channels) |
| Second law of Kirchhoff | $M_1 = M_2 + M_2$ (around island) |
| Telegraph equation | Lorentz equation for tides |

In this analogy $b$ is the breadth of part of cross section, say 30 ft; $b_1$ the total breadth of channel, $h_1$ the average depth of channel (the channel has to be considered as having a rectangular cross section); $Q$ the total flow through cross section (ebb + flood per cycle); $\alpha$ the slope of water level; $c$ the constant of Manning; $M$ the motive area = area between tidal graphs of two successive stations (*Figure 23*); $l$ the distance between these stations; $\phi$ the angle of lag, generally about 0·9 in tidal channels as well as in electric nets.

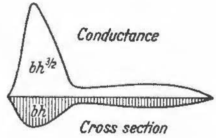



*Figure 22. Conductance of a cross section*

*Figure 24* can be found in all elementary books dealing with electrical currents. It gives the relationship between the vertical and the horizontal tide or streams. The slopes cause the stream currents, the latter lagging $\phi$ behind the former because of inertia.

A tidal net, containing many channels, receives its impulses from the sea, the boundary conditions being some miles outside the inlet mouths. All components of the tides in any new net of channels can be calculated, the horizontal tide (currents) as well as the vertical tide. The tides which occur when the river discharge is low, normal, high or very high can also be calculated for the proposed net of branches of the tidal delta.

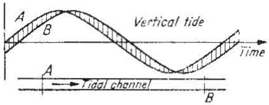



*Figure 23. Motive area between two tide gauge stations A and B*

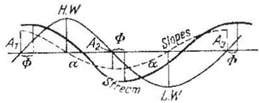



*Figure 24. Relation between vertical tide curves, the slopes, and the horizontal tide*

When the wind effect or storm surge in the sea is of importance the tides in the future net have to be calculated also for high sea levels and low sea levels.

Tides are imitated in an electrical circuit of conductors, condensers, resistances *etc* though there is one marked difference between electrical and water currents: in electricity we have the basic formula (Ohm's law)

$$\left.\begin{array}{l} e = ir \\ \text{with water (Chézy's law) } e = i^2 r \end{array}\right\} \qquad \text{............(5)}$$

In equation 5, $e$ = electromotive force, or slope $\alpha$; $i$ = current or flow of water per sec; $r$ = resistance.

Lorentz of Leiden University, when having to calculate the future tides outside the Zuider Zee dam in 1918, did not use the quadratic (hydraulic) law but the linear one, by taking a new constant $k = ci_0$; therefore $e = i^2 r$ became $e = ki$ and so the telegraph equations could be used. This linear method can be easily imitated electrically and all components of the tides can be measured electrically or made visible with a cathode ray tube. The more exact quadratic law can also be imitated electrically by using special rectifiers or special valves. An analogue computer has been working at the Hague since 1953 on delta work problems. A new computer, more exact and based on new discoveries, is now being built.

Conductances in the different cross sections vary in a 'wild' estuary, especially when man has used groynes instead of good smooth streamlines. For a steady well-regulated or quiet section of a natural channel, the relation

$$F = \frac{Q}{bh^{3/2}} \qquad \text{............(6)}$$

should be more or less a constant. That is, the conductance and the total flow (ebb + flood per tide) should become larger, both in the same degree, when going towards the sea.

For two cross sections, distance $l$ apart, the following formula gives the difference in conductances:

$$b_1 h_1^{3/2} - b_2 h_2^{3/2} = \frac{2\,ABl\cos\phi}{F} \qquad \text{............(7)}$$

where $A$ is the amplitude, $B$ the fill breadth of tidal river, and $\cos\phi$ is about 0·9.

When for navigational purposes depth $h$ is made a constant, we obtain the flare formula of Chatley:

$$b_1 - b_2 = \frac{2{,}000AB^2}{Q} \text{ ft/km} \qquad \text{............(8)}$$

A 'flare' is often not advisable, however, when currents due to differences in specific gravity and sand streams have to be taken into consideration. Streamlining, even outside the river mouth, the prevention of the formation of flood channels, the forestalling of a bar *etc* may be of greater interest than a regular flare.

The 'left tendency' of tidal channels is caused by a tide in the sea coming from the left (*e.g.* the mouths of the tidal waters along the south eastern shores of the North Sea). The theory of electricity (or of tides) can easily explain this (*Figure 25*), because the motive areas will be greater in the left hand channels than in the right hand channels. The co-tidal lines and the amplitudes of the tide define the cross sectional areas of the channels. When the tide in the sea comes from the right there is a 'right' tendency.

Harmonic analysis is the empirical fixation of the amplitude and phase of the component sinusoids in tidal graphs. Instruments, called harmonic analysers, resembling a planimeter, can be used without much trouble; for learning the tidal components used for actual tide predicting, however, one of the methods developed by tide experts must be followed (Doodson and Warburg).

A tide predictor is a machine in which the component sinusoids are running each in its own phase: one of the famous tide predictors can be seen in the Tidal Institute, Birkenhead, England. This Institute will also undertake the harmonic analysis and prediction of existing tides at any place.

Horizontal tides (streams) can be predicted as well as the vertical tides for any date in the future when the component sinusoids are known, but the wind and other meteorological influences are not taken into account. Near shallow coasts these influences are great.

Harmonic analysis and tidal calculation differ. The first is the analysis of existing tidal curves and prediction of them when no hydraulic changes occur in the channels; the other uses the fundamental law of Euler and calculates new tides in new channels.

Because of the quadratic relation between friction and current the higher harmonics $M_4$, $M_6$, $M_8$ *etc* are produced more and more when the tidal wave travels landward, *i.e.* the front of the wave becomes steeper. These harmonics are called shallow water harmonics. They change in amplitude and phase when dredging is going on, which is when the resistance changes.

A bore is a breaking tidal wave which only occurs where the tidal amplitude is large and the depth is shallow; it vanishes when dredging increases the depth.

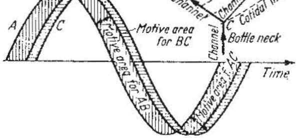



*Figure 25. 'Left' tendency caused by tidal propagation from the left*


*Figure 26. A 'Wheatstone bridge' channel (Dutch, 'Wan tide')*

A 'Wheatstone bridge' channel, *Figure 26* (the Dutch *Wan tide*, wan meaning abnormal, queer) is a place in a tidal channel in which only weak tidal streams occur: generally it is in a channel more or less parallel to the coast. The vertical tides remain normal.

## CURRENTS

When measured with good instruments the current velocities are generally highest near the surface, diminishing towards the bed according to the law in which $v$ is the velocity at height $h$ above bottom, $q$ is a figure ($\approx$ 5 to 7), $a$ is the velocity at $h=1$ m above the bottom (*Figure 27*).

This is for homogeneous water, without wind effect. In the North Sea $q \approx 5$; in rivers we find $q$ higher, approximating to 7 or 8. There are other formulae but equation 9 is the most simple and its graph lies about in the middle of the graphs of other formulae sometimes used.

In deep channels there is relatively more scouring because $a$ is dependent on $\sqrt{h}$.

The formula for stream verticals which is used most nowadays is a logarithmic one. The writer does not quite agree with this use, not because the velocities differ so much from those of the parabolic formula quoted above, but because the parabolic formula is more simple and it gives better results as regards the sand movements. The discrepancy of the logarithmic formula is too great near the bottom, where for $h=0$ the velocity becomes $-\infty$, whereas it should be 0.

Much research is being done to try to express the sand movements, caused by currents, in some mathematical formula. The sand content at any point in a vertical line can be expressed by an exponential equation.

