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Sir ALEXANDER RICHARDSON BINNIE, President,  
in the Chair.

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(*Paper No. 3565.*)

**"The Outer Barrier, Hodbarrow Iron Mines, Millom,  
Cumberland."**

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**THE HODBARROW MINES.**

THE County of Cumberland terminates towards the south in a promontory, which lies between the estuary of the River Duddon and the Irish Sea. This headland is known as Hodbarrow Point (Fig. 1, Plate 4), and is formed of carboniferous limestone, the highest part of the headland standing about 50 feet above sea-level.

Veins of red hæmatite are found in the limestone where it abuts on the shore, and the late William, Earl of Lonsdale, as Lord of the Manor, worked one of these veins at Towsey Hole (Fig. 1), and followed the vein for some distance into the hill; but as the workings proceeded the vein "nipped out," and the venture was ultimately abandoned. In 1855 the same Earl of Lonsdale granted to the founders of the Hodbarrow Mining Company the right to search for minerals over a large area in this locality, and boring-operations were begun, with the result that in 1856 one of the bore-holes passed through about 80 feet of solid hæmatite ore (X, Fig. 1, Plate 4), thus discovering the first deposit, which has now been almost entirely worked out. It was comparatively shallow, being covered by not more than 60 feet of limestone in any part; indeed, in one place the ore came almost to the surface, and it also rested on a limestone sole, the whole deposit being practically surrounded by limestone as indicated in Fig. 2, Plate 4, which is a diagrammatic section of the mines.

While this deposit was being worked, the company built workmen's cottages on the adjacent ore-mains, little knowing what lay

beneath the buildings; and it was an endeavour to supply these cottages with water that resulted in the discovery of the great body of ore which has since required so much outlay upon sea-defences for its successful extraction. A well had been sunk for some distance, but the supply of water being insufficient, in the year 1868 a bore-hole was put down at the bottom of the well, and this bore-hole pierced hæmatite ore at a depth of 180 feet below the surface. Boring being continued, it was proved that the ore-body extended over a very large area. Shafts were sunk without delay, and workings were begun in this main deposit in 1873, since which date an average annual output of about 450,000 tons has been maintained.

As will be seen from the section, the deposit has no limestone roof over the landward portion, but as the ore dips seaward a limestone roof begins and gradually thickens in this direction. It is probable that the ore was originally entirely covered by limestone, which has been partially denuded by the action of ice, and that the boulder clay took its place when the glacial period passed away. Above the boulder clay lay irregular beds of sand, gravel and clay, apparently deposited by the sea, as marine shells were found therein while shafts were being sunk through these beds. Difficulties arose occasionally through rushes of sand and water from these overlying strata into the workings of the mine, and very powerful pumping-machinery had to be provided to deal therewith. Another danger arose from the fact that the sea was encroaching upon the low sand-banks which formed the sea-margin, and with a view to stop this encroachment a timber revetment was erected in 1882-4.

*Timber Revetment.*—This first attempt at sea-defence was formed, at the site indicated in Fig. 1, of 6-inch timber sheeting driven 6 to 8 feet into the ground, with walings in front, and main piles of pitch-pine 12 inches square, driven 20 feet. The main piles were tied with iron rods to back piles driven at a distance of 60 feet behind them. This structure, however, was breached by the sea, in November, 1884, during a heavy gale and exceptionally high tide.

The company's lease of the minerals extended only to high-water mark of ordinary spring-tides on the south, and inasmuch as the surface caved in when the ore was extracted, it was absolutely impossible to work out all the ore up to that limit, a barrier of unworked ground 360 feet wide having to be left to protect the mines from the sea. Drifts in solid ore were, however, carried up to and along the seaward boundary, proving beyond doubt that a considerable field of ore existed outside the area then leased by the company. The lessor, however, was not at that time

disposed to grant an extension of the area so leased, although the foreshore was vested in him; but when it became apparent that unless some more efficient provision was made for sea-defence there was considerable risk of the mines being flooded, consent was given in 1886 for the construction of the first sea-wall (Fig. 1, Plate 4), as designed by the late Sir John Coode, Past-President Inst. C.E., which was completed in 1890. This wall is a rigid structure of concrete, backed by a clay embankment, and rendered water-tight by a wall and trench of puddled clay immediately behind the concrete wall, keyed into the natural clay bed beneath. The site of this work was so arranged that while it afforded an absolutely water-tight barrier, it also enabled the company to extract all the ore up to the then existing boundary. The lessor at the same time granted the company permission to put down bore-holes on the foreshore for the purpose of ascertaining the extent of the ore-ground seaward, and under these powers boring-operations were continued for some years under great difficulties, the gear and staging being frequently carried away bodily by the sea, which in south-westerly gales is very heavy on this part of the coast. In spite of this, however, the bore-holes, which were arranged in sectional lines, were successfully carried out, and an extent of ore-ground large enough to make a further enclosure desirable was proved.

In 1898 a bed of quicksand was tapped in the mine, which established a connection between the sea and the underground workings, a cavity being formed on the foreshore outside the sea-wall; and a heavy rush of tidal water into the mine took place, passing many fathoms below the foundations of the sea-wall. This inflow was checked by filling up the cavity on the foreshore with furze, brushwood and clay, but not before the sea-wall had begun to show signs of distress through deflection caused by the removal, by the current, of material from beneath it. The clay embankment behind the wall then subsided about 5 feet, and this subsidence had the effect of shutting off the connection with the sea, and the influx of tidal water shortly afterwards ceased. Thereafter, upon the advice of Mr. William Matthews, Vice-President Inst. C.E., the damaged portion of the sea-wall was protected from heavy strokes of the sea by a wave-breaker of pell-mell blocks of concrete, each 20 tons in weight; the subsided embankment behind it was levelled up, raised in height, and added to in width, thus giving additional weight to aid in shutting off the leakage into the mine; while the cavity on the foreshore was surrounded with sheet-piling, and within the enclosure clay was deposited, which was covered with a heavy layer of limestone.

This accident had the effect of hastening the negotiations for the erection of a further protective structure, and the lessor having granted to the company a new lease of the mines, including the foreshore minerals, the work of designing an outer barrier to exclude the sea from this extended area was entrusted to Messrs. Coode, Son and Matthews in the same year. The contract for the work was let to Messrs. John Aird & Co. in 1899, and the construction was begun early in 1900

#### GENERAL DESCRIPTION OF THE OUTER BARRIER WORKS.

The area reclaimed by the construction of the Outer Barrier is 170 acres. That the whole of this ground is not ore-bearing, though a very large portion of it is so, will be seen from Fig. 1, Plate 4, whereon the approximate edges of the ore-deposit are shown. It was necessary, however, to include a certain portion of barren ground, more especially upon the west side, where it was considered advisable that the Barrier should be located a considerable distance outside the treacherous ground in which the subsidence before alluded to had taken place.

In the design of the Barrier the primary objects kept in view were, first, that the structure should be flexible instead of, as in the case of the first sea-wall, rigid, in order that, should subsidence take place beneath it at any time, the Barrier itself should also subside, and thus close any cavity that might be formed, when, by adding material to the superstructure, its efficiency as a protection to the mines would be maintained; and, secondly, that it should be of great weight, in order to compress the upper stratum of sand on the foreshore and thus aid in preventing percolation beneath it, and also to secure its subsiding if necessary. A further consideration to which prominence was given was that, as far as possible, material obtainable in close proximity to the work should be utilized in its construction.

As will be seen from Fig. 3, Plate 4, the Barrier has the form of an arc, the east end springing from Hodbarrow Point, while the west end is situated near the mouth of the Haverigg River. It is 6,870 feet in length (Fig. 4), and consists primarily of a main outer bank of limestone, an inner bank which it was originally intended to construct of iron slag, but which, for reasons to be stated hereafter, was largely composed also of limestone, and a filling of clay between these two banks (Figs. 5). These materials fulfil the condition mentioned in the preceding paragraph, there being, as already stated, large deposits of limestone overlying

the ore of the Hodbarrow Mines, while clay was obtainable in large quantities upon the property of the Mining Company, and slag was readily procurable from the adjacent works of the Millom and Askam Hematite Iron Company.

As a protection against heavy waves the outer limestone bank is provided, for 1,600 feet from the shore at each end, with a coating of large lumps of rough limestone weighing up to 15 tons. Seaward of this the protective coating is formed of 25-ton concrete blocks deposited irregularly.

For the prevention of percolation of water beneath or through the Barrier, the weight of the structure and the filling of clay alluded to above were not alone relied upon. Beneath the surface of the foreshore, under the centre of the clay embankment, a water-tight cut-off is provided, and for this three methods were adopted: first, where the natural clay bed was near the surface the cut-off was formed by a trench of puddled clay, carried down and well keyed into the clay bed; secondly, where the clay bed existed, but was at too great a depth to be reached by means of trenching, pitch-pine sheet-piling, grooved and tongued, was driven down into the clay; and, thirdly, where no clay was found, or where the bed was so irregular as to be unreliable, steel sheet-piling, of lengths varying according to circumstances, was driven. In order to guard against the passage of water through the Barrier, a wall of puddled clay is constructed in the heart of the clay embankment, immediately above the puddled trench or the piling, as the case may be. It is brought up to 5 feet above high water of ordinary spring-tides, which is 6 inches above the highest recorded tide, a level that has been reached only once, and approached but seldom, in a large number of years.

For the purpose of discharging water which might accumulate in the reclaimed area, four sluice-ways are provided, having pen-stocks worked from the road-level of the Barrier and tide-flaps at the seaward ends.

The work of construction was started at the west or Haverigg end, but operations were shortly afterwards begun at the east end, and were thereafter carried on at both ends simultaneously.

The order of procedure was as follows:—The formation of the water-tight cut-off below foreshore-level was first begun, followed by the main limestone bank and the inner bank; the latter was kept slightly behind the former with a view to shelter, while the filling for the clay portion of the embankment was deposited after such an interval as would permit of the formation of the lower portion of the puddle wall in the manner hereafter described.

*Borings.*—In order to determine the method of construction of the water-tight cut-off below foreshore-level, borings were made at intervals of approximately 600 feet along the proposed line of the work, and opposite each of these a second boring was made seaward of the line of work; while at the west end, opposite to the spot where the inrush of water had occurred in 1898, a third, and in one case a fourth, boring was made on each line. These borings indicated the existence of a good clay bed along the greater part of the line of work, at a depth below the surface varying between 16 and 20 feet at the west end, between 7 and 15 feet along the central portion, and between 3 and 11 feet at the east end; there being two intermediate portions where either no clay was found, or the bed was only thin. From the data thus obtained it was decided to form the cut-off in the following manner, the distances being measured from the west end of the work:—

Puddled trench . . . . .	0 feet to	350 feet.
Pitch-pine sheet-piling . . . . .	350 "	1,200 "
Steel sheet-piling, 34 feet 6 inches in length . . . . .	1,200 "	2,400 "
Pitch-pine sheet-piling . . . . .	2,400 "	2,940 "
Puddled trench . . . . .	2,940 "	4,133 "
Site of sluice-culverts; concrete foundations carried down to clay . . . . .	4,133 "	4,166 "
Steel sheet-piling, 31 feet 6 inches in length . . . . .	4,166 "	6 inches to 4,662 feet
Puddled trench (east end) . . . . .	4,662 feet 6 inches to	6,870 feet.

