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“Littoral Drift: in its relation to the Outfalls of Rivers, and to the Construction and Maintenance of Harbours on Sandy Coasts.”

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In the design of works for the improvement of entrances to tidal rivers, or in the construction of harbours on coasts encumbered with sand or shingle, one of the most important elements for consideration is the movement of the littoral drift.¹ Its effect in the formation of bars has already been dealt with by the Author in a Paper² read before the Institution in 1890; and some existing shingle beaches, and the direction of movement of drift round the coast, as well as the historical and geological conditions relating thereto, have formed the subjects of Papers by the late Sir John Cooke,³ Professor Sir Joseph Prestwich,⁴ Mr. Redman,⁵ and Mr. Pickwell.⁶ It is intended to deal in the present Paper only with coast erosion, and the travel of material as affecting engineering works carried out on the coasts for the benefit of navigation.

In the Paper³ presented by Sir John Cooke and the discussion upon it, a law was deduced from the facts observed at the Chesil Bank as to the direction in which drift moved, and as to the governing agent in its movement, which has since been generally accepted as correct. Further observations, however, and new facts which have since become available, appear to the Author to demand a

¹ See “Principles and Practice of Harbour Construction,” by W. Shield, p. 71.

² Minutes of Proceedings Inst. C.E., vol. c. p. 116.

³ *Ibid.*, vol. xii. p. 520.

⁵ *Ibid.*, vol. xi. p. 162, and vol. xxiii. p. 186.

⁴ *Ibid.*, vol. xl. p. 61.

⁶ *Ibid.*, vol. li. p. 191.

modification of the conclusions then arrived at. The conditions under which the channels of rivers, and the approaches to harbours on sandy coasts can be maintained, have also undergone material alteration during recent years. The successful application of the system of suction dredging to the removal of sand, and the working of these machines in positions and under circumstances which formerly would have been considered impracticable, has placed at the disposal of engineers new and important facilities for carrying out works of improvement.

The propositions which the Author desires to establish are—

1. That the vast deposits of sand and shingle in bays and sheltered places on the coast, are due to causes which occurred in remote ages, and which are no longer in operation.

2. That the drift which travels along a coast is due to the erosion of the cliffs, and is derived from the wasting of the land, and not from the sea-bed.

3. That the quantity of drift is limited, so that it may be entirely stopped or its movement controlled.

4. That while wind and waves are the agents which operate in eroding the cliffs and producing the drift, the regular and continuous travel of the material along the coast is due to the wave-action of the flood-tide.

5. That the regular and continuous movement of sand and shingle along a coast takes place only in the zone lying between low- and high-water mark.

6. That the contour of the sea-bed on a sandy coast, when covered with a moderate depth of water, remains in a stable condition, and that so long as the conditions remain the same the form of the banks and depth of the channels are not altered by winds and waves.

7. That channels can be effectively deepened and maintained on sandy coasts by dredging; and, if properly directed, they will remain stable and retain their depth.

8. That harbours may be projected out from sandy coasts without danger of the entrances shoaling, provided that the piers are so placed as to derange the main set of the tidal current as little as possible, and are carried into a sufficient depth of water, and that, where required, the supply of littoral drift is cut off by protective works along the coast.

In dealing with the question of littoral drift and the accumulation of sand and shingle, sufficient consideration does not appear to have been given to the vast time that has been occupied in their production, and to the fact that the amount now to be dealt with

is comparatively small. There are no forces in operation that could, within any conceivable period, produce the great mass of sand which overlies the rocky bed of the sea round many parts of the coast, and the accumulations which exist in sheltered estuaries, or the large shingle beds such as the Chesil Bank, which extends for 15 miles with a base 600 feet wide, its top reaching between 20 and 40 feet above high water and extending as far below low-water level. These deposits must have accumulated at a time when the agents at work were of much greater magnitude than now, and when the tides rose higher and occurred at more frequent intervals. These sandbanks, although still slowly growing in some cases, have probably not been materially altered in form since the end of the glacial period; when the torrents arising from the melting of glaciers and icebergs assisted in moulding the shape now assumed by the rivers and estuaries, and the shoals and deeps of the sea-bed along the coast.

THE SOURCE OF LITTORAL DRIFT.

The material which is drifted along the coast consists of shingle, sand and alluvial matter. It is derived from the erosion of the cliffs, the degradation of which is more or less rapid, depending on whether they consist of the primitive rocks, or of those which have been at some time degraded, and redeposited. Waves are the principal agents of destruction, by the beating of which on the cliffs at high water in gales and storms, large masses of rock are dislodged, the fragments thus broken off being used as battering rams in further work of disintegration. Incessantly rolled about by the waves, the disintegrated rock becomes ground to boulders, then to shingle, and finally to sand. When the cliffs are of chalk or of clay, the flints, gravel, and boulders supply the shingle and sand; while the remainder is converted into alluvium, the particles of which are sufficiently fine to become mixed with the water and remain in suspension so long as the water is in motion. The degradation of cliffs is further aided by rain and frost; and, where the drainage is imperfect, landslips constantly occur and cause the wasting away of land bordering on the sea. The material thus eroded from the cliffs and broken up, is continually in motion under the influence of the waves and tides, travelling along the coast in a direction determined by causes to be described. The power of waves to move material in heavy storms breaking on the shore is almost beyond comprehension. Stones weighing between 200 and 300 lbs., are rolled along and left

stranded on the beach; and pebbles of great size are thrown to a height considerably above the level of high water. At Brighton it is recorded that, in south-west gales, the shingle has been thrown on to the road 18 feet above high-water level; and shingle banks are frequently found between 8 and 10 feet above high-water level. During a single gale, $3\frac{3}{4}$ million tons of shingle were moved along the Chesil Bank, the greater part of which was thrown back within a few days; and in a subsequent gale, $4\frac{1}{2}$ million tons were scoured out, three-fourths of which was moved back within five days. It has been calculated that at Hove 2,700 tons were removed from the beach during one set of spring tides.

Shingle.—The pebbles sorted from other material eroded from the cliffs become heaped in a bank, the base of which is almost invariably above low-water level. Shingle is rarely found below low-water mark; and the regular travel of both shingle and sand along a coast is confined to the zone lying above low water of neap tides.

Fig. 1.

There are exceptional cases, as at the Chesil Bank, where the shingle extends below low-water level;¹ and isolated patches of shingle are to be found in deep water, but these are stationary and have no connection with the ordinary littoral drift. A remarkable instance of the fact that shingle travels in a direction marginal and adjacent to the shore, is afforded by a fact recorded by Mr. Ellice-Clark, that a quantity of shingle, amounting to about 25,000 tons dredged from Shoreham Harbour, and deposited on the beach in front of Hove, at distances varying between 400 and 800 yards from the sea-wall, was moved up the beach, and deposited along the foot of the sea-wall by the action of the sea.

