

16 April, 1885.

Sir FREDERICK J. BRAMWELL, F.R.S., President,
in the Chair.

“Tides and Coast-Works.”

By THOMAS STEVENSON,¹ President of the Royal Society
of Edinburgh, M. Inst. C.E.

I CANNOT but express my sincere regret, on your account, that Sir John Coode should have been prevented, by unavoidable causes, from giving the lecture on “Tides and Coast-Works”; and all the more, as so short a time has been at my disposal for meeting this unfortunate emergency. I trust, however, you will kindly make, for me, as great an allowance as possible.

As regards the very important but also very abstruse subject of the tides, which forms the first part of the matter which has been remitted to me by the Council, I believe it is not expected that I should enter systematically into it, the more so as there are many treatises which fully embrace all the details in so far as the extent of our knowledge and the state of mathematical science enables the investigation to be undertaken. I may refer in particular to the remarkable Treatise on the “Tides,” in the “Encyclopædia Metropolitana,” by Sir John Herschel, and also to the works of Airy, Laplace, and Newton.

It seems only necessary, by way of preliminary remark, to note the confusion which has been introduced into the subject, by neglecting to take into consideration the large lapse of time, between the passage of the moon across the meridian and the time of high water, due to the inertia of the water, and the irregularities of the shores and bottom of the sea, in connection with what is called the “Establishment of Ports,” or what is generally termed the times of high water on the days of full and change of the moon. As is now well known the tides do not occur syn-

¹ As Mr. Stevenson was unable to attend through indisposition, this discourse was read by Mr. Eaton.

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chronously with the passage of the moon across the meridian, but lag behind for about three or four tides. Another great cause of confusion has arisen from the difference which exists between the phenomena of the flow and ebb of the currents and the vertical rise and fall of the tides; and then again there are many tides which are not directly due to the attraction of the moon, but are strictly of a derivative nature, being produced by their simply spreading from the great primary tide, round points of land and islands. Dr. Whewell did much to establish a map of cotidal lines with the view of extricating the question from those difficulties, and clearing it from the disorder which formerly existed.

It is hardly necessary to notice that, in so far as regards the British coasts, the great tidal wave, after passing over the Atlantic Ocean, splits upon the western coast of Ireland, and proceeds in two courses, one branch forming a wave which passes through the English Channel, and the other through the channels of the Orkney and Shetland Islands, and that these branches meet each other in the North Sea near Yarmouth.

I need scarcely point out how large and beneficial is the influence of these tides on the commerce and wealth of the country, by enabling vessels even of heavy draught to pass inland from the ocean. But in so far as our subject is concerned, viz., "Light-houses," "Coast Harbours of Refuge," and "Coast-Protection Works," we have principally to consider in what way the tidal current influences such works.

All sea-works are affected beneficially or the reverse by the height to which the tide rises in consequence of the configuration of the land, and on the velocity, due to the same cause, which the tidal currents assume. So long as the tidal wave is passing through great depths in the ocean, the tidal range is comparatively small, but when it enters a bay or firth, and especially a tidal river having converging shores, very great changes are produced, as in the case of the Wye at Chepstow, where the tide has been known to rise 56 feet. This, viewed as a mechanical question, may be accounted for, as stated by Dr. Whewell, on "the principle of the conservation of force. When any quantity of matter is in motion, its motion is capable of carrying every particle of the mass to the height from which it must have fallen to acquire its velocity; but if the motion be employed in raising a smaller quantity of matter, it is capable of raising it to a height proportionally greater. In bays and channels which narrow considerably, the quantity of water raised in the narrow part is less

than in the wider, and thus the rise in such cases is greater.”¹ A familiar illustration of this principle is the simple experiment of plunging a funnel with its wide mouth downwards into a vessel of water, when a jet of water springs out of the narrow end of the funnel to a height considerably above the level of the water in the vessel.

As regards the influence of the tides upon wind-waves, it is obvious that the effect of currents running in opposite directions to waves, whether they are merely of an oscillatory nature, or those greater waves of translation which affect the bottom at greater depths, must necessarily result in violent conflict, and give rise to what are called “Races” in England and “Roosts” in Scotland, and which may be witnessed on a small scale in all rivers where the outward current meets the sea and encounters the waves caused by on-shore winds.

In some cases this antagonistic action between the tidal current and the waves increases the height and force of the waves on sea-works and on the shore-line, while in other cases it produces the contrary effect, and acts therefore protectively as would an outer breakwater of masonry.

A well-developed example of the sheltering effect of the Sumburgh “Roost” near Sumburgh Head, the most southern point of the Mainland of Shetland, came particularly under my notice. At one of my visits to that place, I asked the light-keeper to observe particularly during the next heavy gale, whether the waves which reached the shore while the “Roost” was in full action, were not of smaller magnitude than when the action had ceased; and some time after I received the following remarkable testimony on the subject:—

“We had a very severe gale from the south-west yesterday, and being the first gale we have had from that quarter since you were here, I paid particular attention to the state of the sea in the West Voe through the day. By daylight in the morning it was blowing very hard, with a most terribly heavy sea rolling into the West Voe and breaking over the top of the banks, while low-water lasted. But with regard to what you said to me about the tide in the ‘Roost’ acting as a breakwater to the Voe, your opinion is right, for during the last hours of flood and the first two hours of ebb-tide in particular, a small boat could have gone till within a few yards of the ‘Roost’ between the Lighthouse and the Horse Island, although the sea was still in the same raging state beyond

¹ Philosophical Transactions, 1833, p. 204.

the 'Roost,' and as far as the eye could reach towards Fair Isle and away to the west."