*Puddled Trench.*—A beginning was accordingly made with the trench at the west end, but the work of excavating the trench had not proceeded very far when difficulties were encountered. It had been anticipated from the results of the nearest borings that the clay bed would be found at about 12 feet below the surface, but a length of 80 feet of trench was opened out and carried to a depth of 15 to 20 feet without coming to clay. Additional borings were then made between the shore and the first of the original borings, and these revealed the fact that the clay, instead of rising towards the shore, was apparently horizontal for about 350 feet and then dipped downwards. This being so, it was decided that the attempt to carry out this portion of the work in puddled trench should be abandoned, and that pitch-pine sheet-piling should be substituted.

At the east end the puddled trench was carried out for a length of 1,040 feet from the shore. Of this length the first 200 feet was carried down to rock, into which it was keyed to a depth of 2 feet, the recess being excavated by blasting with light charges of dynamite to receive the footing of the puddle. Beyond

this point, for a distance of 180 feet, as will be seen from the longitudinal section (Fig. 4, Plate 4), clay appeared on the surface; but on excavating in this clay to carry the puddle into it to the specified depth of 1 foot 6 inches it was found not only that the clay was of an unsatisfactory character but also that it was underlaid by a water-bearing stratum of gravel. The trench was therefore carried down through this water-bearing stratum and keyed into the rock or solid clay which was found beneath. From this point outwards the trench was taken down through sand and gravel to the clay bed, which was reached at a depth varying between 2 feet and 13 feet.

The trench was generally 7 feet wide, and where the depth necessitated the use of an inner setting of the timber runners or poling-boards by means of which it was sunk, this inner setting had a minimum width of 6 feet. The bottom of the trench, in the clay, was 4 feet wide, being tapered to this width in the depth of 1 foot 6 inches to which it was carried in the clay. The work was undertaken in sections whose length varied according to the depth of the trench: an average length in a trench of a single setting was 20 feet, while in deeper trenches the length was about 10 feet. This work was of course carried on only while the tide was out, the length of the working-period being at first as much as  $7\frac{1}{2}$  hours, which naturally became materially reduced as the work progressed seaward.

As soon as the tide had receded sufficiently to permit of starting work, the water remaining in the portion of trench under construction was pumped out, one 6-inch and two 8-inch centrifugal pumps being used for this purpose. When the trench was dry enough, excavation was proceeded with, the excavated material being filled into tubs which were lifted from the trench by a crane and tipped landward of the site of the inner bank at a sufficient distance to prevent the spoil from being carried back into the work. When the clay bed had been reached, and the footing had been cut into it as previously described, the bottom was carefully cleaned and the puddled clay was deposited. The clay for puddle was obtained principally from fields lying near the west end of the work, where the clay was of especially good quality. Here were two steam pug-mills, whence the puddle was taken to the work. The puddle was deposited in layers of about 1 foot, well trodden down, especial care being taken in forming the junction between the puddle and the natural clay bed. Where possible, the side timbering of the trenches was withdrawn as the puddle was brought up, the latter being then well rammed against the sides of the excavation. In some cases, however, the nature of the surrounding ground rendered it necessary that this timbering should be left in; indeed,

for a considerable length of the work it was necessary to drive permanent 6-inch sheeting on either side of the trench.

When the work had proceeded for some time, the clay bed at this east end began to be very irregular, sometimes dipping almost vertically both in the line of and transversely to the work. Thus, in the width of the trench, 7 feet, there would be a difference of level of as much as 4 feet in the surface of the clay. It was therefore seen that, even if conditions became no worse, it was very doubtful whether a satisfactory cut-off could be made by the proposed method, and early in 1902 a series of borings was commenced at close intervals between the then existing end of the puddled trench and the point at which it had been proposed to terminate the 31-foot 6-inch steel piling. These borings were made on the line of the cut-off and were therefore 25 feet landward of the centre-line of the Barrier, on which line the original borings had been taken. They demonstrated the correctness of the original borings, but disclosed great irregularities in the clay bed between them. The original borings at 5,066 feet and 5,692 feet had chanced to be situated on the summit of ridges in the clay, with deep valleys between them and also westward of the boring at 5,066 feet. How irregular the surface of the clay was will be seen on reference to Fig. 4, Plate 4. In one instance there was a difference in level of 26 feet in 25 feet distance, while between two points 100 feet apart the difference was no less than 43 feet.

Having regard to the information disclosed by these borings, it was decided to discard the puddled trench as the means of forming the cut-off on this section of the work, and to substitute for it steel sheet-piling, 31 feet 6 inches in length where the surface of the clay was reached by this depth, and 34 feet 6 inches in length across the two deep valleys in the clay before mentioned. It was now considered advisable that the additional borings should be continued along the remaining section of the work where it had been intended to form the cut-off by puddled trench, and this was accordingly done. Here no very great variations were found, the surface of the clay being in no case deeper than 3 to 4 feet below the line assumed from the original borings at 3,148 feet and 3,791 feet. Nevertheless, it was apprehended that the puddled trench might not prove satisfactory here, in view of the curious lateral irregularities which had previously been met with, and it was determined that here also it should be superseded by steel piling, though it was not considered necessary that the latter should be as deep as that used for the other sections of the work, 25 feet 6 inches being deemed sufficient,



*Timber Sheet-piling.*—The piles for this work were whole timbers, not less than 12 inches by 12 inches, grooved and tongued. For the first 150 feet of the work the piles were 18 feet in length, and thence onwards they varied between 23 feet and 27 feet, according to the depth of the clay, into which they were to be driven 4 feet. The piling was driven in bays of 10 feet each, that is to say, the gauge-piles were spaced 10 feet apart between centres, and they were driven 2 feet 6 inches deeper than the sheet-piles. A series of gauge-piles was first driven by one piling-engine: a second engine then followed, and drove the eight sheet-piles in each bay, also completing the bay by driving the central key-pile. The grooves in the piles were  $3\frac{3}{4}$  inches wide and  $1\frac{7}{8}$  inches deep, and the tongues  $3\frac{1}{2}$  inches by  $3\frac{1}{2}$  inches, the latter being secured to the piles by 10-inch spikes driven 18 inches apart. When driven to the requisite depth, the heads of these piles stood 3 feet above the ground-level, and at 1 foot from the top a waling 12 inches by 6 inches was fixed on the landward side of the sheeting, being secured to each pile by a  $1\frac{1}{2}$ -inch bolt.

The engines used for driving this piling were of the ordinary type, the monkeys weighing 22 cwt. The drop generally allowed was 4 to 5 feet, and the rate of driving varied between 1 inch at the beginning and  $\frac{1}{3}$  inch at the end, per blow, being affected also by the nature of the stratum through which the pile was being driven. In the case of the key-piles the driving was usually somewhat slower.

Where obstructions were met with, a shaft was sunk and the obstruction was removed, or if necessary the pile was drawn and started afresh. In two places neither of these courses was feasible, and here a boxing of piles was driven on the seaward side of the cut-off to enclose the defective part, the enclosure being subsequently filled with puddled clay.

During the progress of this piling it was possible to ascertain fairly accurately, from the changes in the speed of driving, the levels at which a pile entered the different strata: this was specially noticeable on the pile getting through the bed of gravel and entering the clay, when the freedom in driving increased in a marked degree. A considerable length of the piling had been driven without indicating any notable deviation in the level of the clay bed as shown by the original borings; but towards the end of 1900 there appeared to be indications that the clay was being met with at a higher level than had been anticipated, and on borings being put down between 900 feet and the next boring at 1,154 feet a ridge was found to exist here. It was not considered advisable, however, that the piling should be curtailed in length

here, and it was accordingly driven to the full depth originally proposed (Fig. 4, Plate 4).

The piles having been driven, as each two or three bays were completed the sand on either side of the sheeting, between the outer and inner stone banks, was excavated to form a basin-shaped hollow 4 feet deep at the piling and 34 feet in width where the distance between the two banks would admit of this. The hollow, having been cleared of weeds, mud, etc., was filled with puddled clay, thus providing a flap which should prevent the creeping of water at the upper portion of the sheeting and form the foundation of the puddle wall.

When the first length of 1,200 feet of this timber sheet-piling had been driven, the succeeding section of steel piling was proceeded with and completed, and a beginning was made with the second series of timber piling.

The ground through which the latter portion of the steel piling had been driven had proved exceedingly hard, and conditions became no more favourable when the timber piling was proceeded with. Pile after pile refused to be driven, and showed obvious signs of being crippled. When attempts were made to draw these piles, some parted, only the upper portion being drawn; others came up without their shoes, and with their ends burred into fibre. As these occurrences happened at the same time as the difficulties in the puddle trench, the borings in connection therewith were continued, in order to determine the exact nature of the ground over the site of this proposed length of timber piling. These borings, like those in the adjoining stretch of ground, did not reveal any great irregularities in the clay bed; but it was considered impossible, in view of the experience just detailed, to ensure that timber piling would successfully penetrate the bed of hard gravel and stones and make a satisfactory junction with the clay; and it was decided that this piling should, like the puddled trench, be superseded by steel piling, to be 25 feet 6 inches long and therefore going some 5 feet deeper than the timber piling.

The whole remaining portion of the cut-off was therefore executed in steel piling, forming, with the section already driven, a continuous diaphragm  $\frac{7}{8}$  mile in length.