The material drifted along the coast is sorted by the wave-action, the largest pebbles being driven up nearly to the top of the bank, the size gradually decreasing till the pebbles merge into sand as the low-water level is approached. The summit of a

¹ Minutes of Proceedings Inst. C.E., vol. xii. p. 522.

shingle bank is nearly always above the level of high water of spring tides, generally between 4 and 8 feet, the height depending on the force of the waves which break on the banks. In calm weather the face of the banks becomes heaped up, assuming what is termed a full, or ridge, and hollow parallel with the coast, *Fig. 1*. The slope of the face in the upper layers, in calm weather, is sometimes as much as 1 to 1. In stormy weather it is drawn down to a slope of between 7 to 1, and 10 to 1. The slope of the lower part of the bank is much flatter, or about 30 to 1. The wave, on striking the bank, divides into two parts, the crest running up its face and carrying with it the pebbles, and at the same time pushing forward those that lie above it, *Fig. 2*. The pebbles, on being moved, are actuated by the momentum of the wedge-shaped mass of water, into which the

Fig. 2.

crest of the wave has been resolved, and they are almost entirely waterborne. The advancing wave strikes the bank obliquely, and has the greatest effect when this angle is about 45° . The water returns down the line of quickest descent, or normal to the bank, and carries down with it a portion of the pebbles; but in the case of the upper layer, which is subject only to the thin end of the wedge of water, there is not sufficient depth to affect them, and consequently they remain stranded. Each successive wave acting in an oblique direction, pushes the stones a certain distance forward along the face of the bank; one wave of each series, usually the tenth, rising higher and acting with more force than the others. This process for ever acting is sufficient to account for the removal of an immense amount of material. The lower part of the wave, on striking the bank, curls round and cuts out a hollow in the

face of the bank in the manner shown in *Fig. 2*. Two such hollows will almost invariably be found in all shingle banks, one at the level of the spring tide, and the other at that of the neap tide, and a third also frequently at the level of an extraordinarily high tide. In heavy gales the under-tow of the waves removes a large quantity of pebbles downwards, and flattens the slope of the bank.

The travelling shingle generally follows the coast-line, moving round the arcs of bays, and indents, and round projecting points where the water is shallow; and the back of the bank is connected with the shore. Occasionally the bank assumes the form of a ridge extending along the chord of the indent, being thus isolated from the shore; sometimes also it extends across the mouth of a river, either diverting its course, or blocking its outfall. The most notable instance is afforded by the Chesil Bank, which extends as a ridge for several miles, having on its inside a large sheet of water, receiving the discharge from several streams which at one time emptied directly into the sea. The limit of this bank has been reached, and it has long ceased to advance. Another instance is to be found on the east coast, where a shingle bank, still travelling southwards, has diverted the river Alde out of its course for 9 miles. The river flows on one side of the bank and the sea on the other, being separated by the shingle, which in places is only 70 or 80 yards in width. In the estuary of the Ribble, a shingle ridge, between 10 and 12 feet wide on the top, projects from the land near St. Anne's for $\frac{3}{4}$ mile. In Felixstowe Bay, the shingle runs in a bank across the hollow of the bay, parallel with the low-water line, leaving a considerable space between it and the cliff. In other cases the travel of the shingle has been arrested by some natural or artificial projection; and it has collected in vast beds, as at Dungeness, Pevensey, Langward Fort, and Folkestone.

Sand.—This material consists of minute angular particles derived from the fragments eroded from the cliffs, and which are free from all earthy matter, and so do not discolour the water. Particles of pure sand, owing to their size, only remain in suspension in the water when much agitated, and they rapidly settle as soon as motion ceases. The bed of the sea, round all except rocky coasts, consists principally of sand ranging between a thin covering of the rocks and beds of immense thickness. Sand lies much flatter than shingle, the slope varying between about 1 in 100 and 1 in 300. In exceptional cases, sand beaches have a very steep slope, the face lying at an angle of $1\frac{1}{2}$ to 1 or 2 to 1; and

frequently, when submerged and subject to strong tidal currents, they stand much steeper than the natural angle of repose. Waves breaking on a beach stir up the sand and throw it temporarily into suspension. While in this condition, it is carried along by the flood-tide until brought into contact with some obstruction, when, in the slack water thus caused, the sand settles and accumulates. This deposit is greatest at the point reached by high water of spring tides, and tails down towards low water, and in the direction from which the drifting action proceeds.

Under ordinary conditions the movement of sand takes place only between low and high water, during the time the waves of the flood-tide break on the beach. In stormy weather, with on-shore winds, when the waves break below low-water mark, sand is disturbed and thrown into suspension, and in this condition may be thrown up on to the beach, and accumulated in large masses against any projection from the coast. But the depression thus made in the sea is rapidly filled again, and the general contour of the beach is restored in calm weather.

Silt and Alluvium.—Silt consists of sand mixed with a varying quantity of clay, chalk, or other alluvial matter which gives a certain adhesiveness to the particles, depending in amount on the larger proportion of the alluvial matter. Alluvium found in the sea along coasts, is derived from the erosion and wasting of cliffs composed of chalk or geological deposits of recent formation, and material brought down by rivers. Although the specific gravity of the alluvium is as high as that of sand, yet, owing to the minute size of the individual particles, it is more easily kept in suspension in the water, and becomes diffused by tidal action throughout a very large area. Oscillating backwards and forwards with the tides, the alluvium gradually subsides to the bed of the ocean during periods of calm weather. Beds of alluvial matter are thus found in the sea-bed near the outfalls of all large rivers, but generally in the deeper part of the ocean. Thus in the Bay of Biscay, off the mouths of the Loire and Gironde, there are beds of soft mud, 20 miles in breadth, which extend for about 150 miles; and in the English Channel and North Sea, off the coast of Flanders and the mouth of the Thames, there are also large beds of alluvial matter. Pure alluvial matter is not, therefore, drifted along tidal coasts; but occasionally in sheltered places some portion of it settles on the coast, and, gradually accreting in time, forms the salt marshes to be found in many estuaries. In stormy weather, with heavy on-shore gales, the alluvial matter settled on the

beach is disturbed, and, becoming diffused by the action of the waves, discolours the water for several miles out from the coast, and is carried by the tides into estuaries. Such occasions, however, are exceptional. Thus, off the mouth of the Scheldt, in the pass of Wielingen, where there is a large deposit of alluvial matter, in heavy gales from the north-west, the water becomes so turbid as to cover everything with which it comes in contact with mud, and vessels passing through it require to be scrubbed. On more than one occasion within the experience of the Author, during very heavy gales from the north-east, the whole of the water in the offing along the Lincolnshire coast, from the Humber to the Wash, has been rendered muddy, and the tide flowing up the rivers has left a deposit behind. A similar effect is produced on other parts of the coast; and occasionally, during north-easterly gales, the tidal water enters Harwich Harbour in a turbid condition. It does not, however, penetrate far, and no deposit is left behind, the ebb-current carrying it out to sea again. These occasions are, however, rare; and, as a rule, seawater along a tidal coast is bright and clear.

It is held by some geologists and engineers that the wasting of the clay cliffs of the Yorkshire coast, north of the Humber, supplies the alluvial matter to be found in that river, and "that it seriously affects the navigation of the river, and is the cause of enormous expense in dredging at the Grimsby and Hull docks."¹ The amount of alluvial matter in suspension in the Ouse and the Trent, the two rivers which unite to constitute the Humber, is perhaps larger than that contained in any other river in England. The deposit on land adjacent to these rivers prepared for warping is at the rate of between 2 and 3 inches in a tide. This is quite sufficient to account for the amount of material that has to be dredged out of the docks. It is impossible that this material can be supplied by the sea. The only current along this coast is that due to the tides, which may be taken as running at the rate of $2\frac{1}{2}$ knots. The material thrown down on the beach from the clay cliffs by the waves at high water is not reached till after half-flood, so that the flood, or southern current, only acts on it for about three hours, and cannot transport such of it as is taken up in suspension for a greater distance than $7\frac{1}{2}$ miles. It then becomes subject to the ebb-current which lasts upwards of six hours and carries the suspended material 15 miles northwards, the net result being that each tide leaves the

¹ Minutes of Proceedings Inst. C.E., vol. li. p. 210.

material $7\frac{1}{2}$ miles further north than the point from which it started. With every movement of the tide the suspended matter becomes diffused over a wider area, and ultimately settles in the bed of the sea. If any of it ultimately should reach the mouth of the Humber, it would be in such an attenuated quantity as to be imperceptible. On the flood-tide, the water in the Humber is bright and clear for a distance of between 7 and 10 miles above Spurn Point; when heavy freshets are running, the water is discoloured on the ebb for about 4 miles outside Spurn Point. The Author has taken samples of the water at various parts of the Humber, from its mouth in the North Sea upwards into the Ouse and Trent, and has found the water at the mouth, on an inflowing tide, bright and clear and containing only a few grains of sand, the quantity of material in suspension increasing with the progress up the river. The water in the Trent at 6 miles from its mouth was, on the first of the flood, exceedingly turbid; and the quantity of matter in suspension amounted to 3,150 grains per cubic foot, and at Gainsborough to 261.87 grains.