Starting from the formula

$$v = ah^{1/q} \qquad \text{...........(9)}$$

$$N_z = N_a e^{-[C/k\sqrt{(gHI)}](z-a)} \qquad \text{...........(10)}$$

$C$ = terminal velocity of 'mean bottom sand grain' falling through water

$k = 0{\cdot}4$

$g$ = acceleration of gravity = 9·81 m/sec

$H$ = depth

$I$ = slope

$z$ and $a$ = percentage of height (relative height)

$N_a$ = sand contents at height $a$

$N_z$ = sand contents at height $z$.

Equation 10 is for continuous currents; $C$ is affected by the temperature of the water.

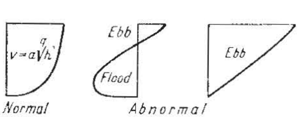



*Figure 27. Normal (homogeneous water) and abnormal (heterogeneous water) stream verticals*

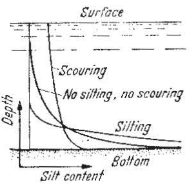



*Figure 28. Silt distribution in stream verticals for scouring, equilibrium and silting*

When checked with actual measurements made in the Mississippi and in Dutch waters (tidal or non-tidal) equation 10 has proved better than the formula based on logarithmic stream verticals.

Generally it is found that the total sand content in a vertical varies with $v^3$ or $v^4$, which means that the total sand transported varies with $v^4$ or $v^5$. If a spring tide current is twice as strong as a neap current the former will transport sixteen to thirty-two times more sand. Tidal channels therefore are kept wide and deep by the scour of spring tides, more than by the scour of the normal tides. Neap tides have little scouring power.

In tidal streams, where silting and scouring change even during the tide, we should not lose ourselves in too much detail. The graph of sand content in a scouring river is markedly different from the graph of a silting one, *Figure 28*.

A sand-laden stream will not pick up more sand than it can carry. This is the reason why bars will not scour. A stream not carrying sand *e.g.* a stream coming through a weir or barrage, is able to pick up its full load. Scour may therefore take place downstream of a patch of rocky bottom, thus originating a sand stream. Narrows (*e.g.* the Straits of Dover) show such a clean rocky bottom with no sand movement above it. Its huge stream is undercharged.

Nevertheless in such regions there may be long and high sand banks lying on the hard bottom in the general direction of the ebb and flood currents Because they offer little resistance to these currents they have remained in their places during the past centuries. They resemble the desert formation called Libyan dunes, *Figures 29, 30*.

When the sand grains are the right size and the currents have the right velocity a sand bottom will produce huge bed dunes, perpendicular to the general current direction. These submerged dunes may be 20, 30 or even

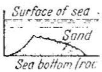



*Figure 29. Cross section of 'Libyan dune'*

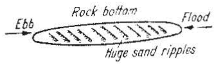



*Figure 30. Top view of 'Libyan dune'*

60 ft (6 m to 18 m) high in the southern North Sea and about 3 ft (1 m) in a river of say 15 ft (4·5 m) depth. Generally the height is about 20 per cent of the free depth. The form of these huge ripples depends on the supremacy of either the ebb or the flood. They give an indication in which direction the sand is moving (*Figure 31*). Regular bed dunes can only occur where much sand is available and do not occur when rock, or a clay bottom, is partly exposed to the currents.

Where only a small quantity of sand is lying upon a rock or clay bottom this sand collects into 'barchan' dunes where the current is continuous in one direction, and into long sand banks, resembling Libyan sand dunes, where there are alternating currents.

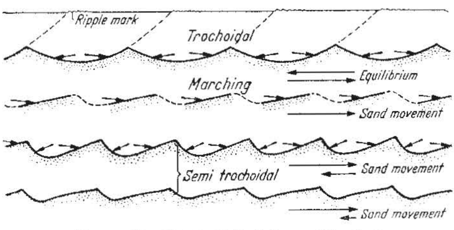



*Figure 31. Types of bed dunes (ripples)*

In estuaries, ebb channels usually make the best navigable waterways, but in the outer part of a delta a flood channel will be the best entrance. The aim of the engineer is to make the ebb and flood channels combine in such a way that a deep fairway results. Here Nature opposes because of sand movements. The way to attain good results is to forestall bend erosion and excessive sand transportation. The lower Scheldt is a fairly good example of what can be attained by good fixation of the shores. With the Scheldt the sinuous ebb channel or shipping channel is kept in fairly good condition by its protected shores. The flood channels spring forth at every bend of the ebb channel: they serve a local function of filling part of the estuary.

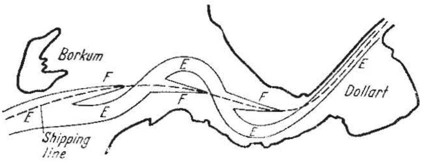



*Figure 32. Channels of the Ems estuary* E *ebb channel* F *flood channel*

The Ems estuary was originally also of the ideal poplar type but the Germans decided to make a straight shipping channel and therefore chose the line of the flood channels, *Figure 32*. Nowadays dredging can force almost any solution.

When a non-tidal river branches off from the main river at an obtuse angle the sand will go mainly into that branch because the weak bottom currents (carrying the bulk of the sand) can be deflected more easily than the stronger top currents which flow straight on. The sand may partly settle at A (*Figure 33*). This angle effect provides a means of diverting part of the river sand into places where it is required. The layout of the dividing points of branching rivers or channels should be constructed with care when they carry sand.

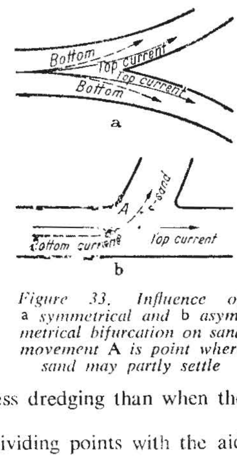



*Figure 33. Influence of* a *symmetrical and* b *asymmetrical bifurcation on sand movement* A *is point where sand may partly settle*

Tidal sand streams can be controlled as follows:

*1* by making the fill area larger or smaller. If the flow into the fill area becomes smaller the sand stream will be much more so and this may mean less dredging than when the currents were too strong

*2* by making good alignments and good dividing points with the aid of spurs and shore defences

*3* by dredging; the new depths attract the currents while those in the undredged concurring (parallel) channels slacken.

The wider and larger the tidal channels, the less man can influence them; if a channel is narrow and deep it is more manageable. Large sea shore currents are extremely difficult to influence. We must accept them as they are, but we should not neglect to study them as well as their results.

*Example*—In the estuary indicated in *Figure 34*a, there are two flood channels $F_1$ and $F_2$. The latter has been diminishing and the former has been increasing, so that it might be expected that $F_1$ would become the main shipping entrance. To accelerate this, it is proposed that $F_1$ be dredged and that a flank embankment *h* be constructed along the outer bend of $F_1$, that several long groynes be made across $F_2$, and that a groyne *f* would serve to make E flow into F without an intervening bar.

This scheme is largely fictitious but serves well as an example for comparison with an alternative scheme (*Figure 35*b), which has the advautage that a parallel embankment on the high sand bank between $F_1$ and $F_2$ would be much cheaper than the groynes *a*, *b*, *c*, *d*, *e* and *f*, because parallel works are easy to construct and the sand bank is high.

Secondly, the action of groyne *f* (*Figure 35*a) projecting far outside the normal lines would be contrary to the principle of a stream line. A large deep hole would be scoured out, a very bad river portion would result, and *E* and $F_1$ would not run into each other smoothly.