#### STEEL SHEET-PILING.

*Original Design.*—The first design for the steel piling consisted of a system of gauge-piles, spaced 11 feet apart between centres, with four sheet-piles and a central key-pile between. The gauge-piles

consisted of rolled steel **H**-shaped joists, 9 inches by 7 inches by  $\frac{3}{4}$  inch, having jaws formed by 3-inch by 3-inch by  $\frac{1}{2}$ -inch angle-bars riveted to the flanges. The flanges of the joists were cut away at the bottom to form a point. The sheet-piles were of  $\frac{3}{4}$ -inch steel plate, 2 feet wide, having on one side 3-inch by  $\frac{3}{4}$ -inch stop-bars so placed as to butt against the jaws of the adjoining pile and leave  $\frac{1}{8}$  inch play in driving, and on the other side bars forming jaws to receive the next pile. On the pile adjoining the gauge-pile these bars were 7 inches by  $\frac{3}{4}$  inch, making a groove  $3\frac{1}{8}$  inches deep, while the next pile had bars 10 inches by  $\frac{3}{4}$  inch, giving a  $6\frac{1}{8}$ -inch groove. These piles had cast-steel shoes, so bevelled as to cause each pile to draw close to its previously-driven neighbour. The key-piles consisted of  $\frac{3}{4}$ -inch steel plate, 1 foot  $10\frac{1}{2}$  inches wide, stiffened by a 4-inch by 3-inch by  $\frac{1}{2}$ -inch **T**-bar on the front and having a cast-steel shoe. The width of the key-pile allowed 2 inches play on either side between it and the adjoining sheet-piles. The gauge-piles were made in one length, but the sheet- and key-piles were made in halves, the upper and lower lengths being secured together, after the driving of the latter, by cover-plates 1 foot 10 inches long over the plate of the pile, and 2 feet 6 inches long over the stop-bars and groove-bars in the case of the sheet-piles, and by a channel-bar  $9\frac{1}{2}$  inches by  $3\frac{1}{2}$  inches by  $\frac{1}{2}$  inch and 4 feet long riveted through both plate and **T**-bar, in the case of the key-pile. Cast-steel driving-heads were provided, which were suitable for driving either top or bottom lengths of the piles.

*First Trial Bay.*—It had been provided in the contract that, before deciding finally that the steel piling should be of this form, material for one bay of the 31-foot 6-inch piling should be prepared, consisting of two gauge-piles, four ordinary sheet-piles, and one key-pile; and that this should be driven near the site of the works, as an experimental bay. A spot was accordingly selected near the west end of the work, and, it having been ascertained by sinking a pit that the ground was similar to that which it was anticipated would be met with in the line of the work, driving-operations were begun. The two gauge-piles were first driven, followed by the two piles adjoining them. Next the lower halves of the two remaining sheet-piles were driven, and the lower half of the key-pile was then started. Up to this stage the driving had proceeded in a satisfactory manner, but when the point of the key-pile was a few feet below the surface, driving became exceedingly hard and eventually progress practically ceased. It being evident that some obstruction had been encountered, a pit was sunk to the foot of the pile, when it was found that the point had struck a boulder, and that, having

thus been started out of its true course, it had gradually turned up until at 10 feet from the surface of the ground it was at right angles to the upper portion of the pile, the upturned portion being that below the end of the stiffening T-bar. In turning up it had burst open the groove-plates of the sheet-piles, the grooves of which were found to be filled with pebbles and sand compressed to the consistency of concrete.

The three half-piles were drawn, and the grooves of the sheet-piles were repaired; the bent point of the key-pile was removed; and a new driving-point was formed by cutting away the corners of the plate and riveting additional T-bars, 2 feet 3 inches long, on either side of the central bar on the front of the pile, and three similar bars on the back. Driving was then recommenced, and the piles were driven to the intended level. An examination-pit was sunk at the back of the piling, when it was found that, although the piles were in a satisfactory condition down to the joints, they were not so below that level. The bottom 3 feet of one of the piles adjoining the key-pile was turned completely upwards in the form of a hook; the plate was much torn; and the groove-plates were stripped from this portion. The corresponding pile on the opposite side of the key-pile had left the groove of its neighbouring pile, and was much twisted; while the key-pile had also left the grooves of the sheet-piles, being 1 foot 6 inches away from one of them at the foot<sup>1</sup> (*Figs. 6*).

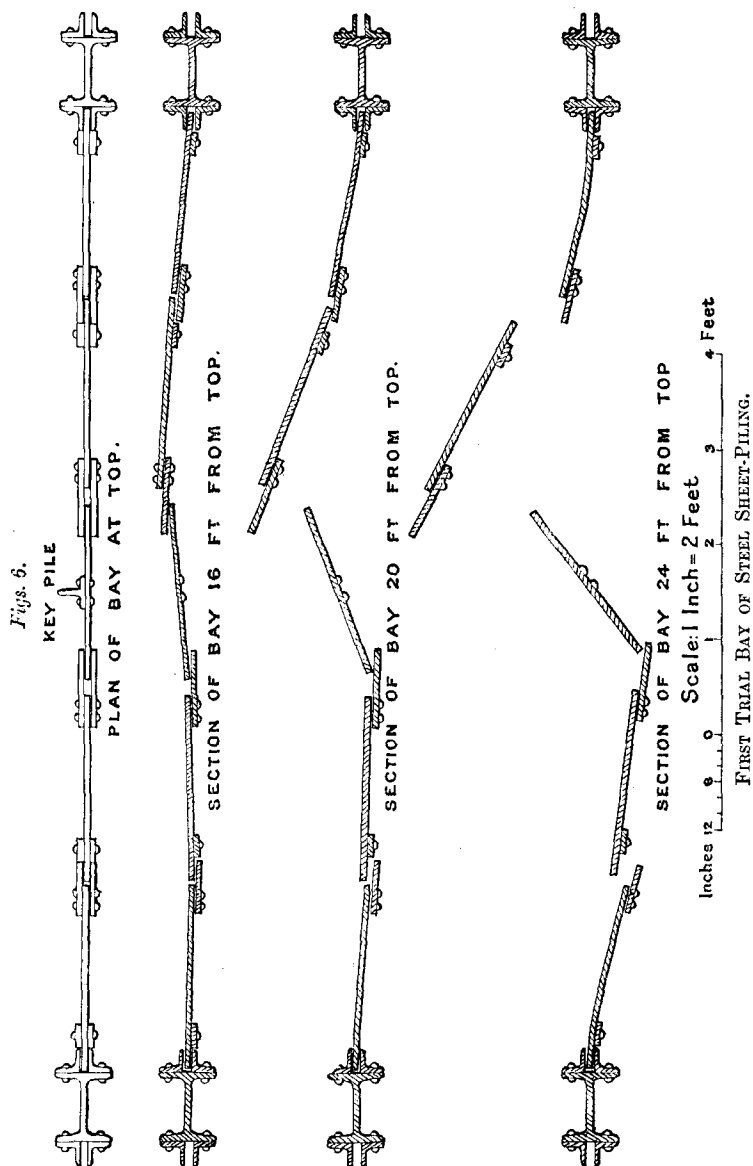
*Revised Design* (*Figs. 7, Plate 5*).—It being thus evident that this arrangement of piling would not be satisfactory, further designs were prepared, and it was ultimately determined to make trial of a system of alternate gauge- and sheet-piles. For this the gauge-piles remained unaltered, and the sheet-piles consisted as before of  $\frac{3}{4}$ -inch plate, 2 feet wide, but were stiffened by having central ribs formed of 5-inch by 3-inch by  $\frac{1}{2}$ -inch T-bars riveted on back and front. The cast-steel shoes were done away with, and the driving-point was formed by T-bars, 3 feet 6 inches long, riveted on each side of the central tee. The point of the pile was shaped to an angle of 30 degrees and the edges were cut so as to form horns to aid in clearing the grooves of the gauge-piles of sand and pebbles. As time was of importance, the material of the first trial bay was adapted for the second experiment, the two less-injured sheet-piles being altered to the new design, and a third gauge-pile being extemporized from a 12-inch by 6-inch by  $\frac{1}{2}$ -inch joist which was on the spot.

*Second Trial Bay*.—These three gauge-piles were then driven, a

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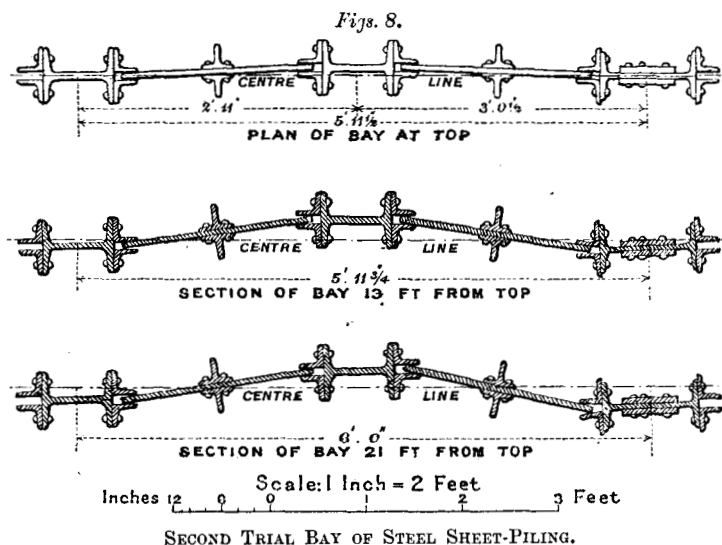
<sup>1</sup> The plates, etc., on the front of the piles are not shown in *Figs. 6*, as their condition could not be ascertained.

clearance of 2 feet 1 inch being allowed between them. The lower



halves of the two sheet-piles were next driven, after which the

upper halves were riveted on and the driving was completed. As before, a pit was sunk, and the piles were duly examined, when it was found that a perfect cut-off had been formed (*Figs. 8*), the sheet-piling being continuously in the grooves of the gauge-piles for a depth of 29 feet from the top, below which point it was not practicable to make an examination, owing to land-water rising in the pit. There was no indication, however, of any tendency to irregularity. During the rising of the tide on the day of the examination, the water in the pit was tested at intervals with a salinometer for the purpose of ascertaining whether percolation of sea-water was taking place. No such percolation could be detected, although the bottom



of the pit was 17 feet below the level of high water of ordinary spring-tides.

The second arrangement having thus been found to be satisfactory, it was decided that the work should be carried out on these lines; though only a portion of the material required was procured, lest any further modification should subsequently be found necessary. The work of driving the first series of steel piles was begun in February, 1901.

*Arrangements for Driving Piles.*—Short timber piles were first driven, to carry the platform on which the engines for driving the steel piling were to work, and for affixing the arrangement for keeping the line of piling true. These piles were spaced 10 feet apart between centres in the direction of the line of works. The

two front rows were respectively 1 foot 4 inches in front of and behind the line of the sheeting, and to them were fixed 12-inch by 12-inch walings, the space left between these being thus 8 inches. These walings were placed so that their upper side was 1 foot 9 inches below the finished level of the top of the steel piling. Between these walings, and secured to them by coach-screws, were fixed distance-blocks, the space between these being exactly that occupied by a gauge-pile, namely 1 foot 3 inches, while their width allowed a clearance of 2 feet  $1\frac{1}{8}$  inch between the flanges of the gauge-piles, the sheet-piles being, as stated, 2 feet 1 inch wide. These blocks had rubbing-pieces of  $\frac{1}{4}$ -inch iron plate at each side, to take the edges of the angle-jaws of the gauge-pile. A considerable length of staging and guides was prepared in this way, so that work could be started at several places at once. As each gauge-piling engine completed the driving of a sufficient number of gauge-piles a sheet-piling engine followed it up. The lower lengths of several sheet-piles were first driven; their upper lengths were then riveted on, and the driving was completed.