It is contrary to all known laws of tidal action in rivers for material to be carried upwards from the sea to any great distance above their mouths. The tidal wave creates only an oscillating current, the same volume of water which moves up the river moving down again on the ebb. Matter in suspension moves upwards under the influence of the tidal current only a certain distance, depending on the duration and velocity of the current, seldom exceeding 10 miles, but never to the full extent of propagation; on the turn of the tide, if it remains in suspension, it is moved back again the same distance by tidal action, and a further distance due to the downward motion of the fresh-water current, depending in amount on the relative volume of the fresh to the tidal water. If there be no fresh water, the downward movement is only equal to the upward movement. Further, the salt from the sea which is more readily diffused than material held in suspension, only penetrates the lower reaches of a tidal river, the water entirely losing its saline properties as the tidal wave progresses upwards. The water in the Ouse and the Trent is free from salt, the specific gravity of that in Goole docks being 1.00, and in the North Sea 1.026. The action of tidal water in transporting material in suspension in rivers has been fully demonstrated by an elaborate series of experiments with floats, and by ascertaining the amount of salt in the water of the Thames, and also on the Clyde, the Witham, and the Scheldt, the

details of which are given in the Author's treatise on Tidal Rivers.¹ It is necessary to draw particular attention to this matter, as it has frequently been held that deposits in rivers and estuaries are due to material brought in from the sea by the flood-tide. Thus the late Sir John Rennie, in the scheme for the reclamation of part of the Wash, which obtained parliamentary sanction in 1851, based his calculation as to the accretion of the land to a great extent on material brought into the estuary from the degradation of the Yorkshire coast. The scheme has been frequently revived in recent years as a means of finding work for the unemployed. The engineers who advised the carrying out of the Norfolk estuary scheme for enclosing 30,000 acres on the north side of the Wash, in like manner calculated that the supply of alluvium brought in from the sea was unlimited. A study of the physical condition of the transport of littoral alluvial drift would have shown the impossibility of this, and thus have saved a large outlay on a practically abortive scheme.

The theory that alluvial matter is brought in from the sea is also advanced in the Memoir of the Geological Survey of the County of Lincoln. A careful examination of the tidal water flowing into and out of the estuary of the Wash from the open sea shows that no such inward drift of alluvial matter takes place. The water of the flood-tide, except during occasional heavy on-shore gales, as it enters the estuary, is bright and clear; and it only becomes turbid as it approaches the upper end of the estuary, and meets the water flowing down the rivers charged with alluvial matter.

The condition of Harwich Harbour, situated lower down on the same coast, affords an example in refutation of the theory that alluvial matter, wasted from adjacent cliffs, is carried by the sea into harbours or up rivers. Until preventive measures were taken, the cliffs extending for some miles north of Harwich Harbour, Fig. 3, Plate 1, consisting of London clay, were being rapidly eroded and worn away by the action of the sea. The drift along this coast is from north-east to south-west, and shingle is carried along the coast and drifted into the harbour; but no alluvial matter, except under the conditions above mentioned, finds its way into it, or becomes deposited on its bed, or on the shores of the rivers Stour and Orwell. These rivers drain only a comparatively small area compared with the size of the rivers and the harbour, and bring down very little alluvial matter, such

¹ "Tidal Rivers, their Hydraulics, Improvement, and Navigation," by W. H. Wheeler, chap. vi.

quantity as is brought down being carried out to sea on the ebb-tide. The water, both in the harbour and rivers, is bright and clear; and no dredging has been necessary to maintain the original depth in Ipswich dock, which has been constructed upwards of fifty years.

The Mersey also contains a large amount of alluvial matter in suspension, which it has been held is washed in from the sea. The Author has taken samples of the water carried in over the bar on the flood-tide, and has found it bright and clear, having only a few grains of sand in suspension. It only becomes turbid as it approaches Liverpool and meets the downward current charged with material derived from the erosion of the cliffs in the upper estuary, and the alluvium and detritus brought down by the rivers.

The Severn, the Usk, and the Parret afford other examples of rivers having a large amount of matter in suspension; but that this is due to alluvial matter brought down these rivers by freshets, and not to material transported from the sea, is evident from the fact that while the water is excessively turbid in the upper reaches, it is bright and clear on the flood-tide in the lower end of the Bristol Channel, turbid water never being met with lower than Lynton. The alluvial matter in these rivers oscillates backwards and forwards with the tide, varying in quantity and position with the amount of fresh water flowing down, the turbid zone being situated lowest when heavy freshets prevail.

Dover Harbour affords another example that the transport and deposit of alluvial matter are due to local sources, and that it is not derived from the sea. Before the construction of the Admiralty Pier, the deposit in Dover Harbour amounted to upwards of 60,000 tons a year, which had to be moved by dredging, in order to maintain a sufficient depth of water.¹ This material consisted principally of chalk and sand derived from the wasting of the cliffs. As the Admiralty Pier extended into deep water, the deposit became less, and finally ceased. The tidal water ebbing in and out, now being derived directly from the sea, with a depth of between 6 and 7 fathoms, instead of from the shallow current running along the shore, enters clear and free from matter in suspension. At Ramsgate where the depth at the entrance is not more than between 1 and 1½ fathom, about the same as it was formerly at Dover Harbour, and where the water is derived from the shore current, the amount of material continually deposited is very great.

¹ Evidence of Mr. E. Druce, Dover Harbour Report, 1875.

QUANTITY OF DRIFT LIMITED.

The quantity of littoral drift to be encountered in dealing with rivers and harbour works on sandy coasts, may be so large as to be uncontrollable, or may only be such as to be capable of removal by dredging at a reasonable cost for maintenance. If the material is not only supplied by the erosion of the coasts, but is also due to sand or alluvial matter thrown up from the bed of the sea, the supply in such case is unlimited and uncontrollable. There is, however, nothing to warrant any such conclusion. If sand is continually cast up from the bed of the sea by the waves, the beach would be steep, and not flat as generally found; and all bays, estuaries, and indents along the coast would have been filled many ages ago. It is found, however, that the beach is denuded during on-shore gales, and grows during those blowing off shore; bays and indents being kept open by the under-tow of the waves, which, when driven into them, create a strong back current which tends to denude the beach, and keeps the bay from accreting. If the movement of sand and shingle along a coast, be arrested by groynes, or other projections, and the supply thus cut off, the beach beyond soon becomes denuded and lowered, showing that the supply of drift is a limited quantity and therefore within control. If also forces were now in operation which could create the great accumulations to be found on some parts of the coast, the task of coping with them would be hopeless, but such is not the case. In Morecambe Bay, the sand-beds cover an area of 90,000 acres dry at low water, and in the Duddon estuary they cover 9,000 acres. It is impossible that this enormous mass of material can ever have been supplied by any forces now in operation. The rivers which discharge their contents into these estuaries are comparatively small streams, and quite incapable of performing such a task; and there is no wasting away of the coast-line at all comparable to the formation of these sand-beds.

The Wash, Fig. 4, Plate 1, covers an area of about 157,600 acres, of which about 84,000 acres consist of sand-beds dry at low-water, the average thickness of which may be taken at 20 feet. The Author has at various times, and under various conditions, analysed the water flowing down the rivers which empty into this estuary, and ascertained that the quantity of matter brought down in suspension is only sufficient to provide material for the growth of the salt marshes which have accreted along the coast, and that it is physically impossible for these sand-beds to have been

produced by detritus brought down the rivers under their present condition.