Thirdly, the parallel embankment *h* should be connected with the shore at the upper end of that embankment, because the tidal area behind it should be filled and emptied from the sea end. The parallel embankment would be expensive, being made in rather deep water. It would have to be protected over the whole length against attack by the currents. It would, therefore, be cheaper to make a parallel embankment on the higher parts of the tidal sands and to construct small groynes of say 300 ft (90 m) length and at 500 ft (150 m) distances apart projecting from the embankment.

The main trouble here lies near the cape at *C* where sand may deposit easily. The estuary should not be too wide there, and the channels $F_1$ and *E* so situated that they join up. Channel *E* has already in the past moved too far seaward towards *C* because of bend action, so either channel *E* or $F_1$, or both, have to be deflected to such an extent that they will coalesce.

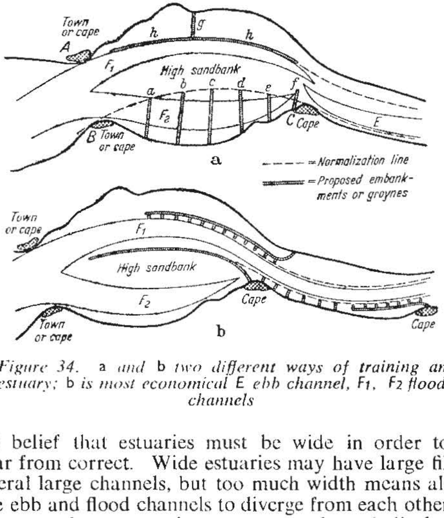



*Figure 34.* a *and* b *two different ways of training an estuary;* b *is most economical E ebb channel,* $F_1$, $F_2$ *flood channels*

The old belief that estuaries must be wide in order to have deep channels is far from correct. Wide estuaries may have large fill basins and therefore several large channels, but too much width means also too much liberty for the ebb and flood channels to diverge from each other. Moreover the ideal is not to have excessive currents and sand displacements, but moderate currents with no sand or mud displacement.

A recent study of the Thames estuary is described in a paper by Inglis and Allen.

One conclusion is that dredged material should not be dumped anywhere in the estuary but should be pumped ashore for land reclamation schemes. (See paragraph on Reclamation, p 502.) The model used for this study even showed the fresh plus salt water currents, and the resulting landward density drift. The 'node or zero point in the estuary', where this landward drift is tending to zero (see *Figure 20*, top-end of salt-wedge) is the critical place where the heavy part of the silt may settle. (In general, this would not mean that dredging would be a maximum at the 'zero point', because fine sea-silt could come much further landward, and, being more voluminous because of excessive water content, up to 90 or 95 per cent, might cause even more dredging.)

The study of the Thames estuary shows clearly what can be achieved by the proper use of models in conjunction with observations made in the estuary itself and mathematical analysis. A good model can serve as a computer for the new tides that will occur in an estuary to be trained or re-formed, and can show density currents and silt movements. Observations in the estuary or the mathematical analysis of tides and sand movements are not, in themselves, sufficient when dealing with estuaries. A model must imitate Nature and model techniques will improve as Nature and its laws become better known.

Though we may expect to be able to calculate sand streams in tidal waters with a moderate degree of exactness in the not too distant future there are some baffling problems, especially in connection with the formation of bars in tidal areas and the formation of bed dunes. We should try to learn by calculation why some estuaries are eroding, while others show accretion; and we should consider whether we can influence the ebb currents or flood currents so that the former may create a larger sand stream than the latter. The mouth of the Scheldt and the lower half of its estuary has deepened more than 3 ft (1 m) in a century (calculated over the whole area of the mouth) and most other Dutch inlets have also increased their mean depth in this period.

## WAVE ACTION

The energy of the wind acting on the water is partly stored in the waves. When these break on the shore this energy is partly spent in destroying the coast or in displacing material. Reflections can be calculated, see Proceedings of Coastal Engineering Conferences.

There are three different coastal zones to be considered: those acted on by stream currents, waves, and wind. They are not sharply separated (*Figure 35*a). The wave zone of a coast is most attacked when an open sea front is concerned; in estuaries the stream currents may be the most destructive.

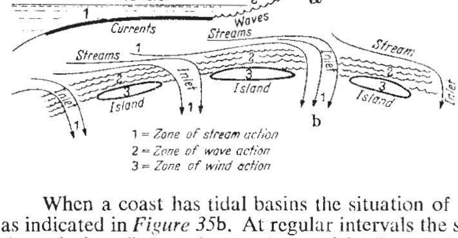



*Figure 35. The three coastal zones* a *section* b *plan*

When a coast has tidal basins the situation of the three zones becomes as indicated in *Figure 35*b. At regular intervals the streams will have broken through the off shore bar, and dune islands may have formed between the breaches.

Waves create strong bottom currents and much turbulence when they break, *Figure 36*: wave action alone can create spits *etc* as can be seen in lakes. Wave turbulence 'lubricates' sand movement by water currents. Wind blowing towards the land causes a surface current in that direction and a bottom current in the opposite direction. This bottom current, especially during storms, may carry much sand seawards. In calm weather some of this sand is carried back by the movement of the breaking waves.

Sand which has been transported during the storm into the deep layers at some distance from the shore does not return; generally the shores lose material and the gains are small.

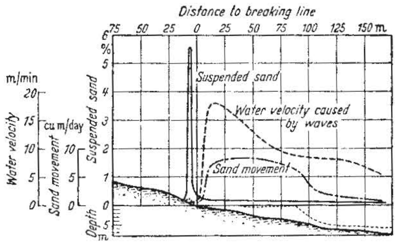



*Figure 36. Currents and sand movement caused by waves, according to Beach Erosion Board, Washington*

The submarine sand shore requires a certain slope, say 1 in 100, to be in equilibrium. Coastal retrogression will occur when the slope is steeper; such a coast is called a 'poor' coast. When the waves throw a bank of sand on the shore the coast becomes 'rich', temporarily.

Waves may create sand ridges of about 3 to 6 ft (1 to 2 m) high, lying parallel to the coast in the breaking zone. These ridges are pushed up the beach when the weather is calm, *Figure 37*.


*Figure 37. Shore and sea ridges or ripples on a sandy coast*

Coastal inlets with sand movement have a submarine delta outside the entrance or bottle neck, *Figure 38*. Such a delta does not grow above a certain level, say about l.w., because wave action opposes further accumulation. A marine delta of this kind may protect the lee shore, because waves break on the sands of the delta and they carry some sand from it on to that shore, making it richer. The littoral drift passes over and along the outer side of the submarine delta. Because of this, and because of the protection which the delta provides, the 'head' of the leeward island or coast of such a bottle neck formation may protrude outside the general coastline. The other shore of the inlet shows a 'tail' or common spit.

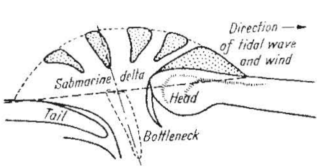



*Figure 38. Submarine delta protecting a lee shore against wave attack*

When a lagoon is silting up the streams in the bottle neck decrease, because the tidal fill diminishes; hence the size of the submarine delta also decreases and the protection this delta provides against wave action decreases. When the lagoon has silted up completely the submarine delta will have vanished and the coastline will have become a smooth line of sand. Heads and tails will then have disappeared.

Homogeneous sand shores always show smooth lines because action and reaction is everywhere the same over long distances. Some danger of losing land may result when man alters this smoothness by making defence works, harbour entrances *etc.* The size of the channels in a submarine delta, as illustrated in *Figure 38*, depends on the motive areas (gradient of tidal levels, see *Figure 25*).