Behind the platform on which the piling-engines stood was a line of railway, along which were brought the boilers for driving the steam-winches of the engines. These were 6-HP. and 8-HP. vertical boilers mounted on railway-wagons, and were connected with the winches by means of flexible armoured hose. They were, of course, brought down when the tide had receded sufficiently, and drawn up on shore again at the close of the working-period.

The driving-gear for the gauge-piles comprised a 30-cwt. monkey, 22-cwt. dolly and 3 $\frac{1}{4}$ -cwt. driving-head or cap, all made of Hadfield toughened steel. For the sheet-piles a similar monkey was used, but the dolly and cap weighed 19 $\frac{1}{2}$  cwt. and 4 $\frac{3}{4}$  cwt. respectively. On the top of the driving-cap, between it and the dolly, was placed a pad of compressed fibre,  $1\frac{1}{8}$  inch thick, to diminish jarring; while in the case of the sheet-pile gear a strip of copper was also beaten into the groove in the cap which fitted over the head of the pile, for the same purpose. At an early stage of the work difficulties were frequently experienced with the attachments of this gear, the monkey-eyes, gauge-bolts, and cotters becoming crystalline after a few hours' work and breaking. Various qualities of steel and other metals and alloys were tried for these parts of the gear, but eventually a return was made to commercial iron of good quality, rubber pads being inserted between the parts to reduce the jarring; and this increased considerably the life of the attachments, and of the monkeys, etc.

In driving the gauge-piles, any tendency shown by the pile to run

outwards from the machine or in towards it was counteracted by packing up the engine at either the back or the front, and so giving it an inclination outwards or inwards, which had the desired effect in bringing the pile back to the plumb; while to check any tendency to run sideways a winch with blocks and tackle was provided, by which a strain was kept on the head of the pile in the necessary direction.

*Use of Water-jet.*—As already mentioned, some very hard ground was met with in driving the steel piles, and as an aid in driving through this ground a water-jet was used. For this double-ram pumps were employed, of  $5\frac{1}{2}$ -inch and 6-inch diameter, worked by 6-HP. and 8-HP. vertical boilers; or at times two pumps were worked by a 10-HP. boiler. The water was delivered from the pumps by a 5-inch pipe, diminishing to 3 inches and again to  $1\frac{1}{2}$  inch in diameter; from this a  $1\frac{1}{4}$ -inch vertical pipe led to the jet-pipes, of which there were two, springing from a T-joint and coming down in front of and behind the pile respectively. These down pipes were tapered to a point  $\frac{3}{4}$  inch in diameter. The pipes were kept working up and down by hand by means of a block and tackle, the points being kept about level with or slightly below the point of the pile. It had been feared that the use of these jets might unduly disturb the surrounding ground, leaving permanent ill-effects; but experiments made before regular adoption of the system proved that such was not the case. After one tide had flowed over the ground it became fairly hard again, and after three or four tides it was found to have returned to its normal consistency. The points of these jet-pipes were not allowed, save in exceptional cases, to be put down lower than 8 feet above the finished level of the point of the pile. The jet was used in driving the sheet-piles only, as the gauge-piles could not have been satisfactorily guided had it been used for them.

Fig. 10, Plate 5, shows the acceleration in speed of driving attained by the use of the water-jet. The fall of the monkey was 3 feet, as it was found that, having due regard to wear and tear on plant, especially on the monkeys, dollies and driving-caps, this should be the maximum fall allowed.

In certain exceptional cases, periods of very hard driving of sheet-piles were experienced. Some of these were caused by meeting with obstructions, probably small boulders, in the gravel bed, as they usually occurred during the passage of the point of the pile through this stratum. In one case a pile which had progressed at about the ordinary speed until 7 feet from the finished depth, met with such an obstruction at this point: the driving became gradually harder, until at 3 feet from the finish one hundred and sixty blows of the



monkey were required to drive 1 inch, the pile apparently carrying the obstruction down with it. Then the obstruction appeared to be gradually pushed aside, as the driving became easier, although still hard, the driving for the last 2 feet being at the rate of forty-eight blows per inch. Occasional hard driving of the sheet-piles also occurred, where the gauge-piles had not been driven quite truly and the sheet-pile ground against either the face of the flange, or the sides of the jaws, of the gauge-pile. In one instance the sheet-pile evidently cut into the flange of the gauge-pile, as it began to carry the latter down with it. An attempt was made to draw the sheet-pile, but without success, and eventually the gauge-pile was driven down by means of a special dolly until the sheet-pile was released, when the latter was driven to finished depth at about the normal rate of driving. The gap which was necessarily left between the two adjoining sheet-piles by this extra driving of the gauge-pile was closed by a plate, secured to each sheet-pile by fishplates.

With the gauge-piles abnormally hard driving was not very frequently experienced, Figs. 9, Plate 5, being representative of the general rate of driving. Occasionally, however, a pile would be diverted from its course to too great an extent to permit of the deviation being rectified by the manipulation of the piling-engine or side-winch to which reference has been made; such piles were drawn by means of hydraulic jacks and repitched, the second attempt to drive them usually proving successful. Where, however, it was evident that an obstruction existed, either to gauge-pile or to sheet-pile, which would entirely prevent the pile from being driven, a caisson was sunk and the obstacle was removed. On some occasions it was necessary to sink both in front of and behind the line of piling, and two caissons were therefore provided. These caissons were 6 feet wide by 5 feet across, and were formed of steel plate stiffened by T-bars. They were made in sections, each 3 feet deep, having flanges formed of angle-bars, so that the successive sections could be bolted together as the sinking proceeded. The bottom length was provided with a cutting edge. By this means obstacles were removed on several occasions. The largest of these were met with in the clay bed and consisted of granite boulders.

When the piles had been driven until their heads stood 2 feet 3 inches above ground-level the adjacent ground was excavated and filled with puddled clay in the manner already described in the case of the timber sheet-piling. By the time that about 400 feet of the piling had been driven it was felt with confidence that the design

was satisfactory, and the remainder of the piling was accordingly all of the type described. The total length of cut-off formed by steel piling was 4,636 feet, the various lengths used being :—

34-foot 6-inch piles . . . . .	1,720 feet.
31-foot 6-inch „ . . . . .	1,258 „
25-foot 6-inch . . . . .	1,658 „
Total	4,636 „

#### EMBANKMENT.

Turning now to the structure of the Barrier above the foreshore-level, the top of the main outer limestone bank is 15 feet above high-water level of ordinary spring-tides, this bank having an extreme height of 40 feet above the foreshore. The top of the inner bank is at high-water level, while that of the clay hearting is at an upward incline of 1 in 40 landward from the inner edge of the main limestone bank, its landward side being sloped down to meet the outer edge of the lower stone bank (Figs. 5, Plate 4).

The main limestone bank is 10 feet wide at the top, exclusive of the width of the protective coating of larger material. It has slopes of 1 to 1 on the landward and  $1\frac{1}{2}$  to 1 on the seaward side. The bank was not in the first instance formed to its full height, but was kept 5 to 6 feet below this, in order to provide sufficient width for the requisite number of construction-roads on the top: the upper layer was deposited later, as the progress of the work permitted. The stone was obtained from quarries adjacent to the east end of the work, and consisted of large and small material mingled together, a preponderance of the larger being used as far as possible for the sides of the banks, especially the seaward side.

The practice in tipping this bank was to keep two tip-heads working, with end-tip wagons, following up at intervals with side-tipped material. For tipping the larger material in the main bank, and also the protective coating of large limestone lumps, special wagons were built, the end-tipping wagons to carry 12 tons and the side-tipping 15 tons. The former had wheels 3 feet in diameter, this increase in size over that of the wheels of ordinary tip-wagons being found advantageous, inasmuch as the wagons ran much more easily, and also were more readily spragged.

*Quarrying.*—The method of quarrying was so arranged that the bulk of the material should be of large size, and the blasting was carried out so as to avoid unduly shattering the rock, the object

being, of course, to minimize the likelihood of disturbance of the stone by the sea after it had been deposited in the bank. Most of the holes for blasting were drilled by Hirnant steam-drills, of which twelve were employed. Two or more of these were worked from one vertical boiler, there being two 8-HP. and two 10-HP. boilers in use for this purpose. The rate of work accomplished by these drills in a hole beginning with a diameter of 3 inches and diminishing to  $1\frac{1}{2}$  inch averaged  $2\frac{1}{4}$  feet per hour. The depth of the holes was dependent, of course, upon the position of the beds in the rock, and varied between  $4\frac{1}{2}$  and 25 feet.

The system of blasting was ordinarily by "chambering," for which purpose a gelignite charge of  $1\frac{1}{2}$  to 3 lbs. was first used; this was followed by a charge of blasting-powder of 8 to 20 lbs., and then the final charge, also of powder, which varied between 130 and 270 lbs. Firing was done by the Bickford fuse. By these means masses of stone weighing up to 15 tons were dislodged, which were used for the protective coating of the bank. This coating was 15 feet in width and was deposited mainly from side-tipping wagons, the lumps being, where necessary, hauled down into place with chains from hand-winches on the shore, the finishing being done by depositing the stones with steam-cranes. An ordinary day's output from the quarry to the embankment when work was in full swing was 900 cubic yards.

*Concrete Wave-breaker Blocks.*—The covering of 25-ton concrete blocks, with which the central portion of the Barrier is faced, is 25 feet in width, and consists generally of successive tiers of two blocks, each placed at right angles to the line of the work, so that their ends are presented to the stroke of the sea. These blocks are not placed flat on their beds, but are deposited as irregularly as was consistent with avoidance of an undue proportion of interstices in the work, and with securing a sufficient weight of block-work. The blocks measured 11 feet by 6 feet by 6 feet, and the concrete was composed of 6 parts of sand and shingle to 1 part of cement, having also a proportion, not exceeding 20 per cent. in the case of any block, of large rough stones incorporated in it.

*Ballast for Concrete.*—The ballast for this work was obtained from the foreshore immediately adjacent to the site of the work, from that of the Duddon Estuary inside Hodbarrow Point, and from the Hodbarrow Mains, bordering on the estuary. The material from the last-named source, though of suitable composition, was somewhat dirty, and in order to remove dirt from such ballast as was not clean enough for use, it was loaded into tip-wagons when excavated, and run to a tip which was situated between the end of Hodbarrow

Point and the east end of the Barrier. Here it was washed by being turned over by the tide, being afterwards again loaded into wagons and conveyed to the block-making yard. In this way about 20,000 cubic yards was treated.