On the north coast of France, the erosion of the cliffs along the Calvados coast is estimated by French engineers to take place at the rate of about 0·90 foot a year, or a quantity equal to 25,000 cubic yards per mile. A great part of this is alluvial matter which becomes diffused amongst the tidal water, and settles in the bed of the English Channel. It has been estimated by Mr. de Lamblardie¹ that the proportion of silex derived from the erosion of the chalk cliffs of the coast of Normandy is three-fifths of the whole, and that the remainder is alluvial matter capable of being carried in suspension. Allowing that one-half of the material produced is sand and shingle, and supposing that its travel was arrested by groynes and accumulated at the foot of the cliffs all along the 36 miles of the shore, over the zone of shallow water which extends for a width of $1\frac{1}{2}$ mile, it would have caused an average deposit of about $\frac{1}{24}$ inch a year; and about 1,500 years would be required for the beach to be raised an average height of 6 feet.

There is a bank extending from the shore at the entrance of the Seine, opposite Trouville, on which the water shoals at 2 fathoms. Allowing that this bank was formed by the littoral drift derived from the waste along 45 miles of the coast of Calvados, and that one-half of the deposit derived from the eroded matter had been deposited there, the time occupied in the operation would have been about 9,000 years. The quantity of shingle drifted along the coast past Dieppe has been estimated as varying between 30,000 and 40,000 cubic yards a year. Even if the whole of this had to be dredged to secure the maintenance of the port, the annual cost would be insignificant compared to the traffic; but that the whole of it might be arrested and prevented from reaching the port is evidenced by the fact that the removal of this material for concrete and ballast had a sensible effect on the supply, and greatly relieved the port from accumulation;² and the erection of groynes on the west shore further stopped the movement. On the coast of Normandy, where the waste of the chalk cliffs is as great or even greater than along the Calvados coast, the supply of shingle drifting along the shore is so limited that, owing to its being used to ballast vessels, the beach became so denuded that special works had to be constructed to protect the coast. The

¹ "Étude sur les Rivières à Marée et sur les Estuaires," by H. L. Partiot. Paris, 1892, p. 97.

² "Harbours and Docks," by L. F. Vernon-Harcourt, p. 147.

same result occurred at Spurn Point at the entrance to the Humber. The clay cliffs between Bridlington and that river extend over a length of about 40 miles, the average height being about 40 feet, and the mean annual waste 6·60 feet,¹ representing a quantity equal to 2,072,160 cubic yards. The shingle from this erosion travelled southwards along the beach to Spurn Point, where it accumulated. The removal, however, of 30,000 cubic yards a year of shingle for road-mending and concrete so denuded the beach at Spurn Point as to threaten its safety. This appears to indicate that about one-seventh only of the eroded material produced shingle, the remainder being alluvial matter and sand. The taking of the shingle was stopped, and the beach again accumulated and the erosion of the cliffs diminished one-half. If the whole of this eroded material had been spread out on the beach between high- and low-water marks, which may be taken as extending over a width of one-fifth of a mile, the beach would have been raised annually 3 inches, and in seventy-two years the shingle bank would have been above the level of high water, and the supply of material from the erosion of the cliffs entirely stopped.

When the pier was projected from the shore of the English Channel at Folkestone, the shingle travelling along the beach from the west was arrested and accumulated in a large bank; but the beach at Dover and eastward of it became in consequence denuded, and the safety of the cliffs was considerably endangered. The supply from the west has also been materially affected by the projection of Dungeness Point, which has acted as a natural groyne arresting the travel of shingle brought from the coast west of this point.² The amount collected here in thirty-five years was found to be 430 acres, $7\frac{1}{2}$ feet deep, representing 7,000,000 tons, or at the rate of 200,000 tons a year. The result of this has been to limit materially the supply travelling eastward of this point.

Between Beachy Head and Dungeness, a distance of 20 miles, the average height of the cliff may be taken as 200 feet. At the rate of 0·90 foot a year, the quantity eroded would be about 1,000,000 tons. The proportion of alluvial matter would then be four-fifths, the remaining fifth being the quantity of shingle annually deposited at Dungeness. The shingle deposit at Dungeness covers an area of nearly 6,000 acres, the surface being between 4 and 6 feet above high water, and the thickness of the shingle

¹ Minutes of Proceedings Inst. C.E., vol. li. p. 211.

² See Report by Sir John Coode included in "Correspondence relative to the causes of the wasting of the shore to the eastward of the Government Pier at Dover." Return to an Order of the House of Commons, 13 March, 1873.

bed being estimated at 22 feet. If this shingle is derived from the wasting of the cliffs between this point and Beachy Head, it represents the accumulation of 1,662 years.

At Felixstowe, Fig. 3, Plate 1, a natural groyne, composed of septaria, projected from the cliffs and held up the shingle to the north of it. On the removal of this stone, about thirty years ago, for cement-making, the shingle at once began to travel southwards, and the sea encroached on the cliffs. To prevent this, considerable expense has had to be incurred in constructing groynes to arrest the travel of the shingle and consequent wasting of the beach. The shingle set at liberty began to travel across Harwich Harbour, forming a spit nearly $\frac{1}{4}$ mile long. To prevent this, a large groyne was constructed extending a considerable distance from the coast at Languard Point, and this arrested the travel, the shingle accumulating at the back of the groyne. The result of the stoppage of the travel has been that the shoaling across the harbour has ceased, and the beach inside has become so denuded as to cause the wasting away of the land, threatening destruction to the fort. To prevent this, part of the groyne has been removed and a portion of the shingle allowed to escape, the inner beach being protected with groynes.

TRANSPORTING AGENCY.

Attention was first directed to the moving agent of shingle in a Paper presented by Mr. Palmer in 1834 to the Royal Society,¹ in which he divided the action into three classes: (1) Heaping up or accumulating; (2) disturbance or breaking down; and (3) progressive movement; and contended that all of these were due to the effect of wind, and that tidal action alone was not capable of effecting the result produced. Sir John Coode, in his Paper² on the Chesil Bank, adopted the view that the progressive action of littoral drift is due to, and moves in the direction of, the prevailing winds, and "that the ultimate movement of shingle is always found to be in the same direction as, and never against, the heaviest seas; and that it is frequently in opposition to the prevailing or strongest tidal current." This view has since been generally accepted. Prof. J. Prestwich,³ in a subsequent Paper, expressed agreement with the conclusions arrived at by Sir John Coode, "that the

¹ "Observations on the Motion of Shingle Beaches," H. R. Palmer. *Philosophical Transactions of the Royal Society*, April 1834.

² *Minutes of Proceedings Inst. C.E.*, vol. xii. p. 532.

³ *Ibid.*, vol. xl. p. 63.

shingle is propelled along the coast by the action of wind-waves, and the heavy seas due to the prevailing and strongest winds," in which opinion the majority of the speakers who took part in the discussion again concurred. Sir James N. Douglass, however, differed, and expressed the opinion that "the travel of shingle along the coasts was due to the effect of the ocean-wave or ground swell."¹ Other writers attribute the effect not to the "prevailing" but to the "dominant" winds, or those which blow on shore with the greatest force and in the direction of the flood-tide; the prevailing winds being regarded as those which blow with the greatest frequency from one particular quarter. Mr. Vernon-Harcourt² ascribes the progressive movement of littoral drift to the combined action of the winds and the tidal currents, and considers that the action is most powerful when the waves and tides act in the same direction; the tidal action being only due to the difference in force of the flood and ebb. Mr. Shield, in his recent work on harbours, remarks "that the direction of littoral drift is in the great majority of cases determined almost solely by that of the prevailing winds."

