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SECT. I.—MINUTES OF PROCEEDINGS.

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November 9, 1875.

THOS. E. HARRISON, President,  
in the Chair.

No. 1,447.—“The Manora Breakwater, Kurrachee.” By WILLIAM  
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1. SKETCH OF KURRACHEE HARBOUR WORKS. (Plate 1.)

THE harbour of Kurrachee is situated on the north border of the Arabian Sea, 51 miles west of the principal mouth of the river Indus. It is the natural port of Sind and of the Punjab, bearing much the same relation to those provinces and to the Indus that Alexandria does to Egypt and the Nile, and is 500 miles from the nearest port on either side. The sea-bottom off Kurrachee shelves rapidly, not being sensibly affected by deposit from the Indus, the drift of which, under the action of the prevailing winds, is in the opposite direction, towards the Gulf of Cutch. Kurrachee harbour is essentially a backwater, as the only river opening into it—the Layari—never flows for more than a few days in each year. The area of the backwater at high tide is 18 square miles, a portion of which, however, is not freely open to the tidal flow. The range of tide is  $7\frac{1}{2}$  feet at mean springs; at extraordinary springs it is sometimes 12 feet.

Manora Point is a headland 90 feet high above mean sea-level; it consists of a capping of conglomerate, resting on clay. The clay has been undermined by the sea, and the rock has in the lapse of ages fallen in great masses, which, for about 700 feet from the shore, in a depth of water of from 10 to 25 feet, crop up thickly from the sandy bottom in irregular forms. For the remainder of the length of the breakwater, in a depth of water of 4 or 5 fathoms, a few boulders

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rise here and there above the sand. Clay occurs at a depth of from 8 to 14 feet below the surface of the sand.

Up to about twenty years ago, the difficulties of the bar rendered the harbour unfit for any except native craft; and though some improvements were effected, the general question was left in abeyance until 1856, when, at the instigation of Mr. (now the Right Honourable Sir) Bartle Frere, then Commissioner in Sind, a reference was made to the late Mr. James Walker, Past-President Inst. C.E., who sketched out the main features of his final plan, and in 1858, aided by Mr. William Parkes, M. Inst. C.E., prepared a design for the deepening of the bar and the general improvement of the harbour, indicating also the sites for docks, basins, and quays. Sanction was, in the first instance, confined to works bearing on scour; but this postponement of the breakwater directly checked the full benefit from the other works, and was indirectly injurious, giving a temporary apparent support to objections raised during their progress, which caused great delay.

The works were commenced in 1860, and were carried on up to 1874 under the superintendence of the Author, excepting for two years, 1864-5, during which Lieutenant (now Major) Merewether, R.E., Assoc. Inst. C.E., held charge. Up to 1865 the general control was in the hands of the superior officers of the Public Works Department. From 1866 to 1868, the undertaking was suspended, though the staff continued surveys and observations; the works were resumed in 1869, and from 1868 to 1873, Mr. Parkes was the Consulting Engineer, the conduct of operations still remaining, however, in the Public Works Department.

The chief works besides the breakwater are: a stone groyne 8,900 feet in length along the east side of the lower harbour; dredging on the bar to assist the tidal scour; the excavation of a rocky obstruction (Deep Water Point) on the west side of the lower harbour; the formation of a channel  $2\frac{1}{2}$  miles long through the upper harbour, for the passage of native craft and lighters, and for the collection of tidal waters; a jetty 1,400 feet in length, faced with masonry wharf walls, to which access is afforded by the channel just mentioned; an iron screw-pile bridge 1,200 feet long, over an opening in the Napier Mole, to tap the east backwater; and an embankment 2,780 feet long, to close the "Chinna Creek," a secondary entrance to the harbour. Of the works, the breakwater is the only one of which the construction would seem to present special interest as viewed from the standpoint of European practice.

The immediate results, so far, may be briefly summarised as follows:—A new direct entrance channel, 6 feet deeper than the old circuitous one, has been formed to a depth of 20 feet at low water. This, with the breakwater, trebles the former capabilities of the entrance during the south-west monsoon season, and doubles them in the fair season; renders the harbour accessible to vessels of the largest class; greatly saves the use of steam-tugs, and allows of the regular arrival and departure of the mail steamers. The breakwater, also, enables native craft to use the port at all seasons.