## SHORE PROTECTION

### GENERAL

Shore protection probably started with planting willows (fresh water) or other plants. Protection with wooden boards or stones may have followed soon after, but it is said that the Chinese, who in early times excelled in making embankments and river improvements, neglected the underwater part of their defences. This is still one of the main faults of many coast defence works.

The building of embankments seems to have first started in England near Chatham in the 6th century (Dobbie states that Romney Marsh was diked before A.D. 772).

In Holland most of the alluvial land was reclaimed by embankments (dikes) before 1200; but after that year much land was lost again because the level of the land had sunk due to settlement of the soil resulting from better drainage. From 1200 to 1930 more land was lost to the sea in Holland than has been reclaimed from it. The old embankments may still settle 2 ft or sometimes even 10 ft in a century. Settlements of 10 in a year as a maximum have been measured in the delta of the River Po. The cause of this settlement is in dispute. The settlement of alluvial soils may be important.

The embankments of the Low Countries were originally protected by heavy wooden structures and by mattresses of willow boughs below l.w. These costly wooden structures were eaten up by the pile worm after about 1730, which caused much anxiety throughout the country. Stone defence, based *on the principle of grading material* (*e.g.* fine, coarse, coarser, very coarse) was found to be the solution. By this principle sand can be protected by small gravel, and small gravel by coarse gravel, debris, or broken stones, and the latter by stones heavy enough to resist wave attack.

The pores must be as small as possible and be made smaller and smaller in a downward direction. No sand may pass through the pores of the layer of shells or gravel; no shell or gravel may pass through the pores of the coarse gravel; no coarse gravel may pass through the pores of the bigger stones; *etc.* This is the principle of grading and it is of the utmost importance; neglect of this principle has resulted in many failures. Mussels and other small shells should be allowed to cement the stones together.

An example of a defective revetment where this principle has not been observed is shown in *Figure 39*. The defects are:

*1* sand will be washed away through the pores of bricks, rubble and basalt.

*2* unless there are groynes, or the beach is in equilibrium, the toe of the revetment is not safe; there is no grading to prevent the washing away of sand through the large pores of the toe.

Therefore the method should be slightly changed. Sand is protected by a layer of good clay, this clay is protected by a layer of straw, *krammat*, and above this the layers of rubble (or gravel) and heavier stones can be placed. Straw is not a permanent material, however, as it will rot. The clay must, therefore, be protected with small sized material as well. The wave currents seeking to penetrate the pores must not be able to reach the layer of clay.

When underwater protection of a sandy bottom is needed, the use of willow mattresses is the ancient well tried method. By using reed (with the leaves still on) as the central layer between the willow layers, the *zinkstukken* (willow mattresses) become less penetrable to currents.

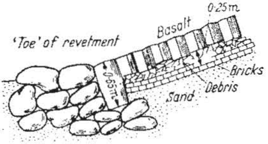



*Figure 39. Example of revetment with weak toe*

Willow mattresses are of great value in protecting the shore below water level. They consist of a lower grid of fascines consisting of bundles of willow boughs, diameter about 4 in (10 cm), spaced 3 ft (1 m) apart, with an upper grid of the same construction. Between the grids two or three layers of willow boughs are pressed down and bound with ropes. Sometimes a layer of reed (preferably with leaves) is put in the middle instead of a layer of willow boughs; the purpose is to prevent bottom scour under the mattress as far as possible. Instead of willow boughs, other local material can be used such as millet stalks, papyrus, blackthorn *etc.* The total thickness of a mattress is about 2 ft (0·6 m).

Because the closing of the Zeeland estuaries ('Delta-works') would need about 2 million sq m of mattresses and brushwood could not be grown in such quantities, experiments with asphalt sheets, plastics sheets and nylon woven fabric are being made in the Netherlands. Asphalt sheets allow sand to pass through the overlapping seams, plastics sheets do not lie flat on the bottom because of pockets of air underneath; nylon fabric (meshes about 0·2 by 0·2 mm, thickness about 0·5 mm) suited best because air and water pockets cannot form underneath and the sand cannot come through the fine meshes. (This system is the subject of Dutch patents.) Nylon fabric hoses, pumped full of sand, the water escaping through the meshes, are used to hold down the sheets. The first enclosure, at Veere, will need 36,000 sq m in 1960-61.

A general rule is to use local material as extensively as possible. Heavy clay, dredged from the sea bottom in the neighbourhood, may serve as ballast for the mattresses, but this clay may dissolve after some time by molecular action. Also certain stones may crack and split up after some years and such stones and clay should not be used.

The art of making coastal defence as economical as possible is difficult because of the variety of shores and material. Often much rock is wasted by lack of a mattress foundation, which should prevent scouring while the work advances. A sand bottom should be well covered with a mattress or with good layers of fine and coarse gravel before the coarser material of the training wall, which causes a strong current in front of it, is brought into place.

The construction of dams on a rock bottom was carried out with success at Scapa Flow. Crates of steel mesh, 6 ft cube, were filled with rip-rap and placed with the aid of a cable spanning the fierce tidal streams from island to island. Plastic sacks filled with sand were tried in 1957 in the Netherlands with good results (weight of the filled sacks 2 tons). Nylon fabric sacks can be pumped free of sand and the water escapes through the meshes. In the gaps of the Zuider Zee dam heavy barytes stones were used.

When it is desired to construct a dam across a gap with an erodible bottom, a rock apron (or mattress) strong enough to resist excessive erosion should first be laid. In the breaches of the 1953 flood many concrete pontoons (7,000 ton weight each) were sunk at the turning of the tide. The use of large special units is the latest development in closing tidal gaps.

For closing the huge gaps of the 'Delta-plan', (1955-1980), many large concrete structures may be used which can be shut at the moment of still water.

STREAMLINE PRINCIPLES

One of the main methods of coastal defence is to build artificial capes which can be placed at regular or at irregular distances; for the latter, existing strong points are used. The aim is to divert the streams from the shore *i.e.* to protect the land. Vierlingh (1570) laid down the principle that streams should be gently deflected: 'he who exerts force on water, will have to meet the force of the water.'


*Figure 40. Effect of single groyne*

Fargue in the second half of the nineteenth century formulated his well known rules for correcting rivers; they were rules bearing on streamlines and their objects were to make the river carry its water, sand and ice rather than to protect the shores of the river, though this was included. On shores of estuaries and coasts, the streamline principle should also be taken into account, especially when the shore itself is streamlined by nature.

Where a series of groynes is built, *Figures 41, 42*, scour will occur on either side if the series ends abruptly. Sometimes a salient point *e.g.* a harbour pier, is specially required and a large deep hollow will be formed just in front of it.

This very simple, self evident, rule of action and reaction is the principle of streamlines. No one would think of fixing an angle section on the wings of a plane with one leg at right angles to the wind, but in hydraulics we sometimes meet with such obstacles. Single groynes create much turbulence and very irregular cross sections with extraordinarily large local disturbances, and they will attract the channel instead of pushing it from the shore, *Figure 40*. Moreover they are costly, because the force of the stream makes frequent repairs necessary.

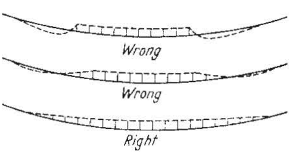



*Figure 41. Ways of ending a series of groynes*

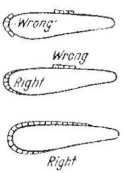



*Figure 42. Groynes on an island*

The top of the wing of an aeroplane has a lifting function as well as the under surface. In the same way the inner bend of a river can be streamlined with a parallel embankment (revetment) in such a way that it attracts, or keeps, the current so that good navigable depths may be obtained even near the shore of the inner bend. This is, as seen from a theoretical viewpoint, totally different from the irregular depths found along shores defended by groynes.