The prevailing winds in England are from the south-west, the wind blowing from this quarter for about two-thirds of the year; and some of the heaviest gales also come from this direction. If the movement of littoral drift is due to this cause, it must be in the same direction all round the coast, whereas on the south coast the general direction is easterly, on the west coast northerly, and on the east coast southerly. On the north coast of France, Belgium, and Holland, where the prevailing winds are also south-westerly, the drift travels in several directions, but principally to the east and north. On the west coast of France and Spain the prevailing winds are from the north-west,³ the general direction of travel of the drift being opposite to this and northwards with the flood-tide. In the Gulf of Gascony, the tides produce littoral currents which travel up the coast from south to north with the flood-tide; and the sand travels along the coast from the south, and proceeds north to the point of Négade, and then north-easterly to the mouth of the Gironde following the set of the flood-tide.

On the American coast from Sandy Hook to Cape May, along the sea-coast and in the inlets and bays, the prevailing wind being

¹ Minutes of Proceedings Inst. C.E., vol. xl. p. 103.

² Harbours and Docks, p. 62.

³ Admiralty Sailing Directions, Coast of France.

north-easterly, the beach travels in some cases north and in others south, these directions corresponding with the set of the flood-tide along the shore.¹

On the south coast of England, the material travels round Lyme Bay² with the flood-tide, in a direction varying from north-east to south-east; along the south-east coast, from Bognor to Beachy Head, the general direction of the drift is almost due east; from Beachy Head to Dover it is north-east; from Dover to the North Foreland northerly; from the North Foreland to the mouth of the Thames westerly; and north of the Thames south-westerly. Over such a limited area the "prevailing wind" can only blow from one direction. On the east coast north of Harwich Harbour, the shingle travels south-easterly; and, until preventive measures were taken, part of it was gradually extending in a long bank or spit across the harbour (shown by dotted lines, Fig. 3, Plate 1), the remainder rounding Langward Point and travelling along the beach in a north-easterly direction, in both cases working with the flood-tide. Further up the east coast, north of the Wash, the travel is south-eastwards; south of the Wash, along the coast of Norfolk, there is a large shingle bank the travel of which is eastwards; while in the Wash is another travelling southwards, in each case following the set of the flood-tide. The long shingle bank at Aldborough, 9 miles in length, travels south-west with the set of the flood-tide. On the west coast, north of the Ribble estuary, the travel of the shingle past South Shore and Blackpool is northwards, up the Ribble estuary past St. Anne's and Lytham the travel is eastwards, in each case in the direction of the flood-tide, the prevailing and dominant winds being south-west.

In the Bay of Bengal, where the monsoon blows continually for several months, there are two movements of the sand in opposite directions. During the north-east monsoon, the movement is from north to south, in the same direction as the wind; but as soon as the north-east monsoon ceases, the direction is reversed, and the drift moves in the opposite direction with the set of the flood-tide. In the north of the Arabian Sea the drift is south-east, the flood-tide setting from the north-west, the monsoon which blows from the south-west for a time arresting the progress of the material.³

On the east coast of Africa, although the Mozambique current

¹ "Littoral Movement on the New Jersey Coast," Lewis M. Haupt. *Transactions of the American Society of Civil Engineers*, vol. xxiii. pp. 123 and 148.

² "Tidal Rivers," by W. H. Wheeler, p. 162.

³ *Minutes of Proceedings Inst. C.E.*, vol. xliii. p. 4.

passes along the coast from north to south, the sand travels from south to north, in the same direction as the set of the flood-tide.¹

The general effect of the wind on the travel of drift is as follows: Gales blowing obliquely on-shore, in the same direction as the flood-tide, cause the waves to rise higher, and they are then the most active agents in eroding the cliffs and providing and transporting material. Strong direct on-shore gales denude and cut out material that has been deposited, and lower the beach. In off-shore winds and calm weather the material accumulates and raises the beach. Winds blowing continually from one quarter, in an opposite direction to the ordinary travel of the drift, will have the effect of causing the waves to strike the beach at a different angle to that caused by the tidal waves, and reverse the direction of movement. Under such circumstances, shingle or sand may become deposited across the entrance to a river or harbour mouth and block the entrance for a time. This effect ceases when the gale abates; and the movement of the material resumes its normal direction.

With regard to the effect of the tidal current alone in moving material, the velocity of this current along a coast in the open sea is seldom more than 2 to 2½ knots, and never sufficient to move pebbles and stones of the size found in shingle beaches; and, as the flood and ebb last the same time, if the movement were due to the tidal currents it would be of an oscillating character, the sand or shingle being moved backwards and forwards within a certain zone. On shores where the rise and fall of the tide and the direction of the current are not coincident, as is frequently the case in narrow seas, the current outside the range of the waves breaking on-shore will move floating material in one direction, while the wave-action of the on-shore tide is moving the shingle in the opposite direction. Further, the current alone cannot have the effect of heaping up shingle at a height considerably above the level of the highest spring tides.

A careful examination of the movement of littoral drift, on several different parts of the coast in this and other countries, shows that the continuous progressive movement is invariably in the direction of the flood-tide. The Author has not been able to find a single instance in which the regular and continuous movement of littoral drift is in an opposite direction to that of the flood-tide. During long-continued gales, blowing in an opposite direction to the flood-tide, the normal condition may be arrested for a time, yet as

¹ Minutes of Proceedings Inst. C.E., vol. cxviii. p. 86.

soon as this cause is removed the travel again assumes its natural course.

The continuous progressive movement of sand and shingle along the sea-coast is due then, not to winds or tidal currents, but to the wave-action of the flood-tide, this action being increased when the height of the waves is increased by the wind blowing in the same direction as the flood-tide. The action of the flood-tide making along a coast does not consist in a gradual swelling or raising of the water, but a series of small waves are given off from the main tidal wave, which break on the shore in an oblique direction. Even on the calmest days these breaking waves have sufficient force to roll the material of which the beach is composed upward and onward in the direction in which the tide is making. The constant murmur that is heard on a shingle beach even on a calm day, rising to a roar in stormy weather, attests the fact of the pebbles being in perpetual movement. The greater part of the shingle rolled up by the wave in an oblique direction is carried back on its return in a direction normal to the beach; but some stones, and these frequently the largest, remain at the place to which they are lifted. The movement of the drift is therefore of a zigzag form. These breaking waves of the flood-tide approach and retire in sets, the ninth or tenth, according to circumstances, being generally the highest. The stones thrown up on the crest of the wave are gradually lifted higher up the beach as the tide rises; and at high water there is always a certain quantity carried by the crest of the highest wave above the reach of the retiring waves of the ebb-tide.

In addition to the impulse imparted to the pebbles by the momentum of the breaking wave, the material is moved along by the current generated by the wave after it has broken on the beach. The velocity of this current has been estimated¹ as that which water would acquire in falling a distance equal to the height of the wave, or $V = \sqrt{2gh}$, h being the height of the breaking wave. The velocity due to a wave only 1 foot high would be about 8 feet a second, and therefore capable of moving pebbles of considerable size.