The capacity of the harbour anchorage has been increased nearly threefold for vessels of moderate size; and though limited for very large vessels, capabilities exist for its extension by dredging at a moderate cost. In the upper harbour, the lighters and native sea-going craft have been much benefited by the jetty, and the formation of a channel leading to it by the scour of the diverted Chinna Creek waters. Eastward above the jetty, the channel, 1 mile in length, will serve for the extension of wharfrage, for tapping the east backwater, and for maintaining deep water alongside the jetty.

The breakwater forming the special subject of this communication cost rather less than £100,000, but a gross sum of about £450,000 has been expended on the improvements, the value of which will be still more felt when through railway communication with the Punjab and the North-Western Provinces is completed. As it is, the trade which in 1843, when Sind came under British rule, was of an annual value of £116,052, is now worth about £3,500,000 per annum.

## 2. DESIGN OF THE BREAKWATER.

The breakwater extends from Manora Point, on the west side of the entrance of Kurrachee Harbour, in a south by east  $\frac{1}{4}$  east direction, for a length of 1,503 feet, terminating in a depth of 5 fathoms at low water. Its object was, mainly, to shelter the entrance from the violent and dangerous seas of the south-west monsoon, and at the same time to break them so as to prevent their tearing up sand from the bottom to deposit it as a bar.

The characteristics of the locality, as to sea and weather, which influenced the design, may be briefly described as follows:—Storms are unknown at Kurrachee<sup>1</sup>, which is north of the limit

<sup>1</sup> The greatest velocity of wind at Manora, since 1870, was 62 miles an hour, in a squall from N.N.E., lasting one hour, on the 26th of September, 1872. It was of exceptional violence for Kurrachee.

of cyclones; but the south-west monsoon brings a very heavy sea, lasting with full force for about three months, from the middle of June to the middle of September. During this period rain only falls for a few days. From the middle of October to the middle of February strong easterly winds blow occasionally, but do not bring a heavy sea. The intervals between the south-west monsoon and the fair season proper are subject to occasional strong breezes and squalls, raising a sea which is sufficient to interrupt the progress of sea works, though not formidable as regards navigation. The wind during the south-west monsoon is not usually more than a strong breeze;<sup>1</sup> but at that season the local wind has little influence on the force of the sea, which has a fetch of 500 miles; a depth of 100 fathoms is found within 77 miles of the harbour. At this time the waves in the deep water at the head of the breakwater vary from 3 to 15 feet in height from hollow to crest, and from 300 to 600 feet apart, moving at the rate of about 15 to 30 nautical miles per hour. Of the high waves, about three-fourths of the elevation is above, and the remainder below, the mean sea-level at the time. Though called the south-west monsoon, the wind is generally west; but the run of the wave is more southerly than the wind, being usually from south-west by west, so that it meets the breakwater at an angle of 70°. These relative directions of the waves and the breakwater have an important bearing on the stability of the work.

As regards tidal currents, the consideration chiefly affecting the design was the desirability of limiting the length, to avoid, as far as practicable, diverting the flood tide, which makes from the westward, to a more circuitous course in entering the harbour. The strength of tide was not such as materially to affect the work of construction, the flood setting across at the rate of 2 miles an hour at springs; while the ebb, being parallel to the breakwater, was scarcely felt.

### 3. GENERAL CONSTRUCTION. (Plates 2, 3, 4.)

The mode of construction adopted is believed to be novel, at least, as a whole. The base is a bank of rubble stone thrown in upon the natural bottom, chiefly from boats by hand, and levelled off, for the most part, to 15 feet below low water, but near the shore, where the original depth is less than this, to 10 feet. Upon this base a superstructure is raised, consisting, with the exception of some

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<sup>1</sup> Unusual weather occurred at the end of July 1874, in the middle of the south-west monsoon, the particulars of which are given at page 15.