*Manufacture of Blocks.*—In the block-making yard a cement-store capable of containing 1,000 tons was provided. The mixing of the concrete was done by machine, two Messent mixers being used, each of 1 cubic yard capacity. The ballast and cement were conveyed to the top floor of the mixing-house by a hoist worked by a steam-winch; thence they passed to the mixer on the floor below, which in turn delivered the concrete into small steel tipping-wagons of  $\frac{1}{2}$  cubic yard capacity. These were run along staging having an incline of 1 in 100, to the block-moulds, which were on the concrete floor on either side of the staging, of which there were two lines. Moulds were provided for forty blocks, and floor-space for making twice that number, a mould being removed from a block when set and moved on to the site for making the neighbouring block. The moulds were usually loosened after 48 hours and removed after 4 days, and the block was lifted and conveyed to the stacking-ground after about 10 days, the minimum being 7 days. No block was set in the work until it was 4 months old, and stacking-ground was therefore provided for 1,100 blocks. A full week's output from the block-makers was fifty-six blocks, being ten per day for five days of the week and six on Saturdays. This output was naturally not always attained, but block-making having been commenced in January, 1901, by September in the same year, when the first blocks were deposited in the work, there were a large number of well-matured blocks in stock.

*Block-setting.*—For dealing with the blocks in the block-yard, and for setting them in the work, Goliath cranes of 60 feet span were used. The blocks were lifted for stacking and loading by means of lewis-bars, but for depositing them in the work nippers were used. The cranes for setting the blocks were carried on staging formed of iron girders carried on dolphins of four piles each. The bays of this staging were 40 feet in span and sufficient ironwork was provided for six such bays. The piles for the dolphins were driven before the tipping of the limestone bank, and the inner row of dolphins was included within the limits of that bank; consequently these piles, after the superstructure of the staging had been removed as the work progressed, could not be drawn, but were cut off flush with the bank. Most of the dolphins in the outer row were drawn. The centre-line of the staging was on a curve of 2,780 feet radius, and the staging was erected in successive chords of 240 feet,

special dolphins of six instead of four piles being provided for sluing the Goliath at the end of each length.

When blocks were required for setting they were taken out along the limestone bank alongside the staging to the Goliath, which lifted them, passed them through an aperture in its side frame, and duly set them in place. The day's work at block-setting varied very considerably, being affected by such things as the amount of preparation that had to be done at the foot or on the sides of the limestone bank to receive the blocks, the slow rate of setting which was attainable at points where blocks had to be manipulated under girders, and so on. The best day's work accomplished was fifty-one blocks, but it was seldom that more than twenty to twenty-five blocks were set in a day.

The total number of 25-ton blocks set in the work was 5,157; and in addition to these the two hundred 20-ton blocks which had protected the weakened portion of the first sea-wall were removed from their position and placed in the new work after the closing of the Outer Barrier.

After the removal of the staging and the cutting-off of the piles of the inner dolphins, the spaces left by the tops of these dolphins were filled with blocks tipped from wagons off the limestone bank. Over the top of the block-work, which was at a level 5 feet below the top of the bank, being thus 10 feet above high water of ordinary spring-tides, a covering of rough limestone, similar to that which protects the shoreward ends of the embankment, and of the same width (15 feet), was deposited.

*Scour in Front of Tips, and Preventive Measures.*—As the two ends of the banks progressed seaward, considerable scour began, as had been anticipated, to take place immediately in front of them, caused by the flow and ebb of the tide around the ends. In order to prevent this, a covering of a mixture of clay and debris from the mines was spread in advance of the work. This mixture was of a very heavy nature and it also consolidated soon, becoming eventually quite hard and affording practically complete protection against scour. An apron of similar material was also spread at the foot of the wave-breaker blocks over the length where the sea-stroke was heaviest, and prevented the abstraction of sand from this place and consequent sinkage of the blocks.

*Inner Bank.*—The inner bank was intended, as already stated, to be formed of iron slag, and a considerable length was executed in this material. It was found, however, that the weight of the slag was not sufficient to prevent its being clawed down and squandered whenever seas of any strength occurred, and its use was discontinued

in favour of limestone until the sea had been excluded by the closing of the temporary timber dam to be described later, after which a return to the use of slag was made for the remaining portion of this bank. The inner bank was 9 feet wide at the top, with slopes of 1 to 1, and was deposited by end-tipping wagons, the landward side being subsequently trimmed to the desired slope.

*Clay Filling.*—When these two stone banks had been tipped for sufficient lengths, and the hollow before described had been excavated between them and filled with puddle, the clay bank followed. For getting the clay, two steam-navvies were employed during the greater part of the construction, and a third later on, and a considerable quantity was also excavated by hand, all the clay for puddle being obtained in this way, in addition to a portion of the ordinary filling. The material was deposited in a similar manner to the stone bank, commencing with two end tips, the valley left between the two tips being afterwards filled by side tipping, which was also carried on from the stone banks. This clay was chopped, watered, and rammed as it was deposited. Between 900 and 1,000 cubic yards was usually deposited daily in the work.

*Puddle Wall.*—Simultaneously with the tipping of the ordinary clay filling the construction of the puddle wall was proceeded with. The wall was brought up in steps of 1 foot, at a slope slightly flatter than the end of the tip, the ordinary clay, side-tipped from off the stone banks, being carefully packed and rammed against its sides as it was raised. The puddle was conveyed by wooden shoots from the top of the bank to the wall, and was deposited therein by hand, being well trodden in to render the mass homogeneous. The wall was 7 feet wide at the foot where it sprang from the puddled trench, or from the puddled hollow around the heads of the piles, and was continued at this width up to 5 feet below high-water level of ordinary spring-tides, when the width was reduced to 5 feet, the wall being carried 10 feet higher at this width.

*Surface and Side of Clay Embankment.*—The surface of the clay filling, which varies in width between 43 and 58 feet, is finished with a layer of slag 6 inches thick. For this purpose material of small size was selected as far as possible, any pieces which were too large being cracked by hand after spreading, and the whole surface was well blinded. The coating was well rolled with a heavy roller. It was important that it should have a good surface, in order that water should drain towards the seaward side, with which object the inclination of 1 in 40 was given to the surface. The slag coating was not applied until the clay had been deposited for several months; indeed, the landward ends of the

barrier had been finished for more than 12 months before any slag was deposited. Time was thus allowed for settlement of the clay to take place; but notwithstanding this, settlement did take place at some spots after the slag had been laid, and at these places the slag was taken up, additional clay was deposited to make up the hollows, and the coating was relaid.

*Soiling and Sowing Slope.*—The slope of the clay embankment from its landward edge to the inner stone bank was originally intended to be  $1\frac{1}{2}$  to 1, and the major portion of the work was approximately tipped, and a short length trimmed, to this slope. It was found, however, that there was difficulty in getting the clay to stand at this slope, and it was accordingly modified to 2 to 1, material being taken from the top and put to the lower part of the slope, the quantity of clay thus not being increased. It was also decided that this slope should be covered with soil—of which there was available a large quantity stripped from the fields whence the clay was obtained—and sown with grass-seed, to aid in maintaining the surface of the slope.

*Diversion of Swash Channel.*—It will be seen from Fig. 3, Plate 4, that, although the area to be enclosed, and the site of the Barrier itself, were left almost entirely dry at low water, there was one channel, known as the Swash channel, which still existed after the receding of the tide, and that this channel crossed the line of the work at about the centre, and again near the east end. Between the making of the survey and the beginning of the work some change had occurred in the position of the channel, the eastern point of the crossing having moved much nearer to the shore. It therefore soon became necessary to deal with this. Piles were driven and a staging was thrown across the channel, in the line of the inner stone bank, and from this material was tipped which formed the base of that bank. Clay was also tipped between the two stone banks, and through it the puddle trench was subsequently sunk. In order to divert the channel, and throw it outside the line of the work, material was next conveyed across the channel, and low groynes were formed, consisting of the mixture of mine-debris and clay before referred to. The first groyne was at an angle of about 60 degrees to the work, and extended 100 feet seaward of it, being about 16 feet wide at the top and 3 to 6 feet high. Next, a similar low bank was tipped in the line of the work, just beneath the future foot of the main limestone bank at its seaward side, being thus eventually entirely incorporated in the work. At 250 yards further seaward a second groyne, 350 feet in length, was thrown out at an angle of 35 degrees to the work.

These groynes had the effect of gathering sand and training the channel seaward, and the bank along the edge of the site of the work being continued right round to join the west arm of the embankment, the channel was eventually thrown entirely outside the line of work. Subsequently three similar groynes, each 250 feet long, 400 feet apart, were constructed near the centre of the work, to encourage the deposition of sand there; and they are having the desired effect.

#### SLUICE-CULVERTS (Figs. 11, Plate 5).

The four sluice-culverts for discharging water through the Barrier from the reclaimed area are situated near the centre of the work, and are formed of concrete, the landward and seaward ends being faced around the openings with granite, as are also the faces entering the penstock-chambers; while the remainder of the face-work of the end and wing-walls is of limestone. The coping around the tops of the penstock-chambers is also of granite.

The centre-line of the penstock-chambers is on the line of the cut-off, and the chambers are 5 feet 6 inches wide transverse to the culverts, and 4 feet 6 inches wide in the line of them. The length of the culverts seaward of the penstock-chambers is 130 feet 6 inches, and landward thereof 59 feet 3 inches. Aprons of concrete, 10 feet wide at the seaward end and 14 feet 6 inches wide at the landward end, were formed; the total length of concrete foundation being 218 feet 9 inches. The width of the seaward portion of the culverts is 4 feet 6 inches, with 3-foot walls between and 3-foot 3-inch outside walls; their height is 5 feet 6 inches. They have a semicircular top and a square bottom, and the inverts have a fall of 2 inches between the penstock-chambers and the mouth. The inner culverts are 4 feet wide and 5 feet high, with semicircular top and bottom, the walls being 3 feet 6 inches thick; the invert here is level, and is 21 feet below high water of ordinary spring-tides. The concrete of the foundations was intended to be of a thickness varying between 6 feet 1 inch and 6 feet 9 inches, which it was assumed from the borings would allow the work to be founded on the clay bed. This thickness, however, was increased in parts, owing to irregularities subsequently discovered in the clay. The concrete of the arches is 3 feet thick. All the concrete for the culverts was mixed in the proportion of 5 parts of shingle and sand to 1 part of cement, and was mixed by hand on the spot. When the subsidiary borings on the line of the cut-off were taken, one of them was situated on the centre-line of the culverts, and clay



was proved at about the anticipated depth. Nevertheless it was deemed advisable, before beginning the execution of the foundations, to make additional borings; accordingly ten bore-holes were put down over the area of the work and apparently showed a practically level bed of clay to exist, no variation exceeding 1 foot being found. The work was therefore begun by enclosing the area with 4-inch sheeting, and dividing it into ten compartments in the same manner, so that the excavation could be undertaken in sections, each 22 feet long, and of the full width of the foundations.