The material moved upwards by these tidal waves varies in size between grains of sand, pebbles weighing only the fraction of an ounce, and stones weighing 5 to 6 lbs., the average weight of the pebbles being about 4 or 5 ounces. With a perfectly calm sea, the Author has observed, on a shingle beach in a sheltered

¹ Minutes of Proceedings Inst.C.E., vol. lxxxiii. p. 323.

position, numbers of stones moved upward and forward, which weighed from 4 ounces upwards when out of the water, and single stones weighing as much as 6 lbs.; and shortly before high water, pebbles weighing $1\frac{1}{4}$ lb. were rolled upward and forward, and left on the bank. The ebb-tide also retires from the beach with an oblique wave-action, the direction of these waves being the same as on the flood; and although the waves roll down more pebbles than they carry up, there is always a certain quantity of material which is moved upwards and remains, pebbles weighing $\frac{3}{4}$ lb. being raised and left on the bank in calm weather. On a sandy beach, the line to which material has been deposited above the influence of the ebb can always be traced by the "wrack" or floating material left stranded at the limit reached by the highest wave, and on a shingle bank by a ridge and hollow. This tidal-wave action is continuous and operates twice every day. Allowing ten waves to a minute, and that the forward movement only takes place on the flood, no less than 7,200 impulsive movements are imparted to the material drifted in the course of twenty-four hours.

BEACHES BELOW LOW-WATER LEVEL.

Except in very heavy storms, the beach below low water is not subject to movement. As already pointed out, moving shingle banks are always above the limit of low water; and it has repeatedly been shown that there is no travel of shingle in deep water. During and after the construction of the Admiralty Pier at Dover, divers were employed to examine the bed of the sea at the foot of the wall to ascertain whether any shingle was travelling eastward along the wall, and it was found that such was not the case, although there was a considerable movement eastward along the beach up to the groyne which extended out from the shore immediately to the west of the pier, and a large accumulation at Folkestone.¹ Instances are recorded of large stones and other heavy material being raised from the bed of the sea in gales and cast up on the shore.² While, however, the deposit of these heavy substances may be cited in favour of an increase and accumulation of a beach in stormy weather, the effect does not extend

¹ Dover Harbour Report, 1847. Evidence of Capt. Washington. Sir J. Coode's Report, 1873.

² Minutes of Proceedings Inst. C.E., vol. lviii. p. 284.

beyond the deposit of the heavier materials. The under-tow of the waves, as they break on the shore, if not of sufficient force to move back these heavy stones, carries with it the sand or small pebbles thrown up. It is found that, except when large rivers bring down a great quantity of alluvial matter, or where high cliffs, consisting of soft material, are being eroded, there is very little change in the formation of the sea-bed near the shore, so far as any historical records afford a basis of comparison. So long as the natural conditions remain unaltered, and the set of the tides is not interfered with by piers projected out from the shore, or other artificial works, the equilibrium originally established between the several contending forces remains.

The two principal forces at work are the tidal currents and the action of waves. So far as wave-action is concerned, the effect diminishes very rapidly as the depth increases. Gales that affect sandbanks covered with only a moderate depth of water occur only occasionally; whereas tidal action is constant and continuous. Submerged banks disturbed by the waves are therefore quickly restored to their normal condition by the tidal currents. It has been found that when there is considerable motion on the surface of the water, divers can continue their operations below the surface, although they may have to cease work from not being able to stand against the strong current which prevails at certain states of the tide. As to the effect of tidal currents on the movement of submerged sand-beds in tidal channels, and, as showing that this movement is one of oscillation and not transportation, an instance is recorded by Mr. Partiot,¹ which occurred at the mouth of the Gironde. A steamer was sunk by a collision opposite Verdon, and rested on her keel at the bottom of the channel in 6 fathoms at low water, the masts and chimney only showing. At the end of the ebb-tide, the sand was so scoured as to leave a space under the keel at both ends, leaving the hull only supported in the middle; and at the end of the flood-tide, the vessel was completely buried in sand, the sand-bed extending 100 yards fore and aft of the vessel and 50 yards from each side.

A careful comparison of all the charts from 1801 shows that on the north coast of France and Belgium there has not been any appreciable modification of the shores, the banks and channels occupying the same relative positions and depths. At Dunkirk, the works carried out since 1836 have caused the coast to accrete westward for several miles; but this advance of the beach

¹ "Étude sur les Rivières à Marée," H. L. Partiot. Paris, 1892, p. 56.

has not altered the limits of the roadstead. In the banks and channels of the estuary of the Scheldt there has been very little change since the beginning of this century, the alluvial matter brought down by the rivers being deposited within the estuary and not carried or deposited on the sea-coast. The same remark applies to the great range of sandbanks along the Netherlands coast. At Nieuport, the bottom of the sea has preserved the same form and the same depths since the commencement of the century. At Ostend, the Grande Rade tends slightly to deepen; the Petite Rade has not changed for one hundred years. In the channels in front of Blankenberge, no change is observable; and the Pass of Wielingen tends to deepen.¹ A comparison of the charts of the North Sea off the Kentish and Essex coasts in use at the beginning of the century with those of the present day shows very little alteration in the position of the sands or channels, the only change being a lengthening of the sand-beds, and, if anything, a deepening of the channels. Further up the east coast, the sandbanks between Yarmouth and the Humber, and in the Wash, so far as can be ascertained from ancient charts, remain in the same position as they were a century ago; and the same is the case with the sandbanks at the mouth of the Tay, the great sandbanks at the mouth of the Mersey, the Dee, the Ribble, and in Morecambe Bay. In all these cases there has been a certain amount of alteration due to causes which can be traced, and an accretion in the estuaries from alluvial matter brought down by the rivers or eroded from cliffs; but the main features of the channels and the great sand-beds remain probably in the same condition as they were left at the last great physical change of conditions.

STABILITY OF CHANNELS IN SAND.

The same remarks apply to the channels which intersect these great sand-beds. Through the great mass of sand constituting the bed of the ocean between the south-east of England and the coasts of France, Belgium, and the Netherlands, there exist several deep channels lying between sandbanks, such as the roadsteads in front of Havre, Calais, Dunkirk, Ostend, and other ports of the coast, with depths varying between 3 and 15 fathoms; and on

¹ "Étude sur l'amélioration et l'entretien des Ports en Plage de Sable," P. De Mey, Paris, 1894; and Minutes of Proceedings Inst. C.E., vol. lv. p. 79.

the English coast, the Wallet, the Sunk, Barrow Deep, the East Swin, &c., with depths varying between 5 and 15 fathoms; also the deep inshore channel known as Yarmouth roadstead, running parallel with the coast for 21 miles, from Winterton to Covehithe, having a depth of 4 to 7 fathoms. In fact, the whole of the lower part of the North Sea consists of deep channels lying between beds of sand. These channels have retained their depth and width without change, so far as any records exist; and as the result of a comparison of the present condition of the channels from Dunkirk to Flanders with the ancient charts, the Belgian engineers reported "that these channels taken as a whole have been maintained in a most remarkable manner."¹ The sandbanks which bound these channels are all steep on their inshore side, and spread in a gentle incline to the offing. The outer Ruytingen Bank, which borders a channel between 5 and 6 miles wide, and between 14 and 18 fathoms deep, rises almost perpendicularly from the bottom on the inner side, having a gentle slope on the seaward side.

So also the channels through the Straits of Dover have retained their depths, notwithstanding the stormy character of the locality and the drift from the cliffs by which both sides of the channel are bounded. On the coast of Holland, off the Texel and in the Skaw between Sweden and Jutland, are vast sand-beds having permanent deep-water channels through them, the sides in many cases being very steep, dropping suddenly from shoal water to 10 or 12 fathoms. A sand-ridge in the North Sea, known as the Lemon Bank, near Yarmouth, extending for 20 miles, with a width of $\frac{3}{4}$ mile, is so steep on the east side that a vessel would strike the bank before obtaining soundings in 20 fathoms of water.² The Stroombank which forms the protection for the roadstead at Ostend, composed entirely of sand, exposed to strong tidal currents and the impact of waves from the sea, has a very steep slope on its inward slope, and a depth at low water in the channel of between 3 and 5 fathoms.

About half of the Wash on the east coast consists of sand-beds rising above low-water level. Through these run a great number of tidal channels. In comparing the Admiralty chart of 1829, the first reliable one which is to be found, with that of 1891, a period of sixty-two years, it will be found that, except at the upper end of the estuary, where training works have been carried out, there

¹ P. De Mey, "Ports on Plage de Sable."