smaller blocks used in special positions near the shore, of concrete blocks, each 12 feet by 8 feet by  $4\frac{1}{2}$  feet, of 27 tons weight, set on edge without bond; so that an end view presents six blocks, two forming the width, and three the height. This makes a solid vertical wall, of which the width and depth are alike 24 feet. The blocks were laid with an inclination towards the shore of 3 inches to 1 foot to insure the stability of the end during the progress of the work. This plan enabled each block to fall into place easily, and helped to obviate distortion from slight errors or subsidence of the foundation. The inclination also secured the upper blocks against displacement by lifting, and proved of great service by causing the tiers to tighten together under the action of the sea. The bottom of the lowest course of blocks was shaped so as to set level on the rubble base. For 108 feet from the shore the breakwater is levelled off on the top with concrete to 4 feet above high water of spring tides, to which latter level it was gradually dropped in the next 468 feet, and so continued to the end; but it has since settled, more or less, in the middle and outer portions as much as 3 feet. Between 108 and 1,180 feet from the shore the heads of the top blocks were left square, so as to form a jagged top, which, it was thought, would afford a better bond for a concrete capping if required. For the outer 323 feet, however, as the top did not then seem likely to require raising, the heads of the upper blocks were made oblique, so as to finish with a level top. In the work executed after the first season, from 270 feet outwards, a stone dowel was inserted between the heel of the top course block and the head of that below. This forms the only connection between the blocks, excepting that a few of the top course near the shore were reset in cement mortar, and a few at the outer end were lately connected by chain ties when refixing the iron beacon, which has been erected on the end as a warning to native craft at high water; the guidance of pilots and the light on Manora Point serving for larger shipping.

#### 4. RUBBLE BASE WORK.

The rubble base was formed so as to give at the foundation level a width of about 100 feet, two-thirds on the sea, and one-third on the harbour side of the centre line. The outer end was extended 60 feet beyond the superstructure, and fanned towards the harbour, to guard against flood-tide scour. At first the rubble, to about one-half the length, was deposited in a ridge up to low water, in the belief that the sea during the next monsoon would lower it to

about 12 feet. It was not, however, lowered more than from 7 to 9 feet; but, to provide against greater effect in deeper water or on more obstruction, the foundation was carried as low as the irregularities of the bottom admitted, until the full proposed depth of 15 feet at low water was reached. The clearance of the foundation for the first season's work was consequently heavy, the more so through the rubble having become clogged by sand and shell-fish; but during the second season progress was aided by using a steam dredger to excavate the high bank. Want of funds caused the deposit of the outer half-length of the base to be postponed to the season during which it was built upon, and the result was considerable settlement, though without dislocation of the superstructure. This portion was formed so as to leave only a depth of about 2 feet to be excavated by the divers; and it would, no doubt, have been throughout an advantage to have left a top-layer of 1 foot or 2 feet to be put on during the season of building, in which the foundation bed could with ease have been formed.

#### 5. DIVING WORK.

The divers were employed chiefly in levelling the foundation bed; they also saw to the proper setting of the blocks below water, and disengaged the lewises. They used Siebe's helmet-dress apparatus, and worked from a boat ahead of the superstructure.

Two European mason divers were employed during the first two seasons, but during the last season only one. These were aided by native divers trained on the work, of whom six were employed when it was in regular progress. The party was divided into three shifts of three hours, each consisting of one European and two native divers, excepting in the last season, when one of the shifts was worked by natives only, at excavating the rubble. When there were two Europeans, each made by turns two shifts one day and one the next; but during the last season the one European diver made two shifts daily—no small effort in an Indian climate. The natives, as a rule, worked only one shift each daily. When not diving, the Europeans were generally employed in repairing the dresses, which required much attention.

The divers excavated the rubble generally about 2 feet, though for the first season their work was exceptionally heavy. For shifting the rubble, iron basket skips were worked by hand crabs from outriggers on the outer end of the Titan, and when filled by the divers, were hoisted and discharged alongside the superstructure, chiefly on the harbour side. When blocks were being set the divers were always withdrawn in their boat out of danger.

from accident in the lowering. The diving work was throughout free from accident, though the Europeans had no easy task in working with and watching the untrained natives. Excepting the sickness latterly of one of the Europeans, which was not ascribable to the nature of his work, the divers enjoyed good health. The diving party was throughout rather weak in number of skilled men, dependence on local resources having been urged too far, though, fortunately, the strain did not seriously tell upon the work.

#### 6. CONCRETE BLOCK-MAKING.

The practicability of obtaining hard stone of sufficient size for the more exposed portions of the superstructure was considered, but after an extended search by Lieut. Merewether, R.E., it was decided to use concrete blocks throughout. The question then arose as to the comparative merits of artificial hydraulic lime made on the spot, and Portland cement imported from England. After careful experiments by the above-named officer, this was settled in favour of the cement, on duly balancing strength and cost; though at a distance from the seaboard, or with cheaper materials for the lime, the latter would have had the advantage. The composition for one block of 16 cubic yards, weighing 27 tons, was for the most part as follows:—

	Cubic feet.
Portland cement, <sup>1</sup> 9½ casks, of which the weight (at Kurrachee) was 3,729 lbs., and the bulk . . . . .	44
Sand (gravelly), from the bed of the Layari . . . . .	180
Shingle, from the Manora conglomerate quarry . . . . .	252
Quarry lumps from the same, 14 to 28 lbs. each . . . . .	144

The ratio of the bulk of the cement as it left England to that of the finished block was about  $\frac{1}{11}$ , and that of the bulk of the same cement in India about  $\frac{1}{10}$ , the difference arising from absorption of moisture in transit and in storage.