I may remark that wherever the land projects far from the general coast line, "tidal races" will be found to exist, because the currents which oppose the passage of heavy waves are there intensified. Probably the best illustrations of tidal and wave action are to be found in the Pentland Firth, which may be regarded as the most dangerous navigation of any on the British coast, presenting as it does so many "races" or "roosts." Some writers have alleged that these "roosts" are due to the meeting of contrary currents, while many sailors, on the other hand, believe them to be due to shoal water produced by abrupt vertical changes in the rocky bottom. But the true cause is undoubtedly the large oceanic waves encountering a tidal current running in a direction more or less opposed to their own. For the "roosts" on the west coasts of Orkney and Pentland Firth are known to be worst with ebb-tides and westerly gales, because the Atlantic swell and the current of ebb-tide are opposed; while those again on the east coast are worst with flood-tides and south-easterly swells. The depth of water where the Sumburgh "Roost" runs is not less than 40 fathoms, showing that it is not due to shoal water or to any submerged upstanding rocks.

VELOCITIES OF SOME OF THE MOST NOTABLE "RACES."

Names of Places.	Authorities.	Velocity at Spring Tides in Statute Miles per Hour.
Portland Race	Admiralty Channel Pilot .	5·75 to 6·9
Open Ocean between Orkney and Shetland	" North Sea Pilot	5·76
Hoy Sound, Orkney	" " "	6·90
Holm Sound "	" " "	6·90
Sumburgh Roost, Shetland	" " "	8·06
Burger Roost, Orkney	" " "	8·06
Hellgate, New York, east current .	Prof. H. Mitchell . . .	8·50
Doris Mor, Argyllshire	Captain Bedford, R.N. . .	9·22
Gulf of Corrie Vreckan, Argyllshire	" " "	9·83
Roost near Louth, Pentland Firth	Admiralty North Sea Pilot	10·36
" Swona, "	" " "	10·36
" Pentland Skerries "	" Survey	12·20

A further proof of the influence of the tide upon the waves is afforded by the experience derived in conducting coast-works, where it has been found that the time at which waves of abnormal height gave rise to damage, was when the tide running near the shore was at or nearly at its greatest velocity. Murdoch Mac-

kenzie, the justly celebrated marine surveyor and hydrographer of last century, remarks, in speaking of the Orkney tides: "that the spring tides acquired a considerable degree of strength in less than one hour after the quiescent state; neap tides are hardly sensible in two hours after still-water; the stream is most rapid commonly between the third and fourth hour of the tide."

In cases where the tide runs close to or near the shore, many examples might be given to show that the damage to harbour and other works took place after the tide had attained its greatest velocity. It is sufficient to refer to Peterhead harbour, where, at two hours' ebb, after vessels had got aground in the basin, three abnormal waves burst over the seaward pier, knocked down the protecting sea-wall, and washed sixteen persons off the quay into the water. The volume of these waves was such as to set afloat again vessels which had already taken the ground. The contractor's agent stated that, at Alderney breakwater "the heaviest seas and the greatest rush of water over the wall occurred an hour after high-water."

Criteria of exposed Coasts.—As the result of many observations, I regard the following as being descriptive of those parts of the coast which are most liable to the impact of unusually heavy waves. (1) The waves are most destructive when they come in at right-angles to the shore line. (2) Their power is increased in proportion as the direction of the main body of the tide approaches to coincidence with the direction of the heaviest swell, and they are probably worst at those headlands on which the tide splits. (3) Where a considerable part of the coast retires, there will be less sea during the strength of the tide, even although the waves come in at right-angles to the shore, because the tide keeps outside, following the direction of the regular trend of the coast; but this will probably not hold true of small re-entrant hollows of the shore. (4) Where the line of exposure and the tide-current are parallel to the coast, if the tide runs in a line very near the shore, as is the case in short narrow channels, where the velocity of the current is increased, there may nevertheless be an unusually heavy sea.

Level assumed by Mud as a measure of Exposure.—In the Proceedings of the Royal Society of Edinburgh, vol. iv., p. 200, I referred to a feature which will be found of very considerable value in judging of the exposure of a coast. This is the level below the surface of low water at which mud reposes on the bottom. Though at first sight it might appear unlikely that the disturbance of the sea-level by wind-waves would be propagated to

great depths, there are numerous facts which prove the contrary. Although the absence of mud in any locality proves nothing, because the tide currents may sweep it away, or the geological formation may not produce it, yet its presence seems both a delicate and certain test of the lowest limit to which the disturbance originating at the surface has reached. Thus, as the waves progressively decrease in magnitude in the North Sea between Shetland and the coasts of the Continent, the level of repose of mud progressively rises nearer to the surface, from a depth of 80 or 90 fathoms to only 8 fathoms at the mouth of the Elbe, and to 12 fathoms off the coast of Holland, where ships can take the open beach in nearly all weathers without any protective harbours. If therefore we find, in front of a proposed harbour or coast-work, that mud reposes within a few fathoms of the surface, I believe we have in that fact certain ground for concluding that our works will never be assailed by a very heavy sea.