When the current in a branch of an estuary is not strong enough to cause scour, yet is sufficiently strong to prevent silt from settling, the streamline principle can be neglected to a large extent. These channels make good sites for harbours and industries because extra wide river sections can be made that may remain stable.

The alignment of tidal channels should be in accordance with their breadths as flood and ebb should be led through the same parts of the channels (*Figure 43*).

A good type of a half trained, half natural estuary is the Lower Scheldt. As has been explained already, the reason why the Lower Scheldt has a good fairway is that the shores offer the right resistance at the right places. If the shores of the Scheldt estuary had not been protected, or had been protected in other positions, the Scheldt would have no more navigable depth than the East Scheldt, north of Walcheren, and would be 'wild'. Streamlining was not, however, the object; the aim was to fix the bends.

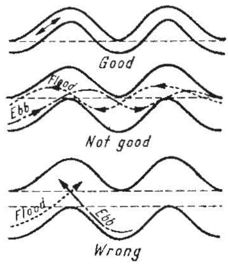



*Figure 43. Alignment of tidal channels according to breadth*

TYPES OF GROYNES AND OTHER SHORE DEFENCES

There are so many different coasts and so many ways of constructing groynes and revetments that it is not possible to give one solution only. Experiments with the materials at hand have been made on many coasts and have resulted in some method being devised which is economical and successful. These experiments still go on however, a sign that the art of finding the most economical way of defending a certain coast is not easy.

Three main types of coastal defence can be discerned:

*1* revetment type
*2* groyne type (artificial cape type)
*3* small groyne type (using the coastal drift as a means of defence).

*Revetment type*

The whole shore surface is protected from a low level up to a certain height above high water (*Figure 44*). This is a very costly method. The streamline principle can be followed, so that the stream shows little turbulence near the

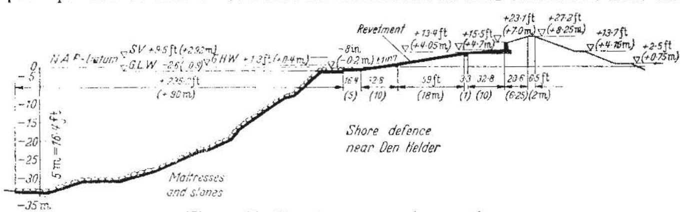



*Figure 44. Revetment type of protection*

shore, but nevertheless the cost of upkeep is often enormous. The defence works near Den Helder in Holland, shown in *Figure 44*, are the most costly shore defence works in the world; mattresses and stones have had to be added at frequent intervals for more than 150 years. Instead of using expensive Belgian stone an experiment is now being made to use local diluvial clay, dredged nearby. The revetment type of protection should extend further than the lowest part of the channel, when the current is the cause of coast recession. For wave eroded coasts less depth may be sufficient.

When there is a stable beach, or when there are saltings, only the part above the beach or saltings need be protected. But great care should be taken that such a revetment cannot become undermined. Often such a high beach or salting has to be protected by groynes, or if possible with plants. A row of wooden stakes or faggots at the toe may be of some slight use to allow the beach or salting to be lowered a little by the waves without causing damage to the revetment, but they will not stand much loss of beach height.

Waves act fiercely on a revetment as they arrive unbroken. The upper layer of stones should be heavy enough and well placed and keyed, so that only small amounts of water may penetrate into the revetment. Mussels must be allowed to grow on them. Some engineers used to prefer wooden poles sticking about 3 ft (1 m) high out of the revetment in order to break the force of the waves. Most engineers now object to this construction because they consider that the poles are vibrated by the wave action and loosen the revetment.

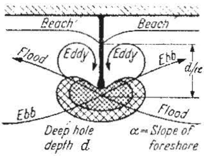



*Figure 45. Groyne effects (length of groyne should be greater than $d/\alpha$)*

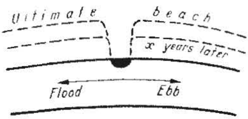



*Figure 46. Possible effect of groyne (ordinary Dutch type)*

Several experiments have been made using grout for closing the pores, but a rigid closed surface has the disadvantage that large holes may form underneath it. Even on old, well settled embankments, large concrete slabs or a rigid closed cover of concrete are hardly advisable. Asphalt in the pores allows more settling, but the engineer should beware of making a non-flexible, closed surface where the foundation and footing are not very stable. Bitumen filling can, however, be recommended in the case of many old stone revetments.

Bitumen slabs can be made of 13 to 20 per cent bitumen, 70 per cent sand and the rest small gravel. Plants often are activated by asphalt so that they may grow through the slabs; the bottom must therefore be made sterile before the slabs are laid. Reinforced asphalt slabs can be handled by crane but the difficulties are considerable. Nylon fabric can be used under a revetment, see p 493.

Small wave action may be opposed with small means; concrete tiles or clay bricks, or even loose debris may suffice, and grass and weeds should be encouraged to grow between them. Willows, reeds or rushes may be planted to protect the revetment; willows need fresh water, reeds and rushes may grow in slightly brackish water. Saltings or foreshores can be encouraged to silt up to a higher level, see p 502.

Straw thatching (*krammat*) and wood thatching have their uses for temporary defence. *Krammat* is also used as a protection for a clay layer under a stone revetment, but modern practice is to use nylon fabric.

*Artificial cape type of groyne*

Groynes of the artificial cape type have to be of solid construction and have to be stronger than natural capes. The most important feature of such a groyne is its head. The stones on it must be heavy enough to prevent their being rolled away by the waves and, to prevent the stones settling into the sandy bottom, willow mattresses are needed, or else the principle of grading should be used. The underwater part of the head must be frequently examined and the sea bottom around it must also be sounded regularly.

The length of the groyne, *Figure 45*, must be longer than $d/\alpha$, when $d$ is the depth to be expected in the deep hole in front of the groyne and $\alpha$ the slope of the sand along the groyne.

If the groyne is made too short, Nature will take material from the shore until it is satisfied, *Figure 46*. Especially with single groynes and strong currents the depth $d$ will become greater and greater and the shore will, therefore, recede more and more.

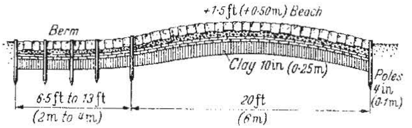



*Figure 47. Body of groyne (ordinary Dutch type)*

The 'body' of the groyne connecting the head with the shore is of less importance than the head. Its object is to prevent a gully forming behind the 'cape'. In the ordinary Dutch types the body is usually of stone (*Figure 47*) and much attention has to be paid in making this solid enough to prevent waves destroying it. When the beach loses sand, as is often the case, the stone groyne is left as a high unnatural ridge on the beach and, having lost its side support, topples over or has to be lowered. Often a side berm has to be made on both sides to obtain a new streamlined cross section. *Figure 47* shows only one berm; when the right hand beach lowers still further another berm will have to be constructed and when the beach lowers still further the whole construction will have to be made anew. Bitumen should be used to fill the gaps of the upper layer of stones.