Excavation was commenced in compartment No. 1, at the landward end of the work, and operations had not proceeded far when irregularities in the clay bed were found to exist, the bed apparently entirely disappearing at the north-west corner of the work. On further extension of the excavation it was discovered that between two lines of borings just previously taken there was a complete break in the clay bed, a gully of silt 25 to 30 feet in width crossing the work. As it was not practicable to found the culverts on this, it was decided to pile this portion of the foundations: accordingly, piles were driven 4 feet apart over the area of the gully and extended into the clay bed on either side. The piles in the first compartment were driven to 15 feet below the normal level of the bottom of the foundations, and those subsequently driven were put down 7 to 8 feet deeper. On the heads of these piles, secured by dogs and spikes, were fixed whole-timber cap-sills, which were crossed at intervals by half-timbers, the whole arrangement forming a grid. The heads of the piles were at the normal level of the foundation, which was here carried 1 foot 6 inches deeper. Numerous additional borings were made, and no further great variations in the clay bed were revealed, though when the excavation of compartments Nos. 9 and 10 came to be executed, a fissure 4 feet wide, extending from the seaward face 25 feet into the work, was discovered, lying between two rows of bores 10 feet apart. This was bridged over with a flooring of half-timbers, 12 feet in length, and a protective boxing of sheet-piling was subsequently driven in front of it, to confine the silt.

The conditions described above raised apprehensions as to the efficacy of the cut-off already provided at this spot, which had been made by carrying the 25-foot 6-inch steel piling across the site of the culverts; it was deemed advisable to provide additional protection here, and accordingly an auxiliary line of steel piling, of the 31-foot 6-inch length, extending across the foundations and for 11 feet 9 inches on either side thereof, was driven 21 feet seaward of the

original cut-off, to which it was joined by return lines at the ends. The corners were turned, and the junctions with the existing line of piling were made, by means of gauge-piles which had no angle-bar jaws on one flange, and which were driven with this flange fitting into the breast of the neighbouring gauge-pile, to which they were at right-angles, the flange being chipped to shape for this purpose.

Where the piling crossed the foundations of the culverts, both gauge- and sheet-piles were made with removable upper lengths, which were taken off when the subsequent excavation had been carried out. On this being done the piling was found to have driven accurately and to form a very efficient cut-off. Around the heads of the piles thus left, a recess 3 feet 6 inches wide was formed in the concrete, which was carried to an additional depth of 3 feet, the bottom being 2 feet below the head of the pile, allowing 1 foot for possible settlement. This recess was filled with puddled clay. A similar arrangement had been carried out in the case of the first line of piling. In addition to the extra piling described above, it was necessary to form a boxing of steel piling immediately landward of the original cut-off at the east side of the foundations, in order to enclose a piece of extremely bad ground which existed here under a corner of the work. This was done with 25-foot 6-inch piles.

Where the work was founded on clay the concrete was carried down 6 inches into it. In depositing the concrete over the portion where no clay existed, great trouble was experienced owing to water springing up through the silt, this water apparently finding its way from a pool which remained inside the line of the barrier. In order to deal with this it was found advantageous to lay down a carpeting of felt immediately before the concrete was deposited; this was weighted with stones, and the concrete was laid upon it as quickly as possible. The concrete of the foundations was usually deposited in two layers, the successive sections having a horizontal bond of 5 feet, while keys were formed vertically to prevent lateral sliding. The upper layer was brought up to 6 inches below the invert-level, the top skin in the culverts being put on subsequently. After the culverts had been constructed, the concrete work was surrounded, above shore-level, with a covering of puddled clay, 4 feet thick seaward of the penstock-shafts, and 3 feet thick landward thereof. The puddle wall also divides where it meets the penstock-chambers and is brought around the sides of them, making a casing of puddle, 4 feet thick, on either side. The puddle casing, where it was under the site for the wave-breaker blocks and the outer and inner

stone banks, was covered with a rough paving of stones, as large as could be handled by men, packed to as great a height as was practicable before the banks were tipped across it, so as to prevent stones from piercing through the puddle and damaging the concrete. These banks were brought across the work with great care; the outer bank was lowered at the end as it approached the culverts until it was 8 feet below finished level, and on reaching the side of the culverts the stone was drawn down by hand on to the work, then more stones were carefully tipped, and the same process was repeated until the culverts were crossed. The inner bank was deposited in the same manner, and the first portion of the clay filling was side-tipped from these banks, the puddle casing around the penstock-chambers being brought up at the same time. In this way the weight of the embankment was imposed gradually upon the concrete work. Notwithstanding these precautions, unequal settlement took place to a slight extent, and cracks appeared in the concrete of the culverts where junctions in the concrete of the foundations had been made. None of these cracks was large, and the settlement was very slight. It was considered desirable, however, to put a lining into those portions of the culverts where the cracks were most pronounced, and, at a later period, after the closing of the Barrier, and when all movement appeared to have ceased, a ring of blue brick was built as a lining to these parts.

After the embankment had been raised to its full height and the wave-breaker blocks had been deposited, a parapet 8 feet 6 inches in height, formed by two tiers of concrete blocks, was constructed on the limestone bank over the culverts. It is 96 feet in length on the upper course of blocks and 102 feet on the lower course. The blocks were in the first instance placed temporarily in position and allowed to remain for some months, with a view to consolidating the bed on which they rested. They were subsequently lifted and re-set permanently with cement-mortar joints in the usual manner.

Attached to blocks in the lower course of the parapet, on the landward side, are the winches for raising the tide-flaps at the seaward end of the culverts. The chains from these are led over four guide-pulleys in each case, one on each edge of the upper block of the parapet, one on the edge of a wave-breaker block halfway down the slope, and one on a bracket fixed to the face-wall immediately over the door.

The penstocks fit in cast-iron frames let into recesses in the granite of the inner face of the penstock-chambers, and are raised and lowered by square wrought-iron rods, to the upper ends of which are

attached shrouded racks of cast steel, which are worked by crabs at the top of each chamber. The penstocks are so designed that two men can lift them when there is a head of water of 8 feet above the bottom of the culverts on the inside; while four men would do the work with a head of 20 feet on the sea side. They would of course be used under the latter condition only in the event of its being desired at any time to flood the reclaimed area.

The landward end of each culvert is provided with a wrought-iron grating fixed in a rebate in the granite facework.

At each side of the concrete apron of the seaward end are placed concrete blocks of the same dimensions as the wave-breaker blocks, forming wings. These were built in situ and are held in position by cramps of railway-rails which were built into the concrete of the apron with their ends projecting up into the blocks.

#### CLOSING OF THE BARRIER.

It had been foreseen that as the ends of the embankment approached each other the inrush of the tide through the aperture would tend to produce scour immediately inside the Barrier, and that it might become necessary to adopt protective measures here. These anticipations were verified, the scour being very considerable and causing the pool, of which mention has already been made, to be deepened to an extent that was considered to threaten danger to the work; as it was feared that if this action were allowed to continue, the surface here might be lowered so as to be below the level of the foot of the steel sheet-piling. Accordingly, in order to prevent further denudation, an apron of clay covered with limestone and mine-debris was deposited, the surface of this apron being on a level, at its front, with the sill of the temporary dam which was then in course of construction, and being given a slight upward incline towards the shore. The apron extended shoreward 150 feet from the line of the foot of the inner slope of the Barrier, and was carried to some distance on either side of the gap. It effectually protected the ground immediately behind the Barrier; while as a check to the rush of the water, and to prevent, as far as possible, scour from taking place beyond the edge of the apron, mounds of large stones were deposited at short distances apart, in two rows, on its surface. These expedients had considerable effect in the desired direction, for although some scour still took place, it occurred with much diminished rapidity, and in no case reached alarming proportions.

*Temporary Closing-Dam* (Fig. 12, Plate 5).—The method of closing

the Barrier provided for in the specification for the work was that the ends of the embankment should be advanced towards each other, leaving space for the construction of a dam which should have the necessary sluice-area to admit of the free flow of the tidal water into and from the area to be reclaimed; and the work was carried out in conformity with this plan. Calculations of the requirements were made before the letting of the contract, and further calculations were made after the design of the dam had been decided upon. The accuracy of all these calculations was borne out in the result.

The form of closing-dam adopted was a single-skin timber dam, 292 feet in length, with coffer-dams 65 feet long at each end. The dam was situated slightly to the east of the centre of the work (Fig. 3, Plate 4), and a short distance west of the permanent culverts. It was constructed in the line of the embankment, its face being 5 feet landward of the steel piling, and the banks were advanced so as to house in the dam to the extent of 83 feet at each end, the coffer-dams enclosing the puddle wall.

The quantity of water contained behind the Barrier at high water of ordinary spring-tides was calculated to be 105,000,000 cubic feet, and for its inflow and outlet thirty-six sluices, 6 feet by 4 feet 4 inches, giving a total area of 936 square feet, were provided in the dam, the permanent sluices, which were also taken into account, having an area of  $66\frac{1}{4}$  square feet. The sills of the sluices in the dam were 17 feet below high water of ordinary spring-tides, being 4 feet above those of the permanent sluices. It was calculated that the greatest head of water against the dam that could occur would be 4 feet 9 inches on the flood-tide and 3 feet 6 inches on the ebb, and the greatest head actually observed during the few days when the water was passing through the sluices was 4 feet on the flood-tide and 3 feet 7 inches on the ebb, the height of the tide on this day being 1 foot 6 inches below that of ordinary spring-tides. The top of the dam was 8 feet above high water of ordinary spring-tides. The main piles were 16 inches by 16 inches, and were driven 24 feet into the ground or 15 feet into the clay bed. The sheet-piles, which were 6 inches thick, were driven so as to extend not less than 10 feet into the clay.

The sluices were arranged in six bays of six sluices each, with a counterfort between each bay. Where the sluices occurred, and for the portion enclosed in the banks, the main piles were spaced 4 feet 4 inches apart, and at the counterforts 5 feet 4 inches apart.