Salt water was used for the mixing, ordinarily 432 gallons to each block, but increased in hot and dry weather by about 10 per cent.

In the earlier blocks (about one-fifth of the whole) 50 per cent. more cement was used. The reduction is believed to have been carried to the utmost extent consistent with the soundness of the blocks, which was aided by the excellence of the sand (a mixture of various sizes), by the 'key' of the conglomerate lumps, and by the large shingle being rough in parts with natural cement.

<sup>1</sup> This refers to the heavy cement, which weighed in England 118 to 120 lbs. to the bushel, and which is taken as the standard. The proportion of cement was regulated by weight, after having been fixed in relation to bulk.

The cement was supplied by Messrs. Knight, Bevan and Sturge, the Wouldham Company, and Messrs. J. B. White and Brothers. The heaviest (as shipped) was 118 to 120 lbs. to the bushel, and the lightest 104 to 108 lbs. The weights used of each per block were the same, and the cost thus varied but slightly. All three made excellent work, the lighter cement having somewhat the advantage in quick setting, but the heavier, after a time, in hardness. Ordinary fir casks were employed for packing, and the percentage of damage and loss on the voyage and in keeping in India was insignificant. About 3,500 tons of cement were used in the breakwater, at a cost of from £3 17s. 6d. to £4 10s. per ton in 1870-71; the variation of cost was chiefly in rates of freight. The cements all increased slightly in weight and bulk (mostly in the latter) on the voyage and in keeping in India, owing, no doubt, to the absorption of moisture. The lightest cement increased most in weight and the heaviest in bulk, so that the specific gravities were from  $1\frac{1}{2}$  to  $9\frac{3}{4}$  per cent. less than at shipment. The seasoning thus indicated was probably beneficial—by slaking minute particles of quicklime—though making the cements rather slower in setting.

The mixing-station and block-ground (the latter reclaimed from the sea) were on the inner side of Manora Point,  $\frac{1}{2}$  mile from the breakwater. Four 'Messent' mixers were erected against the berm of the cliff; they were worked by an 8-HP. engine, and were very efficient. It was seldom necessary to use more than three, which number sufficed to make  $1\frac{1}{2}$  block per hour. The mixers and engine, as well as the other special plant, were supplied by Messrs. Stothert and Pitt, of Bath. The cement, sand, and shingle were brought along the upper railway line in wagons, and, having been measured on the platform, were shovelled into the mixer hoppers. From the mixers the concrete was discharged into wooden skips, each holding  $\frac{1}{2}$  cubic yard. The skips were conveyed on trucks to the block-ground, and were tilted into the moulds by hand travellers, of which four ran on the Goliath rails, the quarry lumps being at the same time incorporated. The blocks were moulded on a platform of concrete and rubble masonry adapted to the slope in which they were to be set, and to the lift of the Goliath. They were ranged in six rows, three on each side of the main railway line, and leaning towards the latter, for economy of space. The platform was 1,200 feet in length, and held five hundred blocks. The blocks were chamfered 3 inches all round, and panelled 13 inches wide and  $\frac{3}{4}$  inch deep along the front and back edges at the top and bottom (except the bottom of the lowest course) so as to facilitate



close setting. The moulds were of 3-inch pine planking, tied with iron straps, and with five bolts (slightly tapered) running through. These bolts were drawn out six hours after the block was made, and the moulds were removed after eighteen hours. The two oblong holes for the lewises were formed by moulds of cast iron or wood, and were recessed at the bottom by inverted wooden cups slotted so as to admit the lewis head. The lewis moulds were lifted a little and dropped again into their places, after four hours, and were finally removed after twelve hours. The blocks were watered for a week after being made, so as to keep them moist for equal and proper setting under the Indian sun. The quality of the blocks proved in every way satisfactory under severe tests; they were sometimes set in one month after being made, and on one occasion within ten days; a block was safely lifted as an experiment seven days after being made. The period of one month, or even somewhat less, might usually have sufficed for the two lower courses, though with a liability to flushing in transit, but not for the upper blocks, which had to bear the weight of the Titan near their ends; and, in fact, a few of the blocks, six weeks to two months old, cracked from this cause during the last season's setting. The number of blocks made was one thousand six hundred and forty-seven of 16 cubic yards or 27 tons each, two hundred and eighteen of sizes varying from 15 to 10 cubic yards each, and one hundred and seven of 2 cubic yards each.