Line of maximum Exposure.—The effect of the action of waves against the shore must obviously vary with the line of maximum exposure, or in other words, the line of the greatest fetch or reach of open sea, which can be easily measured from a chart. The engineer has then to ask himself in what ratio, to the lengthening of this line, the height of the waves may be expected to increase. The result of many experiments on canals and on the Firth of Forth in 1850 and 1852 was that the heights of the waves increased most nearly in the ratio of the square roots of the distances in miles from the windward shore, or when h = the height of the waves in feet from crest to trough, d = distance in miles, and a a coefficient varying with the strength of the wind.

$$h = a\sqrt{d}$$

so that the height of the waves increases in a parabolic curve as they leave the windward shore. For short reaches and very violent squalls a modification of the formula is necessary; but in all ordinary cases and ordinary gales the coefficient in the above formula may be assumed as 1·5.

For shorter distances and violent squalls the following formula is more applicable $h = 1\cdot5 \sqrt{D} + (2\cdot5 - \frac{1}{4}D)$.

It should be carefully noted, however, that there are modifying elements attending the cases of waves approaching the land obliquely; for in consequence of the reduction of the depth, they change their directions and approach the general line of the beach more nearly at right angles, and thus strike with greater force than might be expected. There are also exceptions due to geo-

graphical configuration of the land. In Loch Fyne (Fig. 1), for example, the wind and waves seem to alter their direction with the winding character of the Loch, so that the effective fetch is greater than the length of free water in the Loch would lead one to expect. In other cases the height of the waves is reduced by increased width of water as at Craignure in Mull, shown in Fig. 2, where, during the winter of 1853-54, it was less than the formula indicates.

Another modification in the opposite direction is shown in Fig. 3, where the waves which enter a harbour-mouth at B, though apparently generated by the fetch A B, are also largely due to the fetch C B.

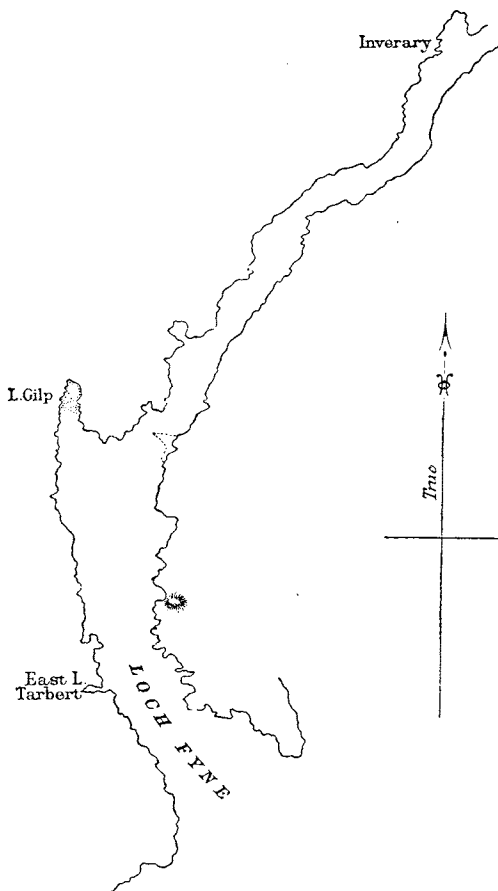
APPROXIMATE HEIGHTS OF WAVES DUE TO LENGTHS OF MAXIMUM FETCH
by OBSERVATION and by FORMULAS.

Place of Observation.	Length of Fetch in Nautical Miles.	Observed Height of Wave.	Height due to Fetch calculated from Formula $h = 1.5\sqrt{d}$.	Height due to Fetch calculated from Formula $h = 1.5\sqrt{d}$ $+ (2.5 - \frac{1}{\sqrt{d}})$.
		Feet.	Feet.	Feet.
Scapa Flow	1.0	4.0	1.5	3.0
Firth of Forth.	1.3	1.8	1.8	3.2
Granton	2.8	4.0	2.5	3.75
Craignure, Sound of Mull	3.5	2.0	2.9	3.9
Granton	6.0	4.0	3.7	4.6
Lough Foyle	7.5	4.0	4.1	4.96
Clyde	9.0	4.0	4.5	5.25
Colonsay	9.0	5.0	4.5	5.25
Dysart	10.0	4.2	4.9	5.5
Invergordon	11.0	3.5	5.0	5.7
Lough Foyle	11.0	5.0	5.0	5.7
Glenluce Bay	13.5	5.5	5.6	6.1
Anstruther	24.0	6.5	7.5	7.7
Lake of Geneva, stated by Minard	30.0	8.2	8.2	8.37
Buckie	31.0	7.0	8.4	8.5
"	38.0	7.0	9.2	9.2
"	38.0	8.0	9.2	9.2
"	40.0	8.0	9.55	9.5
Macduff	44.5	8.0	10.02	9.9
"	45.5	10.0	10.2	10.0
Douglas, Isle of Man . . .	65.1	10.12	12.0	11.76
Kingstown	114.0	15.0	16.0	15.25
Sunderland, distance mea- sured from Broken Bank)	165.0	15.0	19.3	18.15
		149.82	165.57	162.68
Mean		6.5	7.1	7.07

Reduction of height of Waves occasioned by shallow Water.—Another all-important matter is the destruction of the waves, or reduction

of their height, produced by the shallowing of the water near the shore. That this influence, in the case of heavy seas of the kind called waves of translation, is felt at great depths and at great distances from the coast line, is obvious from a statement by

FIG. 1.