After the main piles and the sheet-piles had been driven, and during the erection of the superstructure of the dam, the ground between its face and the steel piling was excavated down to the clay

bed and the space was filled with puddle. The hollow between the stone banks was also excavated, and the puddle was deposited, the latter being covered with a coating of mine-debris before fixing the decking of the dam, up to the underside of which it was brought. The decking, which was 5 inches thick, extended for a width of 48 feet in front and 38 feet behind the skin of the dam, and the space between the underside of the decking and the ground was filled with mine-debris over which a layer of clay was laid immediately before the planking was laid down. This was to prevent scour from taking place beneath the decking. The coffer-dams at the ends were formed by driving a row of piles 10 feet 8 inches in front of the main piles and fixing thereon 6-inch timbers placed horizontally: with the 6-inch vertical cleading of the dam, this formed a casing which was filled with puddle in continuation of the puddle wall. The row of piles was continued to form the outer row of the gantry on which the cranes for construction purposes, and subsequently for raising and lowering the sluice-doors, were carried. The inner row of gantry-piles was the same distance behind the main piles of the dam. Two lines of railway were carried on this gantry. The piles of the gantry had triangular cut-water pieces attached to them up to the height of the top of the sluices, to diminish their obstruction to the flow of the water.

The counterforts between the bays of sluice-ways were formed by a system of raking struts at front and back of each pile, and a similar arrangement was made at the back of each alternate pile between the counterforts. Each set of struts was connected together with half-timber bracings, and on the upper struts behind the dam were fixed half-timber horizontal lacings, running the whole length of the work, to prevent racking. As an additional guard against such action, ties formed of steel-wire rope, 1 inch in diameter, were attached to the heads of the counterfort-piles and carried back to those of the piles upon which the feet of the upper raking struts rested, one tie being in the line of the strut and the other being carried diagonally across to the next counterfort. These were tightened by means of union screws.

The cleading of the dam was 6 inches thick, each panel being formed of four timbers over the sluices and five at the counterforts. These panels were put together and caulked on shore and fixed into the work in one piece.

The sluice-doors were 6 feet 8 inches high and 5 feet wide, and were formed of  $4\frac{1}{2}$ -inch timbers placed horizontally, with two vertical stiffening pieces 9 inches by  $4\frac{1}{2}$  inches. A central rib was formed by a piece of rail of 81-lb. section, to the top of which was

attached a rail of 56-lb. section, which, being carried up to the top of the dam, formed the lifting-bar. The weight of these rails acted to prevent the doors from being floated up from their seatings.

At the side of the first counterfort at each end a timber retaining-wall was constructed to keep up the end of the clay bank, which was finished off with a slope of 4 to 1 and covered with a layer of bags filled with puddle to prevent it from being drawn down by the wash of the sea. The ends of the limestone banks were formed of large masses deposited by a crane.

*Closing of Sluices.*—The construction of the dam was practically completed on the 14th July, 1904, and on the 20th the closing of the sluices took place, the permanent culverts being closed immediately afterwards. Operations were then suspended until the morning of the 22nd, when, all having proved satisfactory, the sluice-doors were caulked and pitched and a beginning was made with stripping the decking of the dam and removing the coating of mine-debris over the puddle in the trench and hollows. At the same time tipping of slag in the inner bank was proceeded with. By the following day arrangements had been completed for continuing the tipping of the main limestone banks, and this was pushed forward, in order to protect the dam, with all possible speed. On the 6th August, when these banks had been brought forward to within 30 feet of one another, a strong gale and heavy sea occurred, but no damage of any kind was sustained. With the exception of the decking, the upper raking struts of the counterforts and the struts which passed through the site of the puddle wall, the whole of the structure of the dam was enclosed in the embankment. The upper portion of the gantry was removed after the clay filling had been brought up. Progress was well maintained, and in October, the Barrier having been raised to its full height all round and being therefore practically finished, the Engineers' certificate of completion was issued. Sundry minor works, such as the levelling of the surface of the more recently executed portion of the embankment and depositing the slag coating thereon, the completion of the trimming, soiling, and sowing of the inner slope, the setting of a few concrete blocks, and other details, were proceeded with during the period for which the contractors were responsible for the maintenance of the Barrier, which period was, under the contract, to cover the six winter months.

*Additional Protective Measures adopted after Closing.*—After the Barrier had been closed, water was observed issuing in runnels from certain places at the foot of the inner stone bank. It was at first surmised that it might be water which had been held up in the

embankment and land-water draining out through the stone. It was found, however, that while this might account for some of the runnels nearest to the shore, which ran continuously, it did not account for the majority, as it was soon observed that these were affected by the tide, beginning to appear at 2 to  $2\frac{1}{2}$  hours before high water, and disappearing at 3 to  $3\frac{1}{2}$  hours after the ebb had begun. Moreover, as the tide rose, the surface of the sand inside the barrier for a distance of about 150 feet from it became damp and assumed an appearance of sweating; while as the tide neared its full height, small bubbles appeared, forming small craters in which the sand was kept moving by the water. The force of the water, however, was not sufficient to carry the sand away; nor did there appear at any time to be any material being borne by these bubbles, or by the runnels already mentioned. The sweating usually began about 45 minutes earlier than the runnels, and continued considerably longer. It is a curious fact that these manifestations always began and ended at practically the same length of time before and after high water, although the head of water outside the barrier at such times varied considerably with the state of the tide as regards springs and neaps. At spring-tides, however, the runnels and bubbles were more active and the sweating extended over a wider area.

These indications appeared over a length of about 1,000 feet, behind that portion of the Barrier where the cut-off was formed by 34-foot 6-inch steel piling at the west end of the work, and consequently where the ground was known to be most unreliable; and it was believed that the weight of water outside the Barrier caused the moisture with which the sand was charged to be forced under the steel piling and to the surface inside. In order to check this action it was decided to apply a plaster of clay over the spot, making the weight of this sufficient to counterbalance the pressure on the sea side of the embankment. A patch of clay was accordingly deposited, covering with a good margin that part of the ground where the dampness and sweating had been observed. The depth of water at high water of spring-tides outside the Barrier at this part is 15 feet 6 inches, and at the highest recorded tide it would be 20 feet. The height of the clay filling was therefore made 10 feet 6 inches against the side of the inner stone bank, and a gradient of 1 in 60 was given to the surface, giving an average height of 9 feet. The weight of the clay being 125 lbs. per cubic foot, this gave a weight of 1,312 lbs. per square foot on the ground at the foot of the embankment, or an average weight, over the whole area covered, of 1,125 lbs. per square foot, the pressure of the water outside being 1,280 lbs. at the highest recorded tide and 992 lbs. per square foot at



high water of ordinary spring-tides. The surface of the clay was covered with a coating of slag in a similar manner to the main bank. Since this clay patch was deposited no indication of sweating beyond its boundaries has been observed, and only a very small quantity of water has been seen to issue from the stone bank at a point a short distance below the end of the patch.

In order to prevent the ground immediately in front of the culverts from being scoured away by the necessary periodical openings of the sluices a small apron of mine-debris has been deposited there.

*Lighthouse, etc.*—The Barrier has been completed by the erection upon it of a lighthouse and fog-signalling apparatus. A single line of railway running the whole length of the Barrier will remain permanently thereon.

Particulars of the quantities, plant employed, etc., are given in the Appendix.

The first sod was turned by Mr. H. Arnold, Chairman of the Hodbarrow Mining Company, Limited, on the 27th April, 1900; the sea was excluded from the area by the closing of the dam on the 20th July, 1904; and practical completion of the Barrier as an efficient sea-defence occurred on the 1st October, 1904.

The Engineers for the work were Messrs. Coode, Son and Matthews, M.M. Inst. C.E. The Author acted as Resident Engineer during the construction, having as his principal assistants, Messrs. H. C. Lobnitz, Assoc. M. Inst. C.E., H. G. Mitchell, and A. D. Keigwin, Assoc. M. Inst. C.E.; the two former in succession and the latter during the whole period of construction.

The Contractors, Messrs. John Aird & Co., were represented by Mr. Wm. Liddle, M. Inst. C.E., as chief agent, who had Mr. B. G. Lloyd, Assoc. M. Inst. C.E., as his chief assistant during most of the period, and as engineering assistant, Mr. T. Partington, Assoc. M. Inst. C.E.

The Author desires to express his thanks to Messrs. Coode, Son and Matthews for their kind permission to make use of drawings and other papers in connection with the work; to Mr. Cedric Vaughan, Managing Director of the Hodbarrow Mining Company, who furnished the information relative to the mines which forms the introductory portion of this Paper; and to Messrs. John Aird & Co., whose representatives kindly supplied him with many valuable particulars.

The Paper is accompanied by eight drawings and three tracings, from which Plates 4 and 5 and the Figures in the text have been prepared; also by sixteen photographs.

[APPENDIX.

## APPENDIX.

### MAIN DIMENSIONS OF THE BARRIER.

Length . . . . .	1 mile 530 yards.
Extreme height . . . . .	40 feet.
Extreme width at base . . . . .	210 feet.
Extreme width at top . . . . .	{ 83 feet (including protective coating).
Area reclaimed . . . . .	170 acres.

### QUANTITIES OF PRINCIPAL MATERIALS USED.

Limestone . . . . .	621,000 cubic yards
Slag . . . . .	34,000 „ „
Clay . . . . .	543,000 „ „
Concrete . . . . .	80,000 „ „
Steel piling . . . . .	4,416 tons.
Pitch-pine piling, etc. . . . .	39,000 cubic feet.
Pitch-pine in dam . . . . .	60,000 „ „

### EXPLOSIVES USED IN QUARRYING STONE.

Gelignite . . . . .	58,200 lbs.
Powder . . . . .	588,000 „
Fuse . . . . .	39,100 coils.

### PRINCIPAL PLANT EMPLOYED.

13 locomotives.	30 piling-engines.
3 steam-navvies.	8 steam-pumps.
3 25-ton goliath cranes.	2 pug-mills.
2 12-ton locomotive steam-cranes.	31 vertical boilers.
4 6-ton „ „ „	25 steam-winchcs.
2 4-ton „ „ „	12 rock-drilling machines
3 3-ton „ „ „	363 tipping-wagons.
4 portable engines.	87 ballast-trucks.
2 concrete-mixers.	24 block-trolleys.

Number of men employed during greater portion of period of construction, 1,200.

Fig. 1.