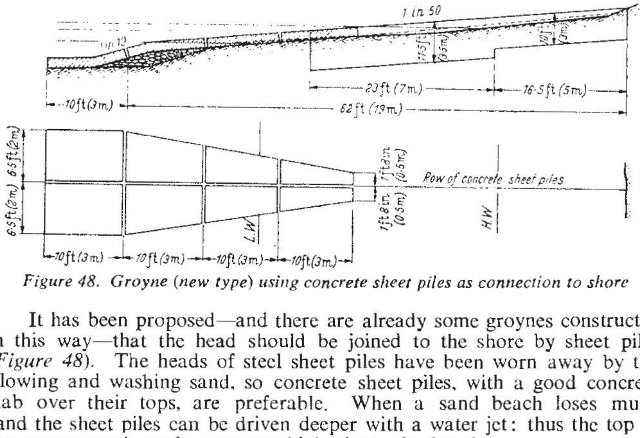



*Figure 48. Groyne (new type) using concrete sheet piles as connection to shore*

It has been proposed—and there are already some groynes constructed in this way—that the head should be joined to the shore by sheet piles (*Figure 48*). The heads of steel sheet piles have been worn away by the blowing and washing sand, so concrete sheet piles, with a good concrete slab over their tops, are preferable. When a sand beach loses much sand the sheet piles can be driven deeper with a water jet: thus the top of the groyne need not become too high above the beach.

*Small groyne*

The small groyne, or beach groyne, resembles a fence and is made of wood or concrete, *Figure 49*. Its object is to retain the shingle or sand of the upper part of the littoral drift. When using wood, the danger of pile worm must be considered; wooden groynes cannot reach to great depths. Most engineers would prefer permeable groynes passing some littoral drift. One of the functions of small groynes is to break the waves.

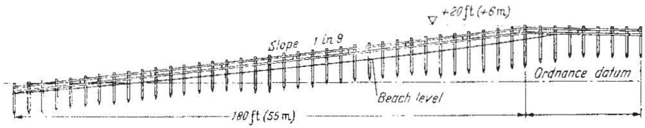



*Figure 49. Typical beach groyne to protect shore above low water, Sussex coast*

Another method of using coastal drift of sand as a means of coast protection is to pump this sand back to where it came from. In 1938 an experiment was carried out with this method on the Dutch island of Goeree. Considering the costs the results have been fairly satisfactory, as far as experience goes. Since then the method is advocated more and more. Groynes are expensive and rather unnatural.

In shallow, tropical rivers, 'bandal training' is used, *i.e.* the resistance to flow along the shallow banks of a river is increased by placing small trees, branches *etc* in order to increase the scour at shoals.

There are three main points in making solid groynes, embankments, revetments, training walls and piers which must be considered carefully:

*1* the top layer must consist of stones heavy enough to lie steady despite the impact of waves, and they must be well keyed, or grouted with a bitumen mixture

*2* the grading towards the bottom must be so gradual that no sand, gravel, shingle or larger stones can be washed out

*3* the 'toe' must be sufficiently low down and adequately protected against scouring.

*Examples*—These points are illustrated in the following examples:

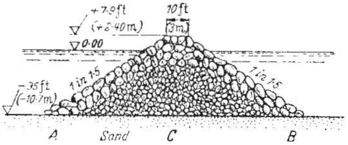



*Figure 50. Unsafe stone training dam on sandy bottom*

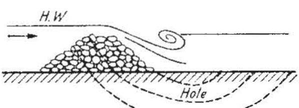



*Figure 51. Action of cross currents on wall of insufficient height*

*Figure 50* shows the cross section of a training dam laid on a sandy bottom. Where there is a littoral current there is severe scour in front of the groyne or training dam while it is being constructed. This is called 'head action' and is the cause of an unnecessary deep foundation of the training dam. The amount of stone may be two or three times the calculated amount, unless the bed is protected by a stone apron before the training dam is constructed. The principle of grading is not wholly neglected in *Figure 50*. Still, the sand from the bottom will be washed out by wave currents or by stream currents particnlarly at *A* and *B* and the stones will topple down. Even tbe central part of the foundation, near *C*, is not safe against being washed out. When a training dam with such large pores is made upon a sand bottom, a mattress should be laid well in advance to prevent scouring by head action and to prevent later scouring because of wave and other currents through the pores.

When there are cross currents at h.w. and the spur or training dam is not made to that height, the water will wash over the structure and cause a deep scour immediately behind it; the training dam will slide into the scour hole. To prevent this the structure should have a mattress where the attack is to be expected (*Figure 51*).

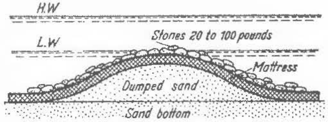



*Figure 52. Cheap groyne for a shore with small cross currents and small waves*

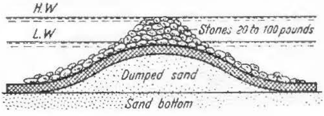



*Figure 53. Cheap groyne for a shore with small cross currents and slight wave action. Height up to h.w. or higher*

*Figure 52* shows a cross section of a cheap groyne often made in Holland. During slack tide, sand is dumped or washed into place and after that this sand is covered quickly with a mattress before the tidal current sets in. These groynes will stand when there is not much wave action and not much cross current, but where cross flow occurs the sand might be washed away from under the mattress.

Because willow boughs will rot above l.w., they should be used only slightly above this level. In order to prevent cross currents flowing over a l.w. groyne a mound of stones can be built upon the l.w. groyne, as in *Figure 53* but such a mound is not water tight. The currents will pass through its pores and the sand may be washed away from under the mattress. This could be prevented by a special layer of gravel or shell as shown in *Figure 54*.

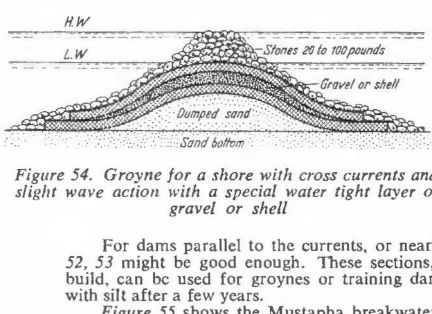



*Figure 54. Groyne for a shore with cross currents and slight wave action with a special water tight layer of gravel or shell*

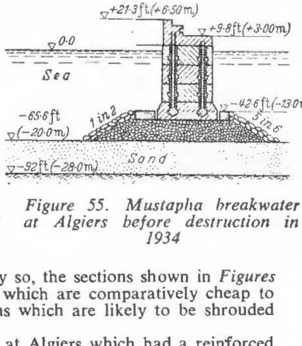



*Figure 55. Mustapha breakwater at Algiers before destruction in 1934*

For dams parallel to the currents, or nearly so, the sections shown in *Figures 52, 53* might be good enough. These sections, which are comparatively cheap to build, can be used for groynes or training dams which are likely to be shrouded with silt after a few years.

*Figure 55* shows the Mustapha breakwater at Algiers which had a reinforced concrete section upwards of 42·6 ft (13 m) depth, but it had a weak foundation. The stones in the top layer were too small and the grading was poor with little regard to the size of the fine sand underneath it. The washing away of this foundation must have been one of the causes of the collapse of the breakwater in 1934.

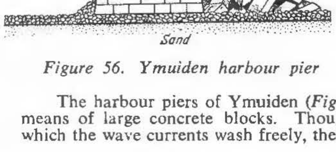



*Figure 56. Ymuiden harbour pier*

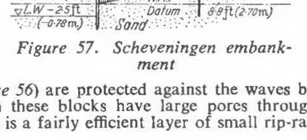



*Figure 57. Scheveningen embankment*

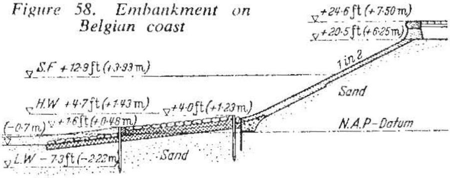
The harbour piers of Ymuiden (*Figure 56*) are protected against the waves by means of large concrete blocks. Though these blocks have large pores through which the wave currents wash freely, there is a fairly efficient layer of small rip-rap as a foundation protecting the sand underneath. Though the grading was far from correct no serious damage has occurred, but blocks have to be added because they sink into the sandy bottom, a sign that sand is still being washed away from under the layer of rip-rap.