Sir George Airy, that heavy ground-swells have been known to break in a depth of 100 fathoms. The great Atlantic seas, before they break upon any but the most exposed portion of our coasts, have probably suffered a considerable diminution of bulk and decrease of velocity. So soon as the lower extremity of the

undulation touches and is reduced by a reef or shoal, the upper extremity, by the process which is known as cresting, loses height in

FIG. 2.

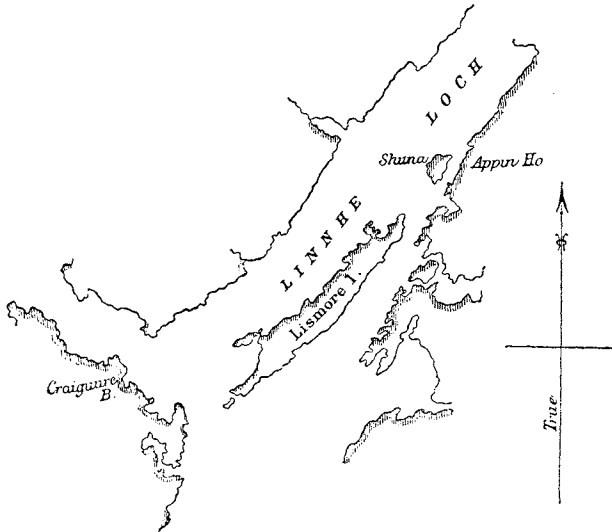
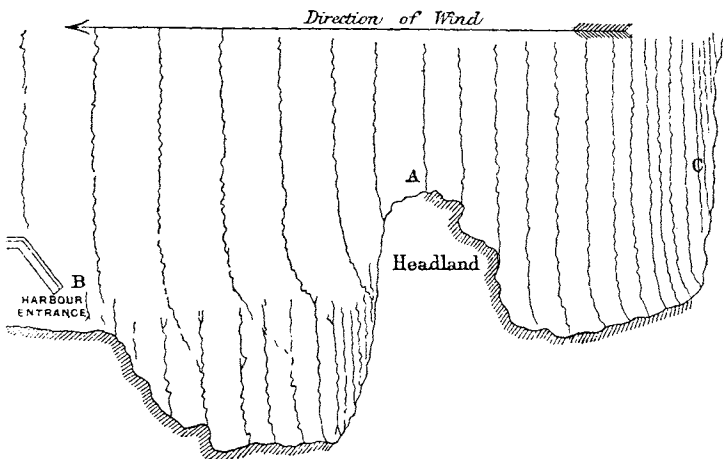


FIG. 3.



proportion. But the wave is not tripped up, and though somewhat lessened and retarded, still continues to rush onward upon the coast.

The actual destruction of the wave takes place in shallower soundings. The late Mr. J. Scott Russell, who has conferred so many obligations on the maritime engineer, found that waves break when they pass into water of the same depth as their height, but there are exceptions to this law. In 1870 I noticed at Scarborough, that waves broke when the depth of water was double the height of the wave, the depth being measured below the mean level, and the height from hollow to crest.

Force of the Waves.—By means of a marine dynamometer, the force of the waves was ascertained at Skerryvore Lighthouse in the Atlantic, when during a heavy westerly gale I found that a force equal to nearly 3 tons per square foot was registered; while at Dunbar, where the observations were continued for a much longer period, a force of $3\frac{1}{2}$ tons was registered on more than one occasion.

COAST-WORKS.

The most seaward and most exposed of sea-works are generally lighthouses erected on outlying rocks in the sea.

As regards the design of this class of sea-works, much as Smeaton's tower has been appreciated, I am distinctly of opinion that, in one very important feature, namely the outline, the former tower by Rudyard is decidedly superior for a small rock such as the Eddystone. It is long since I expressed that opinion, and subsequent experience has only tended to corroborate it. I have given general rules in my book on "Lighthouse Construction and Illumination," 1881, p. 28 *et seq.*, which I think will be found useful as a guide to selecting the safest modes of construction.

The profiles shown in Figs. 4, 5 and 6 are suitable in situations where the rock is either soft, hard, or of small dimensions respectively.

Modifying influence of the configuration of Rocks on breaking Waves.—I am satisfied of the great influence exerted by the shape and height of the rocks on which lighthouse towers are built; and I feel bound to take this opportunity of again expressing my conviction that Smeaton's tower should not be regarded as a safe model for imitation on rocks which are exposed to a heavy sea. Nothing less can be deduced from the remarkable fact that the level above the sea at which fourteen blocks of 2 tons each, set and fixed by joggles, dovetails, and cement, were dislodged and swept away by a summer gale at Dhu Heartach, is the same as that at which the thin crown-glass panes of Winstanley's lantern remained unbroken through the storms of a whole winter. It was

on this principle, and in consequence of this experience, that a change was made in the original design of the Dhu Heartach, and the solid part carried up to the same level above high water as the lantern in Smeaton's tower.

The very remarkable cases of wave-action exerted at high levels

FIG. 4.

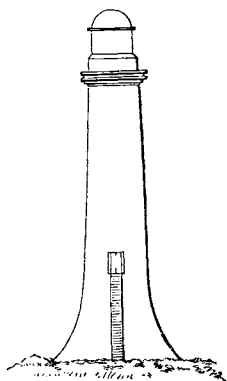
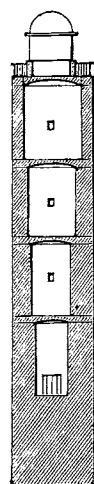


FIG. 5.