² "North Sea Pilot."

is practically no alteration in the position or depth of these channels. The only change that has taken place has been in prolongation of the sandbanks in the direction of the flood-tide and a deepening of the channels. The approach to Lynn, Fig. 4, Plate 1, is through a mass of sand-beds, 8 miles in width, intersected by a number of tidal channels. The main navigable channel which passes through these sands has a sharp curve, its depth varying between 2 and 6 fathoms. Its position is the same, and the depth rather greater now than it was sixty years ago. The other channels leading to Boston and Wisbech have remained the same as they have ever been, so far as the sea-approaches are concerned; and the depth over the bar of Boston Deep has remained unaltered.

Describing the estuary of the Gironde, Mr. Partiot says:—"If only a portion of the river be examined, the risings seem to indicate a filling up; but if the observations are more extended and carried over a longer period, it is seen that the risings correspond to lowerings in other places, and that in the arms of the sea, where all the alluvial matter from the river has been carried during many ages, there exist alternate movements, observations of which seem to show a recurring period; the discharge remains the same, and the divers effects which are produced tend to a mobile equilibrium which effects the conservancy of the estuary." It is unnecessary to multiply instances of the permanency of channels through sand, as a study of the charts of the coasts and estuaries of this and other countries will be sufficient to show that those quoted are by no means exceptional instances, and that, in fact, many harbours owe their existence to the protection afforded by long strips of sand which, running out from the coast, resist the action of the tides and waves and maintain their position.

These facts all point to the conclusion that there is little or no permanent movement of sand below low-water mark. A channel having at one time been established, and an equilibrium of forces set up, the momentum of the volume of water due to tidal action moving in a given direction between two banks of sand is sufficient to overcome any surface action due to winds and waves, and the channel consequently remains permanent, although the sides and bottom are of a mobile character; and this even in channels having a considerable curvature.

DREDGING.

If this absence of change be established, it is fair to presume that channels through sandy estuaries may be permanently deepened and maintained by dredging without the aid of training-walls, provided that the direction be such that the flood and ebb currents shall be led so as to act in the same direction, and that the depth at low water shall be sufficient to resist any surface action due to wind.

Formerly when a harbour was situated on a coast encumbered with sand-beds, it was considered a hopeless task at any reasonable cost to provide a deep-water entrance. The perfection to which sand-pump dredgers have been brought has entirely altered the conditions, and has placed at the disposal of engineers the means of quickly and economically obtaining the depth of water required.

That channels dredged in sand without the aid of piers, training-walls, or scouring basins, can be made and permanently maintained is proved by works recently carried out, of which the following are the most notable examples. The main navigable channel to New York, Fig. 5, Plate 1, which passes through the outer bay to the Atlantic, was obstructed by four long shoals, over which the larger class of vessels could only pass at high water. The Government Board of Engineers, to whom the best means of improving this channel had been referred, advised that permanent results could only be obtained by stone training-walls, 4 miles in length, across these shoals from Coney Island to Sandy Hook, the estimated cost of these walls being £1,250,000. In spite of this opinion, it having been strongly urged that all that was required could be accomplished by suction dredging, sanction was given to experimental trials, which, proving successful, the channel was deepened by this process $6\frac{1}{2}$ feet, giving a minimum depth of 30 feet at low water over a width of 1,000 feet at a cost of £258,551, the work being completed in 1890. The material removed was principally sand and alluvial matter. An official report made a year after the work was finished, stated that since its completion no shoaling had taken place.¹

The entrance to the Mersey is through a vast mass of sand-banks. Through these banks there has always existed a navigable channel, the direction of which has altered slightly from time

¹ "Improvement of the Channels at the Entrance to the Harbour of New York," J. Edwards. Transactions of the American Society of Civil Engineers, vol. xxv. p. 573.

to time, partly owing to works which have been carried out on both sides of the river. At the junction of the channel with the sea in Liverpool Bay there has always existed a sand-bar, Fig. 6, Plate 1. Until recently no attempt was made to improve the depth over this bar, because the general opinion of engineers was that this could only be done at enormous cost by means of training-walls. By the use of suction dredgers, it has been proved that not only has it been practicable to deepen the channel over the bar from 11 feet to 23 feet at low water, over a width of 1,500 feet with a central depth of 24 feet, but that the channel so dredged has not only maintained its depth during the severe tests of the gales of two winters, but shows a tendency rather towards deepening than shoaling.

At Ostend, the channel from the harbour to the deep water in the roadstead, through the sand which lies all along the coast, has been deepened $6\frac{1}{2}$ feet by dredging, giving now $16\frac{1}{2}$ feet at low water, and has been maintained at this depth since 1886 by an annual dredging of about 130,000 cubic yards, of which about one-third is taken from between the jetties. A series of groynes has been constructed along the coast on the west side of the harbour to prevent the travel of the drift along the coast towards the harbour. The depth of the "Petite Rade," or outer harbour, varies between $4\frac{1}{2}$ and $5\frac{1}{2}$ fathoms, and it is separated from the main deep-water sea-channels by the Stroombank, Fig. 7, Plate 1, which runs parallel with the coast, and has only 10 feet over it at low water. In 1889 the Belgian Government gave instructions for a channel to be dredged across this shoal 2,000 feet wide and giving $16\frac{1}{2}$ feet at low water of spring tides. The work was commenced in June 1890, and in November following a depth of 13.76 feet had been obtained. The work was commenced again in March 1891 and continued till October, the depth attained being $16\frac{1}{2}$ feet. No dredging has since been carried out, and the depth is maintained, although there have been several violent storms. The total quantity of sand removed was 771,000 cubic yards, the distance of the place of deposit $2\frac{1}{2}$ miles, and the cost 4.38*d.* per cubic yard.¹

The bar of Charpentier, at the mouth of the River Loire in the Bay of Biscay, Fig. 8, Plate 1, consists entirely of sand. Through the middle of this, a channel 1 mile long and 660 feet wide has been excavated 8 feet by dredging, giving a depth of 15 feet at low water. This has involved the removal of 1,800,000 tons, which

¹ P. De Mey, "Ports en Plage de Sable."

was accomplished in three years, the work being completed in 1893. The deepening has remained permanent.

HARBOURS ON COASTS SUBJECT TO LITTORAL DRIFT.

A knowledge of the special conditions relating to the coasts, and of the natural forces in operation, is essential to the design of any works for the construction of harbours or for the improvement of access to tidal ports. The following principles, however, deduced from the facts recorded in the Paper, appear to be of general application.

1. That piers running out from the coast should be so projected as not to derange the main set of the tidal stream, and be so designed as not to cause an eddy current at the entrance to the harbour.

2. That the entrance to a harbour should be sufficiently large to prevent any strong set into it on the rising tide, and to allow of its being filled with a smaller velocity of current into it than the flood-tide has in front of the entrance.

3. That the piers should project from the coast into water of sufficient depth to be free from the action of littoral drift, and beyond the local influence of matter in suspension derived from the waste of cliffs or detritus brought down by rivers.

The first result of the extension of a harbour-wall or breakwater out from a coast where there is much drift of sand or shingle, is the collection of material in the angle formed by the pier with the beach, and also a gradual increase in the height of the beach for some distance away from the projecting wall. After the beach has extended out a certain distance this process stops, a state of equilibrium is reached, and further accretion ceases, especially where the precaution has been taken of arresting the destruction of cliffs by groynes or other projecting works.