In recent years large concrete tetraeders and 'tetrapodes' (French patent) have been used for breakwaters and for damming rivers and tidal streams. The pores of these tetrapod-dams are relatively small, but underlying layers of rock of the right size and grading should be used, so that neither sand nor rock can be washed out. The use of nylon fabric seems desirable in many cases.

Vertical sea walls like the one shown in *Figure 57* (Scheveningen) are built to protect the higher part of the shores against storm waves. These vertical walls have to withstand earth pressure from the back and therefore should be made stable. They also have to withstand the huge forces of the storm waves. They must not be undermined by the waves, and they must, therefore, have a foundation well below the lowest level of the beach, or they must have a wide stone revetment or 'toe' in front of them. In addition, large groynes are usually necessary to protect the beach and the foundation of the sea wall.

*Figure 58* shows a cheaper method of protecting the higher part of the shore by avoiding the vertical walls. The cross section must be sufficiently streamlined.

*Figure 58. Embankment on Belgian coast*




There is no great earth pressure and the waves do not exert such tremendous forces on the construction, so the concrete slab which has to withstand the attack of the storm may be fairly thin, but the toe should be well cared for lest it becomes undermined. There is always the danger that large holes may form beneath the concrete slabs; the sand should, therefore, be very well tamped before the concrete slabs are poured. The toe of the protection illustrated in *Figure 58* is well below the beach level, and the beach itself is protected by large groynes. The waves on this coast (the Belgian coast) are not very large.

*Figure 59* shows a mixture of steep and other slopes; the cross section has no simple streamlines. The slope of the sand stands almost vertical at places and the wall protecting this vertical sand is only a thin slab. It is no wonder that the waves proved too strong for this structure. The toe is not extended to a low level, but the beach is protected by long and strong groynes.

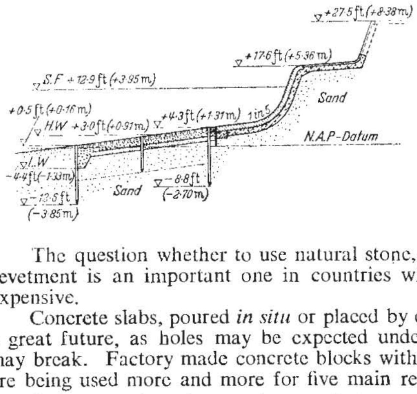



*Figure 59. Embankment at Borkum*

The question whether to use natural stone, concrete or asphalt for the revetment is an important one in countries where good natural stone is expensive.

Concrete slabs, poured *in situ* or placed by cranes, do not seem to have a great future, as holes may be expected underneath them and the slabs may break. Factory made concrete blocks with hexagonal or square forms are being used more and more for five main reasons:

*1* they are often cheaper than good stones

*2* they need no keying, as the blocks can be put very close together. The underlayer, therefore, can be fine gravel, shell, or light debris
*3* they can be placed by almost inexperienced labour in a third of the time; this reduces the cost greatly
*4* they can be made with top surfaces of varying height, so that the waves will break on them, and friction may diminish the uprush of the waves.
*5* the sides of the concrete blocks can be made in such a way that any block is anchored by the adjacent blocks.

The concrete must be resistant to sea water and have a crushing strength of 7,000 lb/sq in (500 kg/sq cm). The water absorption should be under 8 per cent and the density 144 lb/cu ft (2·3 kg/cu dm). These figures can be obtained by vibrating or tamping methods.

Blocks for moderate wave attack can be about 3 ft × 3 ft × 1·5 ft (1 m × 1 m × 0·5 m) with a hole in the centre for handling. The joints between the concrete blocks can be filled with asphalt. There are several types of interlocking concrete block revetment, all protected by patents.

There must be a good layer of debris or gravel underneath any revetment in which these blocks are embedded, to prevent washing out of sand and clay.

The newest development is in the more extensive use of asphalt to the exclusion of stone. In Harlingen (Holland) a breakwater was constructed in 1949, the cross section of which is shown in *Figure 60*. The sand for the core was pumped, the length of the breakwater is 2,952 ft (900 m), the height of the top above mean sea level is 23 ft (7 m), the slopes are 1 : 4 on the sea side and 1 : 2·5 on the harbour side. The thickness of the bitumen-sand slab is 10 in (0·25 m) and on the most exposed part 16 in (0·40 m). Above mean sea level the bitumen-sand mixture was poured *in situ*, below that level cranes or other devices put prefabricated asphalt slabs into place. The method is definitely cheaper than stone construction, especially when stone has to be brought from a considerable distance. The cost of this first breakwater was 2,000,000 guilders (£200,000 roughly) for 900 m.

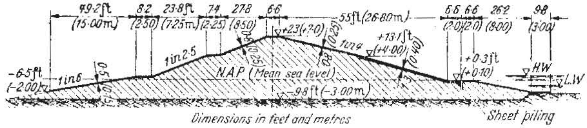



*Figure 60. Breakwater at Harlingen*

Later, another breakwater of the same type was made for the harbour (naval base) of Den Helder. *Figure 61* shows a promising experiment of asphalt dune-protection, made between the Hook of Holland and Scheveningen after the 1953 flood. The asphalt covering is made more or less like an asphalt road. The level of the top, 7 m (23 ft) above mean sea level is not high, so that the waves may reach the asphaltic slab and the filling of dune sand may become more or less saturated. The slope of the asphalt slab must, therefore, not be steep.

In 1953 several miles of new embankments in Holland were covered with such an asphalt sheet, especially in places where no clay was available. The sheet of asphalt is made *in situ* and covers the whole dike, except the lowest part of the inner slope. Trucks and cars can easily ride on the top of these new dikes and on their outer slopes.

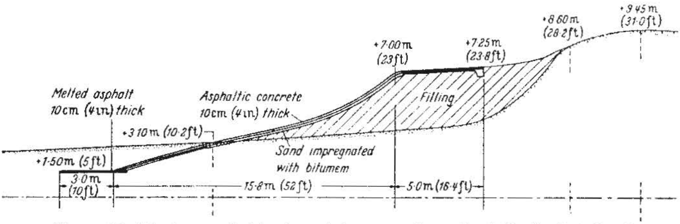



*Figure 61. Modern asphaltic dune-defence work north of Hook of Holland*

## LAND RECLAMATION

Material provided by cliffs receding by erosion may make possible the gaining of much fertile alluvial land. There are three ways of gaining new land:

*1* land accretion by using natural means
*2* pumping dredgings into a swamp or lake
*3* pumping a lake or sea shore dry.

*Land accretion by natural means*

Land accretion can be stimulated in several ways but generally only a small percentage of the total amount of suspended material in the coastal water is retained. The principle is to make silt settle by producing still water conditions by stopping currents and wave action as far as possible.

*Use of plants*—Local plants are easy to obtain and may give sure results when their habits are known sufficiently. Proof of satisfactory growth under varying conditions is needed and it may be necessary to carry out trials in different places over many years. *Spartina Townsendii* is one of the first choices for temperate regions. It will grow in salt, brackish and fresh water but in fresh water rushes or reeds give better results. Both are economic products; there are hundreds of species of reed and it may be possible to select or develop a kind which may grow at a low level.