#### 7. BLOCK-SETTING. (Plate 3.)

The attachment for lifting the blocks was by two lewises 6 feet apart, passing vertically through, and catching by their 1 ends, after a quarter turn, in the wooden cup recesses. The blocks were lifted by the 'Goliath,' a steam hydraulic travelling crane, the span of which was 50 feet, the traverse of the crab 40 feet, and the lift 3 feet 2 inches. The power was supplied by an 8-HP. engine. The trucks, ten in number, carried each one block, standing on edge at its proper slope, but in length parallel to the railway, which was of the  $5\frac{1}{2}$ -feet gauge. The loaded trucks were taken separately by a tank locomotive to the breakwater. The blocks were set by a crane called the 'Titan' (Plate 3), devised in consultation between Mr. Parkes and the Author, and made by Messrs. Stothert and Pitt, of Bath. The Titan overhung the end so as to carry the blocks of three tiers in advance to their places; it was capable of carrying a weight of 27 tons  $26\frac{1}{2}$  feet longitudinally, and 12 feet transversely, and of lowering

and raising it vertically within the limits of the chain. Of the longitudinal travel a length of 22 feet was in advance of the side frames. The whole machine, when not loaded, could also move forward or backward. On the top was a traveller and crab to handle the blocks, all the motions being controlled by one man.

To assist in balancing, when a block was run far out, the Titan was tied down by chains and union-screws to lewises, let into the blocks already set; and the side frames were also blocked up in front. On the top, near the tail-end, stood an 8-HP. single-cylinder engine which drove a horizontal shaft above the platform. This shaft revolved constantly in one direction; all the motions of the traveller and crab were transmitted by bevil-gearing and friction cones, regulated by three levers and a hand-wheel. The Titan was moved by the same engine, but independently of the main shaft.

The method of setting was as follows:—

If a bottom block, on the diver reporting the bed ready, the block, having been slung and lifted from the truck, was let down into the water; the crab was then run out, the block lowered to within 1 foot of its bed, a short distance ahead, and then run back so as to bear hard against the one behind, which steadied and guided it while being finally lowered. The blocks of the second and third courses were also guided into their place by the tier behind. In this way the actual placing required no aid from the divers; but in the case of the blocks under water they reported as to the true setting, and then released the lewises.

For slinging, slewing, and steadying the blocks, laying and shifting the roads, and shunting empty trucks, three masons and twelve labourers were required on the breakwater, and one European engineer and two native firemen on the Titan, all directed by the foreman of masonwork.

During the last working season of ninety-two days, nine hundred and ten blocks were set, containing 14,560 cubic yards, and making a length of 710 feet of breakwater. On some days eighteen blocks, and on one occasion six in an hour and forty minutes were set without special exertion; though such a rate could only be maintained with a calm sea and not too high a tide. The progress of setting was generally limited by the preparation of the foundation and by the supply of blocks.

#### 8. PROGRESS IN EXECUTION.

The rubble base was commenced on the 17th of March, 1869.

At the close of the monsoon of the same year a recess was cut in the rock and clay of the cliff to a depth sufficient to 'stable' the Titan; and thence, projecting to 45 feet beyond low-water mark, was formed a 'stump' of concrete blocks moulded *in situ*, on rubble brought up to low water. Plaster of the local gypsum ("cheroli") proved very useful in protecting fresh concrete or masonry from the wash of the sea. The spaces between the blocks were filled in with rubble, and the top capped with concrete to 4 feet above high-water level.

The works generally suffered from suspension under "deficit" orders in 1869-70; but the arrangements were advanced so as to admit of the block-making being commenced in August 1870. On the 1st of November following, the first 27-ton block was deposited by the Titan. Setting then went on steadily—though retarded by the irregular bottom and by the weakness of the diving party—until the middle of February, when interruptions were caused by the sea, which once swept the breakwater clear of all the roads except the length on which the Titan stood. The roads were quickly replaced without loss of material,<sup>1</sup> so that setting was resumed after two days; but was closed for the season on the 4th of March, 1871. The length built during the season was 225 feet, reaching to 270 feet from the shore, with a 'scar' stepping 20 feet farther. Two hundred and seventy-nine large blocks, and sixty smaller blocks used in the stepping down, were set; but, owing to delays of the foundation, the Titan was not worked to its full powers, eleven blocks having been the greatest number deposited in one day during the season.