The depth into which the piers have to be carried depends on circumstances; a depth of $2\frac{1}{2}$ fathoms has in some cases been found sufficient. Sand and shingle have never been found to work round a pier having a depth of 4 fathoms. A strong illustration in proof of this is given in the works carried out in the construction of Madras Harbour. There is considerable movement of sand along this coast, especially when the monsoon is acting in conjunction with the set of the flood-tide, which is heaped up against any projection. As the breakwater for the harbour was extended out from the shore, a large amount of sand accumulated

on the beach in the vicinity, and also passed round the end of the walls as they projected from the coast into the harbour. As deeper water was approached, this effect became less, until it entirely ceased when the wall reached a depth of 4 fathoms at low water.¹ At Colombo during the construction of the breakwater, although the sand was heaped up as much as 12 feet in height during the monsoon, it exhibited no tendency to work into the harbour round the walls which were placed in a depth of $4\frac{1}{2}$ fathoms. At Port Said, where the foreshore through which the piers extend is sand, and there is also a considerable amount of alluvial deposit in movement from the discharge of the Nile, during the construction of the breakwater there was a considerable growth and advance of the beach, and the sand worked through the loose concrete blocks into the channel; but after a time a state of equilibrium was reached, and there is no longer any apprehension of the material drifting round the ends of the piers and shoaling the entrance. In a report made by Admiral Richards, in 1870, he stated that supposing the rate of accretion along the coast proceeded at the same rate as when the piers were first constructed, it would take three hundred years before it reached the end of them, but he doubted whether it would extend much farther than it had then reached. At Dover, as already mentioned, the projection of the Admiralty Pier into 6 fathoms at low water stopped the accumulation of deposit which had previously taken place in the inner harbour; and no silting has taken place inside the pier. Some shoaling took place at the back of the wall soon after its construction; this, however, was not due to any littoral drift, but was caused by the strong tidal current which swept round the east end of the wall into the sheltered part, scouring out the bed of the sea where the current ran strongest, and depositing it where there was slack water.² In fact it was merely a transposition of material; the quantity of deposited material, however, being 10 per cent. less than that scoured away.

Ramsgate Harbour, situated on the same coast as Dover, affords an example where, owing to none of the principles mentioned above being observed, there is a continual accumulation of deposit, more than half its area being dry at low water, and the harbour being only maintained by continual dredging. The piers only extend into a depth of 4 feet at low water. The flood-tide does

¹ Minutes of Proceedings Inst. C.E., vol. lxx. p. 44. *Ibid*, p. 36. L. F. Vernon-Harcourt, "Harbour and Docks," p. 304.

² Sir John Hawkshaw's Evidence, Dover Harbour Report, 1875.

run truly across the entrance, but creates an eddy-current; and there is a strong inward set which carries into the harbour deposit derived from the waste of the adjacent coasts, and alluvial matter brought down the River Stour. Whitehaven is another example where shallow water at the end of the piers and an eddy-current result in the harbour being filled with silt. The flood-tide here passes the entrance of the pier, and striking Redness Point, eddies back along the shore, and carries the silt and sand direct into the harbour.¹

At Newhaven, the breakwater, commenced in 1880 and completed in 1890, extends out from the shore 2,700 feet into $3\frac{1}{2}$ fathoms at low water. The shingle travelling from the west has collected at the end next the shore, but not to any great extent. There has been some shoaling from the alluvial matter brought down from the River Ouse; but no shingle or sand has travelled round the end of the breakwater into the harbour, and no shoaling has taken place from material brought in from the sea.

At Kingstown there has been practically no silting in the harbour since its construction—nearly eighty years ago—although there are considerable sandbanks in the neighbourhood, and there are shifting sands immediately abreast the entrance. As at Dover, there was a certain amount of transposition of material, sand being scoured away from the western entrance and deposited on the other side. The freedom from deposit in this harbour is due to the entrance being in a depth of 4 fathoms at low water, and exactly in the fair stream of the ebb and flood current, and the opening at the entrance being so proportioned to the area of the interior that no perceptible current flows into the harbour.² The water enters this harbour bright and clear; and when the ebb-tide is coming off the sands in Dublin Bay, the water is running out of the harbour. At Howth Harbour, on the other side of Dublin Bay, where the same conditions do not prevail, and where the piers end in a shallow depth of 7 feet at low water, and where the tidal current does not run fairly in a line perpendicular to the entrance, continual silting has taken place.³ At Tynemouth, although the sandy beach has advanced along the piers, it has not worked round the ends so as to shoal the entrance, but the sea approach has rather tended to deepen. It has been estimated that even if the present rate of progress of the beach is maintained,

¹ Minutes of Proceedings Inst. C.E., vol. lv. p. 95.

² Capt. Washington, Evidence, Dover Harbour Report, 1847.

³ Gibbons, Evidence Dover Harbour Report, 1847.

which is unlikely, it would take 150 years before the accretion reached the seaward end of the piers.¹

At Ymuiden, the projection of the harbour walls led to an advance of the sandy shore; but this effect ceased before the beach extended out far enough to compromise the depth at the entrance, which was in $4\frac{1}{2}$ fathoms at low water. In this harbour there has, however, been considerable shoaling, necessitating continual dredging, due to material brought down the canal from the interior, and sand blown in during stormy weather from the sand-dunes in the neighbourhood, and driven in from the sea during westerly gales. These gales, beating on the coast, cause great erosion of the sand and alluvial matter, which is thus put in suspension and carried by the current across the entrance, where they are met by a strong current flowing directly into the harbour, which carries the suspended material with it.² The tidal current does not in this case run truly past the entrance and parallel with the outer pier walls, but its direction is disturbed by the canted shape given to the walls, which causes the eddy current referred to above.

Piers which are not carried out into sufficiently deep water only act as groynes, and stop the transit of the material moving along the coast, which after a time travels round the end of the pier into the harbour. An example of this is afforded by Lowestoft Harbour, where there is only a depth of 10 feet at the end of the piers at low water. During north-easterly gales, the shingle and sand accumulate so rapidly as to almost block the harbour, and continual dredging is necessary. An extension of the pier on the north side, a few years ago, arrested the travel of shingle and sand to a considerable extent; but the extension was not carried out far enough to prevent material working into the harbour.³ If this pier, on the side from which the drift comes, was extended out into deeper water, like the groyne at Harwich, referred to before, the supply of shingle would be cut off, and scouring would probably take place instead of accumulation.

By the construction of groynes, placed along a coast on the side from which the material comes, the shingle and sand will be stopped in their transit, and the beach raised, stopping the erosion of the cliffs and thus cutting off the source of supply. The drift continuing to travel along the coast on the lee side of the harbour,

¹ Minutes of Proceedings Inst. C.E., vol. lv. p. 83.

² L. F. Vernon-Harcourt, "Harbours and Docks," p. 182. P. De Mey, "Ports en Plage de Sable."

³ Minutes of Proceedings Inst. C.E., vol. lxxxvii. p. 134.

and the supply being cut off, there will be no material left to be driven in by gales coming from the opposite direction to that from which the drift travels.

CONCLUSION.

The Author, in conclusion, desires the Paper should be regarded, not as an attempt at an exhaustive treatment of the subject, but rather as a means of directing attention to an intricate and difficult subject by suggesting deductions from the facts which he has collected.

The Paper is accompanied by eight tracings, from which Plate 1 and the *Figs.* in the text have been prepared.

[DISCUSSION.

Fig: 3.

NOTE. Soundings in feet.
Arrows show direction of travel
of shingle and set of Flood tide.

HARWICH HARBOUR.

Fig: 6.

RIVER MERSEY.

Fig: 8.

RIVER LOIRE.

Fig: 4.

LYNN CHANNEL.

Fig: 5.

ENTRANCE TO NEW YORK HARBOUR.

Miles 5 4 3 2 1 0 Scale 3 Miles = 1 Inch. 5 Miles.

Fig: 7.

NOTE. Soundings in Fathoms.

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