FIG. 6.



on the rocks at Whalsey, Unst, and Fastnet, are further corroborative of this view.

To decide upon the probable exposure of any rock, and the height of the dangerous impact of waves above high water, many elements have to be considered; the height of the waves, the height and configuration of the rock above and below low water, and the depth and configuration of the bottom of the sea; and it is unfortunately necessary to add that the influence and relations of these elements have not as yet been sufficiently studied. What may be the effect, whether as shield or conductor, of a given height of rock upon a given height of wave; what may be the effect of such a deep track in the bottom of the sea as that observed by Mr. D. A. Stevenson near Dhu Heartach; or how much would depend on the direction of such a track, or on the level at which the rock is steep in relation to the height of tide most favourable to heavy seas—are all questions of great importance, still unsolved and well worthy of the attention of the engineer. A rock like Dhu Heartach certainly acts at once as a breakwater against the smaller class of waves, but a dangerous conductor to the heavier.

towards sure knowledge of the general law; and I embrace this opportunity of suggesting this course of observation to the younger members of the Institution.

Harbours of Refuge.—The next class of works, reckoned seawards on approaching the coast, are those large structures to which the name of Harbours of Refuge is given. They are distinguished from tidal harbours by the generally greater depth of water which they require to possess, in order to fulfil the objects for which they are designed, while the area which they enclose must also be larger. The requisites are shelter during storms, good holding-ground, and safe access at all times of the tide and in all states of the weather. A breakwater, though a passive, is yet a real agent, having work to do. Many thousand tons of water are raised and maintained above sea-level by wind-waves, and these waves must either be suddenly stopped, or as suddenly reversed in direction, or else more slowly destroyed within a given space. This is the work assigned to the breakwater, and there are two ways in which it can be done. One way is by means of a plumb wall, which alters the direction of the moving water by causing it to ascend vertically above the parapet of the wall, and then allowing it to fall vertically again, so that the waves are finally reflected and sent back seawards. The other method is to arrest the undulations by a long sloping wall, so as to give room for the mass of the waves to fall down and destroy themselves upon the surface; but if the slope be not sufficiently long to enable the waves thus fully to destroy themselves, they will, though reduced in height, pursue their original direction, pass over the top of the breakwater, and thus disturb the tranquillity of the harbour. In such a case as this, therefore, the breakwater has failed to do its full share of work, and the necessary amount of shelter has not been produced.

Best position for Harbours of Refuge.—Opinions have been recently expressed that a harbour of refuge should be placed in a re-entrant part of the coast, and never at any part which is salient. Now it is of great importance that such a question as this should be fully discussed, as the result must materially affect the interests of commerce and shipping. Various conditions statistical, geographical, and local should be considered in this question.

(1) *Statistical.*—So far from being necessarily placed in the neighbourhood where most shipwrecks have occurred, as has been alleged, or as an escape for vessels locally embayed, the harbours of refuge should, in my opinion, be situated as near as possible to the normal track of shipping. Thus, on the occurrence of a gale,

a refuge will be ready in a position which can be quickly and safely approached by the greatest possible number of vessels, both large and small.

(2) *Geographical*.—The true situation for a harbour of refuge is rather upon a salient than on an embayed part of the line of coast, because: (i.) as I have already stated, a salient part of the coast will lie nearer to the line of the general passing trade than a re-entrant part; and (ii.) Vessels seeking a haven and failing to make it, will not find themselves embayed, but be still well to windward, and have sea-room to bear away for some more distant haven on either hand. There is indeed a sense in which a harbour of refuge in the bottom of a bight may be regarded as a source of danger instead of a source of safety. Cardigan Bay in Wales, for example, is just such a place as might perhaps be selected. But though a harbour in Cardigan Bay might in certain exceptional cases do good, it would be dearly purchased if the presence of the harbour tempted masters to leave the track of safety and unnecessarily to embay themselves. It will, I think, be generally admitted, that if, from fog or snow-showers coming on, a vessel failed to pick up the position of the harbour in the bay, there would be hardly a chance of her escaping shipwreck. A harbour of refuge, on the principle asserted, is either kill or cure, for it offers but one chance to the distressed vessel, which she must seek at the cost of embayment; but a harbour of refuge on a salient part of the coast offers a chance of shelter without necessarily compromising the safety of the ship in case she fails to make it.

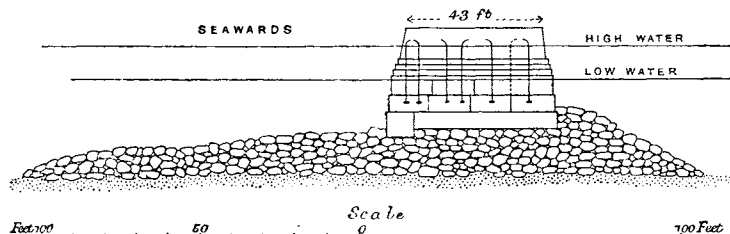
(3) *The local conditions pointing to the Proper Situation for a Harbour of Refuge are*: (i.) The inclosure of the greatest area of sufficiently deep water for the least extent of breakwater to be constructed. (ii.) The quality of the holding-ground in the anchorage thus to be sheltered. (iii.) The proximity of suitable material for the construction of the breakwater.

Best Mode of Construction of a Harbour of Refuge.—With reference to the best mode of construction for a harbour of refuge in an exposed situation, there will always be considerable differences of opinion among members of the profession. I shall simply state the form of construction which, on the whole, I consider to be best in situations where the place is fully exposed to the heaviest class of waves.