The second season's building ahead was commenced on the 28th of October, 1871. After a few more boulders had been passed, the foundation was stepped down to the full depth of 15 feet below low water, and the top was lowered to the same extent. Setting was closed (no more blocks being then available owing to want of funds) on the 23rd of February, 1872. A length of 523 feet, besides the usual 'scar,' had been built in less than four months, and the work was now extended to 793 feet from the shore. The great advance on the rate of the previous season was due mainly to improved progress of the foundation work.

On the opening of the third season, the repair of damage incurred during the monsoon and the preparation of the centre road having occupied the month of October, block-setting was resumed on the

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<sup>1</sup> In after seasons the railway line along the centre of the breakwater was built in with rubble and concrete, for security during the working season.

1st of November, 1872, and was completed on the 22nd of February, 1873, to the full length of 1,503 feet. The wall had thus been two years and four months under construction, of which rather less than twelve months were actually occupied in setting. The length built during the third season was 710 feet; but this was not the full measure of the powers of the Titan, which were still limited by the progress of the foundation and by the supply of blocks. The end was finished with a 'scar' stepping out 20 feet.

During the working season of 1873-4, the monsoon damage of 1873 was repaired, and a landing-slip for boats was built in the east shore angle. On the 17th of January, 1874, the completion of the breakwater was formally marked by fixing an inscribed "memorial block" in the 'Titan' stable.'

#### 9. ACTION OF SEA, DAMAGE, AND REPAIRS.

The characteristic action of the high monsoon waves as they dash over the breakwater is shown in Plate 2. Near the shore the wave is crested with spray, mounting at high water to 35 feet above the superstructure, or nearly 40 feet above the sea-level; while near the outer end the wave rises about one-half as high, but in an almost unbroken mass, until it plunges into the water on the other side. At low water the wave rises to nearly 30 feet above the sea-level throughout, but is greatly broken into spray near the shore, and, near the outer end, is higher though lighter in mass than at high water. At low water, as each wave meets the breakwater obliquely, a marked undulation is reflected to seaward in a corresponding angle, and causes the incoming wave sometimes to break heavily before it reaches the wall. This action takes place in a minor degree at high water. The lap round the extremity forms a secondary wave, which, running up along the harbour side, is gradually reduced (partly by the plunge of the seaward portion), and finally spends itself in the east shore angle. In illustration of the limit of disturbance inside, it may be mentioned that, during the height of the south-west monsoon, open boats have safely approached within 100 feet of the breakwater, up to about 200 feet from the outer end.

The effects of wave-action on the work, and the measures taken to repair the damage, will now be described. (Plate 2.) Shortly after the monsoon of 1871 burst, the centre joint began to open over places where boulders had been met with in the foundation, and by degrees the seaward row beyond 100 feet from the shore overhung more or less, especially at 206 feet, where the

top course projected  $2\frac{1}{4}$  feet. The harbour-side row settled more uniformly; but the sea displaced several blocks of the top course—a few of these being at places where the courses below showed little or no settlement. After the monsoon a curious effect was noticed, in the lateral rocking (apparently of the seaward row) of the breakwater near the outer end, under the influence of a moderate swell. The motion, which was at most  $\frac{1}{4}$  inch, and extended from about 100 feet from the shore to the end of the completed breakwater, even over the deep rubble base, would seem ascribable to the action of the wave on the elasticity of the two separate walls forming the breakwater. Slight wear from this action was apparent along the centre joint, but has not since appreciably increased. No grinding of the cross-joints was apparent; on the contrary, the tiers had been packed closer, the sea having, by its oblique stroke, acted especially on the seaward row of blocks, which at the outer end had receded at the top 10 inches behind those of the harbour side, the difference gradually lessening until it disappeared at about 100 feet from the shore.<sup>1</sup>

With one exception none of the Titan-set blocks were completely displaced, but some slight damage occurred to the shore end in the west angle, where the action of the sea was especially violent. The sea drew down the foreshore rubble, as well as three 17-ton concrete blocks which had been tipped on it, and upset one block from position, behind which, however, the concrete capping fell so as to prevent the breach from extending more than halfway across. Out of the 3,000 tons of rubble proposed for this angle, only 500 tons had been put in; but the quantity was made up during the following season at a reduced rate, the saving by which, as well as by other previous changes, more than covered the cost of repairing the damage. The small rubble of the base, which was originally heaped up about 5 feet along each side, was washed down on the sea side, after the first 120 feet, to about 10 feet below low water, or nearly to the foundation level, but was little altered along the harbour side.