Reeds are used for mattresses in scouring waters, rushes for floormats, binding vines and cattle food (dried). The quality of that food seems to be so high that Eastern Germany made a law to protect rushes and promote their growth.

*Silt trenches*—If there is too much wave action along a coast for plants to grow, the age-old method is to dig small trenches (1 ft × 1 ft) which form a grid pattern of about 10 ft × 200 ft (3 m × 60 m). The silt settles in these trenches and by redigging them once a year or more often the small areas are heightened to a level where plants can grow. The method gives a fine homogeneous soil. Thousands of acres have been gained in this way along the coast between the Zuider Zee and the Weser.

*Small dams*—Dams or embankments are expensive; even when very small ones are proposed preliminary experiments should be made over a long period.

In Germany (Schleswig) and Holland (Groningen and Friesland) large sums are being spent to make shelter by means of willow-filled small breakwaters about 6 ft (2 m) high and 1 to 2 ft (0·5 m) wide, giving a grid pattern with areas of 1,300 ft × 1,300 ft (400 m × 400 m). Ice often destroys the hearting of these small breakwaters and the soil it gives is rather heterogeneous. Direct economy is out of the question in many places.

*High dams or causeways*—Sometimes a railroad or a highway is made across an estuary and this causeway creates quietness in the water. Land accretion on both sides may occur, but generally on one side only. The North Frisian islands (Germany and Denmark) have been connected by means of large dams with the Continent. In 1878 the Dutch island of Ameland was connected with the shore, a distance of about 5 miles (8 km), the object being to gain land, but the dam breached soon afterwards, because it was not high enough. The storm piled the water at the western side up to a great height and at the eastern side the water was totally blown away, so that the western water washed over the dam. The top of a dam of this type should be made well above the storm floods plus wave heights, and a road can then be made upon it. The Ameland dam was a total failure partly because its layout was perpendicular to the prevailing storms. The North Frisian dams run east-west.

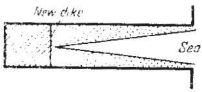



*Figure 62. Natural land accretion*

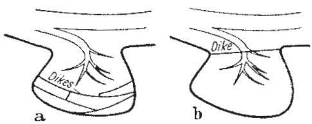



*Figure 63. Reclaiming tidal flats or shallow bays* a *old method* b *modern method*

*Further gains resulting from land reclamation* (*Figure 62*)—When 10 per cent at the land end of the fill basin of an estuary is reclaimed the streams in the rest of the estuary diminish; about 10 per cent at the mouth, and much more near the land end. If there is silt and sand in the water the cross sections of the estuary will therefore diminish and the shores will show natural accretion, because the size of the channel is a function of the fill basin. The action of silting in an estuary is progressive. This action, also called the 'method of pinching an estuary from behind', is quite natural, but it can be accelerated by man, either by planting plants or by pumping parts of the estuary dry.

Narrow rivers and rather narrow ship channels are to be preferred to wide ones. Wide waters show wild, unstable features; the waves are bad for inland shipping; the embankments have to be made extra high because of big waves; and the salt penetrates far into the country because salt and fresh water mix, especially in wide estuaries. There is another advantage in making wide estuaries narrow, namely, the gaining of fertile marine soil.

*Gains resulting from dredging*—When the main channel of an estuary is deepened, the breadth of the estuary will decrease in a natural way when there is any sand and silt suspended in the water.

### *Reclamation by using dredging spoil*

Dredging spoil is often used to heighten a low shore in order to create a new town district or harbour terrain. This is called 'making work with work'. On the river Scheldt about 5,200,000 cu yd (4,000,000 cu m) are dumped annually in the estuary itself. It seems to be a cheap way but some or perhaps much of this sand is added to the circular sand movements. In such a case dredging may go on endlessly when dumping nearby.

### *Reclamation by pumping out lakes* (*Figure 63*)

This is often the most economic way of gaining new land. Land accretion is slow and generally requires more capital expenditure and interest charges than the new land can bear. The method becomes costly especially when artificial constructions are necessary to make the silt settle. Formerly labour was less expensive than it is now and much land could be gained by making silt trenches or by using one of the other means mentioned on p 502 but now that machines have become abundant and more economic, pumps can be used. Often when the methods of land accretion are used, the new polder takes the shape of a segment needing a long expensive embankment to protect it (for a relatively short time only). The pumping method, as used in the Zuider Zee, is much quicker and often requires less capital expenditure per 1,000 acres.

The question of the degree of fertility of the soil then arises. Here agricultural experts are needed. Perhaps there is a layer of clay at some depth which can be brought up with a special machine; such machines exist already for layers at a depth up to 10 ft (3 m). Perhaps there is clay in the neighbourhood which can be transported, and so on. The new soil should not be too clayey. An amount of 20 per cent of silt in the top layer (grains smaller than 20 $\mu$) is often considered to be the best soil, but a committee of experts in Holland came to the conclusion that for the upper layer of 2 ft (0·6 m) a content of silt of only 12 per cent was as good. One of the main factors in fertility is to regulate the height of the ground water with extreme care, and to keep this water fresh.

Now that artificial manure is used extensively, sandy soils become more valuable, but the disadvantage of too sandy soil is that it may be blown away. Grass, bulbs and woods can be grown easily on sandy soils.

The planning of large pumped polders can be much better than the planning of the small segment formed polders. The roads, villages, canals, schools, churches *etc* can, and should, be made before the population moves into the polder. Land reclamation nowadays can hardly be else than a government job.

Land has a private economic value (selling value) and a public economic value. In a well populated country the latter is much higher than the former because the land supports not only the owner but the whole community as well. It is the public economic value of land which must be taken into consideration when planning a new polder to be added to the country.

*Land reclamation by making sand dikes* (*Figure 64*)

Near the sea, blown sand can be caught by means of rows of fir boughs or reeds, height about 3 ft (1 m). In the course of a few years high dunes can be made in this way with little cost. Sand dikes have been made in Holland

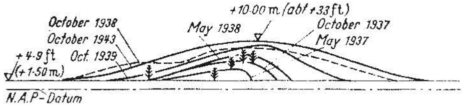



*Figure 64. Brushwood hedges for making sand dunes*

for several centuries, and much new silt land has grown behind them. The method is simple and inexpensive provided that the situation of the sand dike is well chosen. The new sand dikes have to be fixed with marram grass and other dune vegetation. Here the botanist's advice should be sought. Rabbits and holidays makers are the worst destroyers of dune vegetation.

## SUMMARY OF PROMISING RECENT DEVELOPMENTS AND TRENDS

*1* The use of specially shaped precast concrete units, called 'tetrapods', the subject of French patents, for protection against strong currents and waves (p 500).

*2* The use of large concrete structures for closing tidal gaps in embankments, covered by Dutch patents (p 494).

*3* The use of mattresses of nylon fabric (Dutch patents) to reduce erosion of a stream bed (p 493).

*4* The use of nylon fabric sheets under stone revetments in place of brushwood *etc* (p 493).

*5* The surfacing of embankments and the sea faces of sand dunes with an asphalt layer (p 501).

*6* Pumping sand on to a denuded beach instead of building groynes (p 498).

*7* Extrapolation of frequency curves, *e.g.* of high water.

*8* Research into the formation, behaviour and height of waves and the reflection of waves.

*9* Methods of predicting the height of a storm surge from the expected wind forces of an approaching depression. (The error found at the Dutch coast has been within 1 ft.)

*10* Mathematical methods and the use of electronic computers and tidal analogy computers in tidal calculations.

*11* The use of modern electronic measuring and sounding devices for offshore surveys (p 478).

*12* The systematic measurement of the settlement of embankments.

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