A very obvious and very important point regarding the stability of such a structure as a breakwater has reference to the depth below low water, at which the waves cease to exert any considerable

impact upon the materials on which the superstructure rests. Information of great importance was derived from the history of the Wick breakwater, for which my firm were engineers, and which, so far as I have been able to ascertain, was subjected to the heaviest waves that have ever assailed masonry. It is sufficient to state that the results which I have obtained, at many different parts of the coast, by means of the marine dynamometer already referred to, have been far exceeded by the effects produced by the very anomalous waves which assailed the harbour works of Wick, where the contractor's staging, though consisting of greenheart timber, was found quite unequal to resist the stroke of the sea, and where the heavy rubble which formed the substratum of the work was

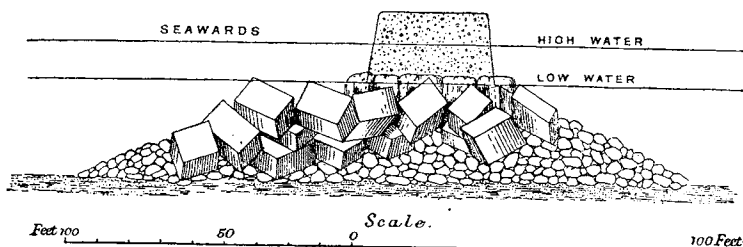
FIG. 7.



moved at a depth of about 18 feet below low-water. In 1872, a huge monolithic block of concrete, weighing in all 1,350 tons, was removed bodily out of its position, and carried to the lee of the breakwater. Extraordinary as this may appear, it was surpassed in 1873, when another concrete mass which had been substituted for the one that was moved, was in like manner carried away, though it contained 1,500 cubic yards of cement and rubble, the weight of which was about 2,600 tons. Yet it is remarkable that after the last damage which took place to the breakwater, when we thought of removing the foundation courses, which were set on edge, we found it impossible to do so, owing to their being so firmly imbedded in the rubble base; no part of the foundation of the breakwater was ever moved, nor any of the rubble base ever disturbed, at a lower level than 18 feet under the water. *I am therefore of opinion that a level of from 18 to 20 feet below low-water level may be safely assumed as that of practical stability.* In Fig. 7, showing a section of the end of Wick breakwater, it will be noticed that the bay consists of a sandy bottom, and it is, as I have said, fully exposed to the swell of the North Sea. I conceive that the safest and most economic profile of construction would be as

shown in Fig. 8, a mass consisting of rubble extending from the bottom to within 20 feet of low-water; when the base had been brought up to this level, blocks of concrete weighing from 100 to 200 tons should be deposited on the top, and outer or seaward surface of the rubble base, till they came above low-water level. Betwixt the spaces at the top of these blocks, bags of concrete should be placed, so as to form a level platform above low-water level. Upon this a solid mass of continuously-built concrete should extend from end to end of the breakwater, which should be not less than 10 feet above high water, and about 40 feet in breadth. I hold that a structure designed on these principles would resist the force of the sea in any situation, provided the sea slope were

FIG. 8.



of sufficient extent. This was the design proposed for the Peterhead Refuge-Harbour, and which was approved of by the Committee on Convict Labour.¹

Mattress Breakwaters, or Training Walls constructed of Fascines.—There are in many parts of the world bays and arms of the sea of so shoal a character as to cause the waves to break several miles off the shore, but where difficulties of another kind arise from the soft nature of the subsoil; so that although there is no very violent sea to be encountered, yet breakwaters of concrete or masonry are unsuitable, owing to this softness of the bottom; for the waves, reduced though they be, are still able to produce sufficient reaction from the outer face of the breakwaters to plough up the bottom. In order to meet these difficulties, structures called mattresses, which possess peculiar characteristics, have been resorted to in various parts of the world, particularly in Holland and America,

¹ Report of the Sub-Committee appointed to investigate the question of the most suitable place for a Harbour of Refuge on the East Coast of Scotland. 1884. p. 8.

where they have been found very suitable. In the well-known case of the River Mississippi, for example, Mr. Eads most successfully removed the bar by means of mattresses. The requisites for such structures are that they should be of small specific gravity and of open texture. They must also project but little above the bottom, so as to avoid coming within the direct influence of the breaking action of the waves, and thus to cause reaction, which would endanger the foundations. They must, in short, operate strictly as submarine breakwaters in stopping the action of the waves at the bottom, while they also possess a certain amount of pliancy to enable them to adapt themselves to considerable variations in the level of the bottom, so as to deflect the under-water currents.

Commercial Harbours.—It would far exceed the limits of this lecture were I to attempt to take up the subject of commercial harbours and the like. It may, however, be right to define the great object which must be kept in view in carrying out works of that nature; and that object is to produce a harbour which may easily be taken in rough and stormy weather, without endangering the tranquillity of the internal area; for it is the combination of an easy and safe entrance and exit, with what sailors call a good “loose,” and a smooth interior, which alone constitutes a good harbour.

It must further be remembered that a bad result may ensue from devoting an exclusive, or too great an amount of attention to one branch of the subject, however desirable the securing of that branch may be in itself; such, for example, as obtaining deep water at the expense of still more important conditions, viz., suitable protecting works, and sufficient internal area. The disregard of a due proportion between the internal area and the depth of a harbour has in many instances produced harbours which cannot be said to deserve that name. In order to show how the tranquillity of a harbour may be affected, and how cautious, therefore, the engineer should be in changing the existing physical relation, I have thought it right to refer to some of the many works which may prove injurious.