On the opening of the season of 1871–2, fourteen of the displaced top blocks on the sea side were reset by the Titan, after the course below had been dressed level transversely. The fallen block of the harbour-side row was replaced by another, and the four blocks ahead of it reset. In other places the centre joint, where unduly open, was filled with concrete. At the close of the season, the gap

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<sup>1</sup> In the second and third seasons' work, the difference at the outer end was respectively 6 and 8 inches.

near the shore was built up with small blocks and rubble masonry.

Shortly after the monsoon of 1872 burst, the breakwater being then 793 feet in length, eighteen blocks were washed out from the harbour-side top course in one length of 86 feet, extending from 579 feet to 665 feet from the shore (Plate 2), and the course below partially shifted. At the same place the two upper courses of the seaward row were driven inwards to a curve of 1 foot offset. Seven single blocks also were washed out, three from the first, and four from the second season's work, all from the top course on the harbour side, the next front block in most cases falling back aslant into the vacant place. The shore end only suffered from some battering by the smaller foreshore rubble. It was accordingly determined to deposit about 1,000 tons of conglomerate lumps of 2 tons to 4 tons in weight. Seven 20-ton blocks had been placed, four in a row, on the sea edge of the superstructure to shelter the Titan 'stable'; of these four were upset, and three 'skidded' some feet by the stroke of the sea. On the moving out of the Titan for the working season of 1872-3, the large breach was repaired in seven days by dressing off the partially-shifted second course to low water, packing the space in the centre with large rubble, on the bed thus formed setting a course of fifteen blocks (oblique pattern) and closing the end with rubble and concrete. The single gaps were repaired with rubble and concrete. After the building ahead was completed, twelve blocks of the harbour-side top course, about 200 feet from the shore, were lifted and reset in cement mortar. This experiment seems to have answered well, though only applicable where the work is dry at low water.

During the monsoon of 1873, the first after the completion of the breakwater, damage occurred in four places, all to the harbour-side top course. In two cases a single block was washed out, in one a mass of concrete occupying the space of two blocks, and in one a mass occupying the space of three blocks. In every instance the site of the damage was either identical with, or close to, that of similar damage in previous seasons. This seems clearly to point to weakness of foundation; while in the third season's work on the deep rubble base, where settlement was regular, the centre joint generally became closer during the monsoon. In the working season of 1873-4 these damages were repaired by filling in the gaps with rubble masonry and concrete.

In the monsoon of 1874, the outer end, which had stood the previous monsoon uninjured, lost five blocks, of which two were

from the harbour and one from the sea side of the top course, and two of the second course, forming the upper step of the 'scar.' This occurred at the end of July, the wind having veered to a gale from the south-east, which, on the morning of the 28th of July, reached a maximum velocity of 46 miles an hour. This brought up a very heavy sea from an unusual quarter, against which no special protection had up to that time been given. Excepting the end, the outer half-length suffered no displacement whatever, its settlement having been moderate and regular; but in the shoreward half there was some irregular settlement and further opening of the centre joint.

During the next fair season, 1874-5, one of the harbour-side blocks washed out of the top course was replaced by rubble built *in situ*, so as to square the end; but the others were not replaced. As an aid to secure the end against similar displacement, the six outer tiers of the top course were tied together by chains arranged diagonally and bolted down to each block. Twenty-one of the seaward top-course blocks, where the greatest settlement had occurred, about 300 feet from the shore, were lifted by the Titan and reset in cement mortar, so as to close the centre joint of the top course and correct the overhang to seaward. To effect this operation one block was blown out by powder, so as to release the others, and was replaced by a mass of concrete. The repairs of the season cost £418, and included the re-erection of the iron beacon, which had been carried away with the blocks from the end.

The nature and extent of the settlement during the four monsoons are shown by Plate 4. The settlement may be ascribed partly to the compression of the rubble base, but more to its sinking into the sand below, under the action of the sea; while the irregularity in some parts was caused by boulders in the foundation.