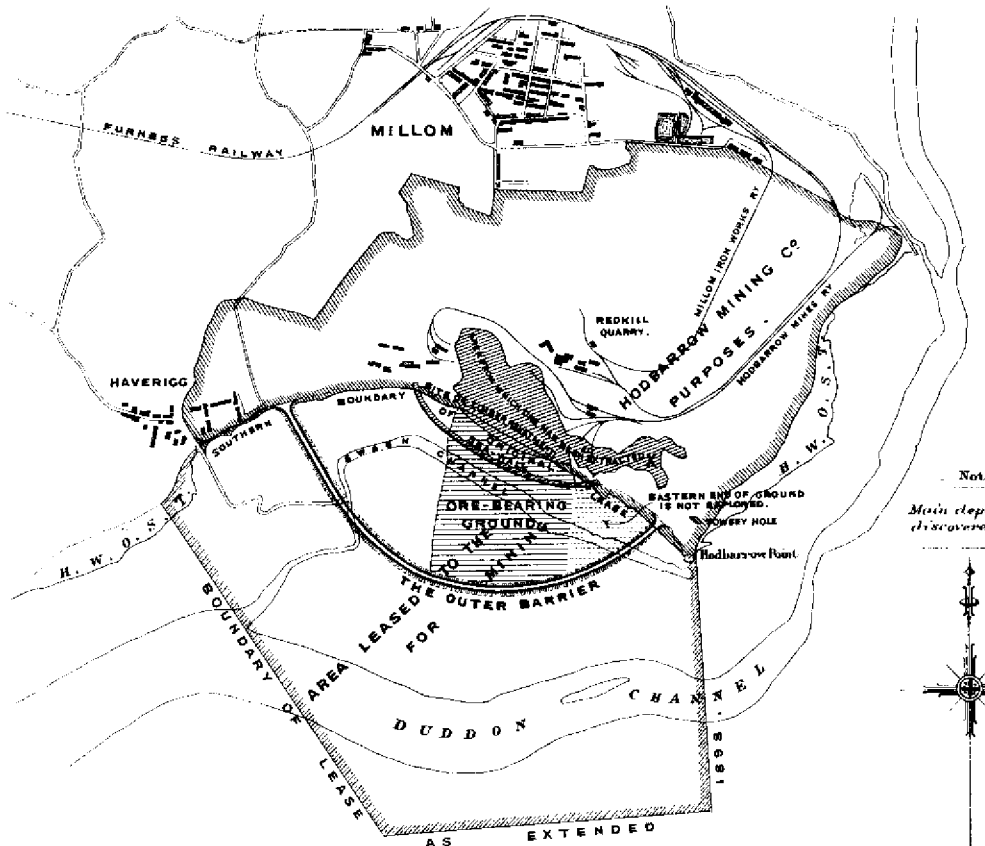


Fig. 3.

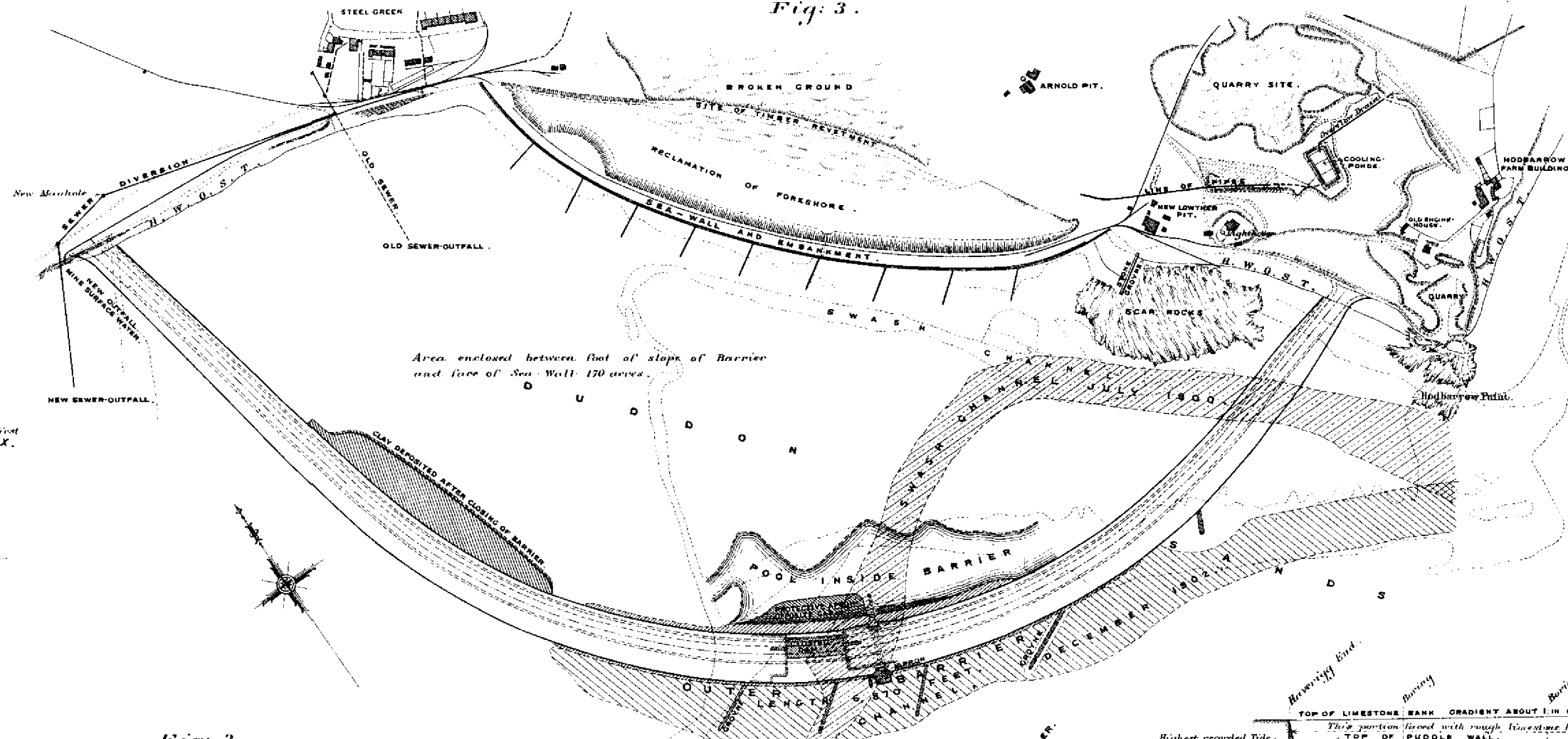


Fig. 2.

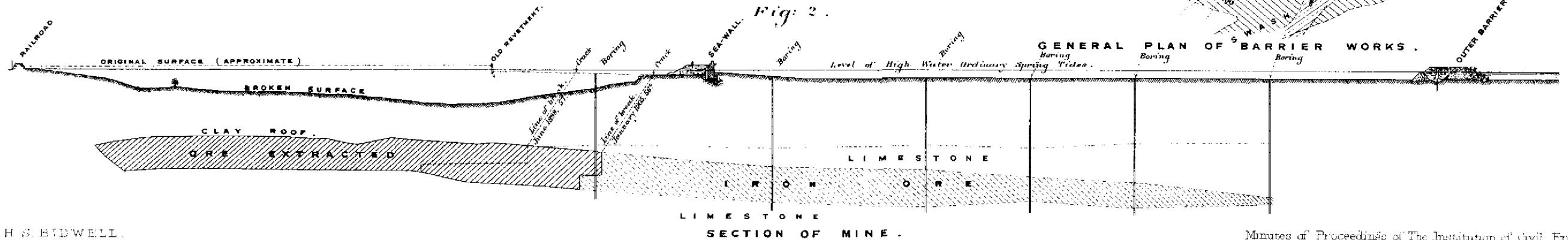


Fig. 5.

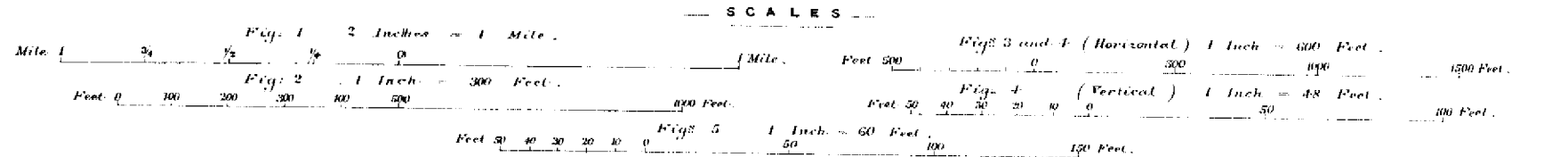
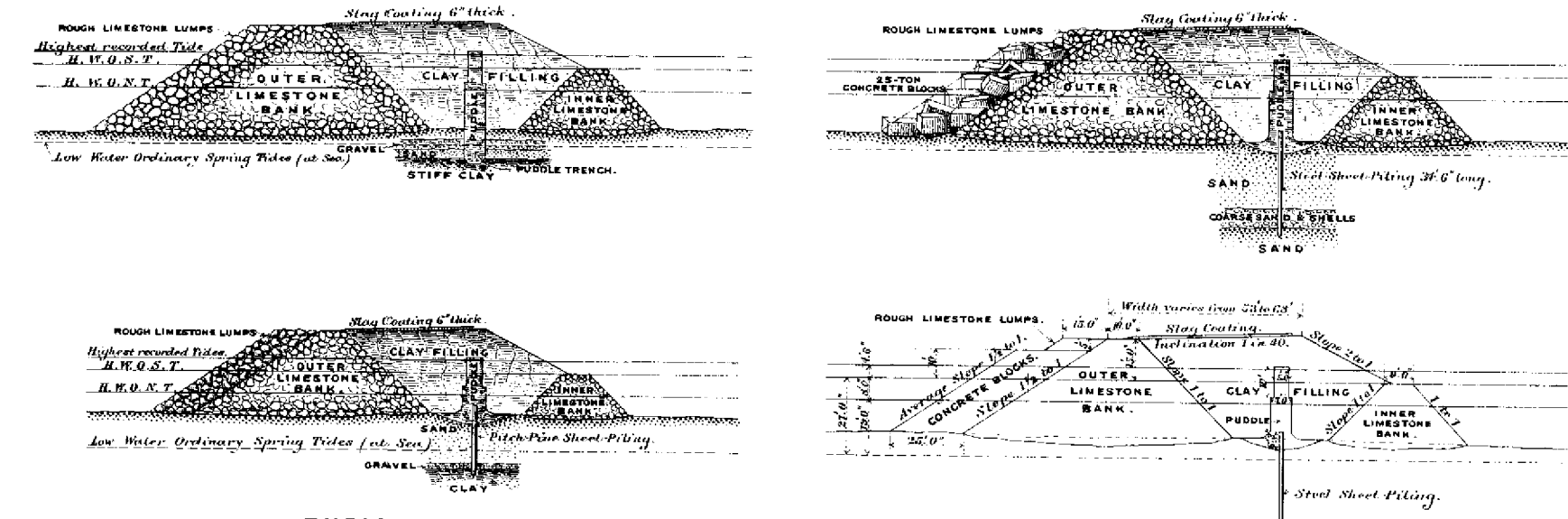


Fig. 4.