Causes of insufficient reduction of height of Waves.—The causes of insufficient reduction of height of waves after entering a sheltered basin may be stated to be too little breadth in relation to width of entrance, or adequate area in relation to the magnitude of the waves outside; also the surrounding of the internal area with vertical walls, and the absence of sufficient length of spending beach to destroy the waves and prevent recoil.

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A formula for calculating the reductive power of harbours will be found in my book on Harbour Construction.¹

Commercial value of depth of Water.—I may state that I have found that the commercial value of harbours or rivers increases as the cubes of the depth of water, although no stated rule can be regarded as more than generally true. The following formula is designed to apply to this subject when d represents the draught of a vessel in feet; t , the burden in tons; a , a constant depending on build,

$$t = \frac{d^3}{a} \text{ and } d = \sqrt[3]{a \times t}.$$

Coast-Protection Works.—The last branch of the subject which has been assigned me refers to works which are furthest from the action of the sea, or those for the protection of the land itself.

The physical configuration of the coast-line affords, as every one knows, a series of the most varied vertical and horizontal profiles. It is generally owing to the effects of atmospheric action, combined with wave-action, that such phenomena are due. The two parts of the British coast, which best illustrate the particular case of moving of sand and shingle, are those of the English Channel and the Moray Firth. I have always been of opinion, I may remark in passing, that the action of tidal-currents has nothing to do with the throwing up of shingle on any coast, and the valuable Paper of Sir John Coode² should, I think, set this matter fully at rest. The breaking of waves at right-angles to the coast is quite sufficient to account for the heaping up of shingle between high- and low-water mark, while the oblique action of the waves sufficiently accounts for the travelling movement of the shingle in the same direction as the heaviest winds. But the cause of the formation of bays or creeks must generally be sought for in the unequal hardness of the different members of the geological formation which confront the sea, and which form a remarkable contrast to the rocky strata or igneous class of rocks, which continue to maintain *their integrity from their greater hardness*.

The general slope of a fragmentary beach must depend upon the size and nature of the particles and the force of the sea. The great object, therefore, in artificial works of protection, is to design the profile of the wall, so as to alter as little as possible the symmetry of the beach. Where isolated rocks or large boulders

¹ The Design and Construction of Harbours. p. 185.

² Minutes of Proceedings Inst. C.E. vol. xii. p. 521.

are left projecting above the surface of a sandy shore, there will generally be formed around them hollows corresponding in depth and form to the kind of obstruction which the rocks present. The principal point in the design of artificial works of protection is, therefore, to avoid great and sudden obstructions to the movement of the water. The best form which could be adopted in any situation would, of course, be the contour of the beach itself; but this would answer no possible purpose; and as the wall is to consist of heavy blocks of stone instead of minute particles of sand, it is clear that a much steeper slope may be adopted than that which we may call the profile of conservancy of the shore, provided the lower part of the slope be flattened out so as to meet the sand at a low angle. The action of a bulwark is to arrest the waves before they reach the general high-water mark, and to change the horizontal motion of the fluid particles to the vertical plane, or to compel the waves to destroy themselves on an artificial beach consisting of heavy stones. To prevent underwashing, the two following requisites should therefore be as far as possible secured:—First, the foundation courses of the wall should rise at a very small angle with the beach, so that their top surfaces may form a continuous curve, with the profile of conservation of that portion of the beach out of which the wall springs. Secondly, the outline of the wall should be such as to allow the wave to pass onwards without any sudden check till it has reached the strongest part of the wall, which should be placed as far from the foundation as possible.

Loose rubble a good protection for the foundations of Bulwarks for protecting Land from the Sea.—Loose blocks of angular rubble furnish, in most cases, the best possible security when the soil is soft or friable, for the waves are swallowed up by the interstices. A regular sloping sea wall or bulwark, with a smooth surface, becomes, when the soil is soft, a double-edged sword in working its own destruction at top and bottom; for it transfers the duty of destroying the waves from the masonry to the unprotected soil at the top, and to the loose sand or gravel at the bottom of the wall. While the foundations are underwashed by the reaction upon the soft bottom, the upper parts of the masonry are deprived of support by the falling water and spray, which are led up by the masonry, and soon wash away the soil at the top.

Vertical Walls.—For the reasons which have been stated, it is plain that a vertical wall is in most cases unsuitable for a sandy beach. Instead of altering the direction of the wave at a distance from its foundation, the whole change is produced at that

very point; and, unless the wall be founded at a considerable depth, its destruction is all but certain. Where the materials are costly, but admit of being easily dressed, I am disposed to think that a horizontal, or nearly horizontal, apron or platform of timber or masonry, connected with a vertical wall by a quadrant of a circle of sufficient radius, may be found answerable. Such a form will prevent to a considerable extent the danger of reaction, by causing the alteration in the direction of the wave to take place at that part where the wall is strongest, and which is also at the greatest possible distance from the toe or curb-course. If the materials are abundant, and of a rough nature, a cycloidal wall with vertical and horizontal tangents, somewhat similar to that erected at Trinity, near Edinburgh, may be adopted with advan-

FIG. 9.

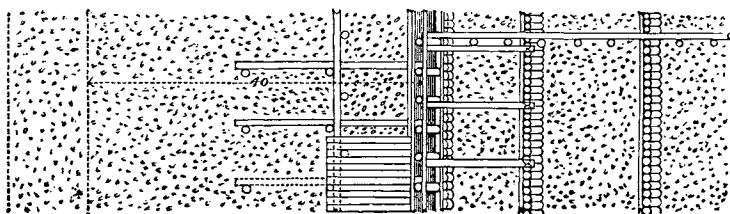
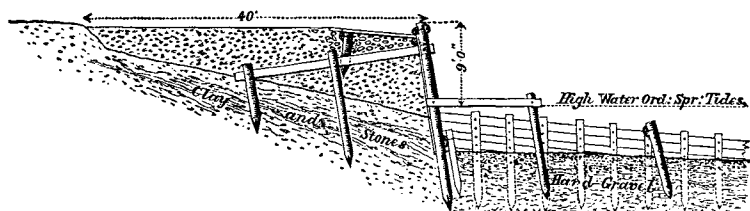


FIG. 10.



tage. But a very serious objection to all forms of curved walls, unless the radius be large, is the weakness which results from the use of wedge-shaped face stones. The impact of the sea on materials of that form may be compared to a blow directed upwards against the intrados of a stone arch—the direction of all others in which the voussoirs are most easily dislocated. This action can only be successfully resisted by very careful workmanship in the dressing and the setting of the backing. Another objection, applicable to all except tideless seas, such as the Mediterranean, arises from the varying level of the surface of the water; for that

profile which may be best at one time of the tide cannot be equally suitable at another.

Works for protecting land in open Estuaries.—In other cases in estuaries more open to the sea, works of a stronger kind are required. Figs. 9 and 10 are a plan and section of a protection which was adopted on a line of shore composed of shingle. Jetties projecting from the shore had at first been used to collect the shingle, but in heavy seas the waves were led along the jetties, and had a hurtful effect at their roots where they joined the beach. A continuous line of piling and planking was accordingly adopted, combined with occasional jetties, and this has proved very successful. In proof of this, it has been found that wherever the upright piling and planking have been formed, there was no influx of anything beyond spray upon the adjoining land, but that at all other parts of the coast (which is about 6 miles in length), where the face of the beach is sloping, the water passed freely over in considerable depth, carrying drift timber far into the fields, and in some places heavy shingle to the depth of 2 feet. The problem to be solved was to oppose an obstacle which should throw back the sea; and the upright face, from which the heavy portion of the sea recoils, was found to do this better than the sloping face. In order to encourage the collection of shingle, a second line of longitudinal piling was, at some places, formed in front, and parallel to the main line of defence; and the works now described have been found a very effective defence on a line of shingle beach, exposed to a considerable sea, on the shores of the Bristol Channel.

In designing all such works, however, the engineer must be guided by the formation and exposure of the shores, the kind of materials most easily available, and above all, the value of the property endangered, as every engineer must know by experience that in some situations protection can only be secured at a cost out of all proportion to the benefit which it would confer.

The notable difference between the subject to which my attention has been directed by the Council, as compared with the other lectures, is the extreme want of exactness which characterises the whole subject. In no other branch of engineering is there so great a prevalence of what may be called "rule of thumb." Indeed, hardly any attempt has been made to obtain observations, reducible to a formula, by which numerical results can be calculated as to the force of waves; the height of waves, in relation to the depth of water in which they move; the reductive power of harbours, by which the waves after

entrance are diminished in height; the shelter due to protecting breakwaters, and the like. I would strongly counsel young engineers to do their best to supply these *desiderata*. Here is a field where they may do good service to the profession and in the interests of mankind. Here is a branch of engineering where we are still in want of facts, and to a far greater degree in want of the means of scientific calculation. No one knows better than myself the difficulty of the task; for I have had a large experience, and have been too often baffled in my best endeavours to obtain coefficients. But we must not look to difficulty; we must look to utility; and I see no branch where the patience, the ingenuity and the scientific accuracy of observers will be likely to produce more useful results than the one to which I refer. Lastly, I would say a word of welcome to a new book: Mr. Vernon-Harcourt's "Harbours and Docks." It is (particularly on the historical side) a treasury of facts, and forms a large addition to the historical library of the marine engineer.

Sir FREDERICK BRAMWELL, President, asked for a hearty vote of thanks which might be conveyed to Mr. Stevenson, to show that his labours had been appreciated by the members, although they had not had the benefit of his presence. Mr. Stevenson himself had revealed the fact that he took up the lecture at very short notice, when Sir John Coode was by professional engagements compelled to leave England, and therefore was unable to deliver this lecture which had originally been assigned to him. Their thanks were therefore doubly due to Mr. Stevenson.

Mr. GILES, M.P., had much pleasure in seconding this cordial vote of thanks to Mr. Stevenson. He was sure they all regretted very much his absence. Perhaps no engineer had had greater experience, more particularly in the wild waves on the coast of Scotland, than Mr. Stevenson, and he was better qualified, perhaps, than most marine engineers to speak upon the effects of water-pressure upon harbour-construction. At the same time, he thought Mr. Stevenson had been a little hard on the profession generally when he said that most harbour-constructions were designed, not upon scientific principles, but simply by rule of thumb. It was very true that engineers ought all to be guided by science in the constructions which were subject to great sea-exposure; but notwithstanding all the science that might be brought to bear upon the construction of harbours, they were still guided to a certain extent by the experience they had gained in their constructions.

The vote of thanks was unanimously agreed to.