The blocks of the superstructure have not crumbled under the action of the sea or weather, and except at the shore angle, where somewhat battered at first by the small foreshore rubble, they retain their sharp edges and good 'skin,' though encrusted on the top (where below high-water level) with barnacles, and on the sides with limpets. The faces have, however, begun to show signs of the attacks of the "pholas," which burrows to a depth of about  $2\frac{1}{2}$  inches. It is found more on the harbour than on the sea side, and mostly on the shore half-length of the breakwater. Its penetration as yet has been only from  $\frac{1}{2}$  inch to  $1\frac{1}{2}$  inch, and in height its limit is half-tide level. The veneering of the faces with trapstone (which was at one time thought of for the sea-face, but on account

of the expense was not carried out) would, probably, have been a protection against the "pholas," which, however, does not seem likely to prove a formidable enemy to the breakwater, as it does not attack stone of the conglomerate class very freely.

The "teredo" also is found at Kurrachee, but only in wood, which it penetrates freely, especially in the direction of the grain.

Since the deposit, after the first season, of the large stone forming the 'toe,' the rubble base close to the superstructure has shown no tendency to wash down (Plate 2); its present depth below low water on the sea side varies from 6 feet near the shore to 13 feet near the outer end, and on the harbour side it is about 2 feet less. From the wall, however, the berm has been lowered to a flat slope, so that at 50 feet off on the sea side the depth declines gradually from 9 feet near the shore to 22 feet near the outer end, and at 20 feet from the harbour side, from 8 feet near the shore to 17 feet near the outer end. As the foundation is now 10 feet deep at the shore and 18 feet at the outer end, no undermining appears likely. The changes in the base took place chiefly during the first monsoon after it had been built upon, and seem mainly due to direct wave action, at low water, but partly also to compression of the rubble, and to its sinking into the sand. The flood-tide has scoured out much sand at the head of the breakwater, acting most at about 200 feet south-east of the end, where a hole 14 feet deep has been formed, down to the clay, at 42 feet below low water. The rubble apron seems, however, sufficient to guard against this action affecting the breakwater.

#### 10. RESULTS.

The shelter afforded by the breakwater has so far proved effectual in stilling the entrance channel, as to keep it free from deposit except at the inner end, where some shoaling still takes place, through causes beyond the influence of the breakwater, which are either capable of removal, or are likely to be remedied by time. The outer limit of this shelter varies somewhat with high and low water; when the waves are at the highest, say 15 feet, outside the breakwater, the wave at the outer end of the entrance channel is generally about 5 feet in height, and gradually lowers to smooth water at the inner end. The lower outside waves are reduced in about similar proportion.

The breakwater has of course deflected the flood-tide to a greater circuit; but, though it must be looked on as some disadvantage that the main streams of flood and ebb do not take the same line in



the entrance, yet no injury has been done to the flood in its principal function of filling the harbour and backwater.

As regards deposits on either side of the breakwater, no diminution of the original depth has taken place, excepting to the limited extent to be expected in the shore angles, especially on the harbour side. During the progress of the work, however, there had been some scouring away of the sandy bottom through the action of the flood-tide along the harbour side; but since the completion of the breakwater accumulation has taken place to the extent of restoring the bottom to its original level.

### 11. COST.

The total cost of the breakwater, the details of which are given in the Appendix, was £93,565, or £62 5s. per lineal foot; but the work was being advanced at the rate of £34 per lineal foot for current expenses at the time of its completion. This is exclusive of the cost of engineering and office establishments, which was borne on a general account for the whole of the harbour works, and amounted to nearly 16 per cent. on their net total, the percentage having been increased by suspensions and delays. The cost will, it is considered, compare favourably with that of similar works in Europe, when it is borne in mind that materials were 25 per cent. to 100 per cent. dearer (the latter rate especially applying to the important items of cement and timber), that plant had to be imported from England, and that European agency and workmanship cost about double English rates. Even the local labour cost as much as similar work in England; for though the wages of the native workpeople were low as compared with English rates (though high for India), their outturn of work generally bore about the same ratio. Suspension, and short supply of funds, also enhanced the cost in the earlier stages of the work. The statement of the cost includes the repairs, not only during the progress of the work, but also, as a fair charge against first cost, for the two monsoons which have elapsed since its completion. The cost of the breakwater, including percentage for engineering and office establishments, was nearly £109,000, or £1,000 less than Mr. Walker's original estimate.

### 12. AGENCY.

The breakwater works were carried out in the Bombay Public Works Department, by the Author and his assistants, advised by Mr. William Parkes, M. Inst. C.E., as Consulting Engineer. The  
[1875-76. n.s.]

works were not as a whole let on contract; but contracts were resorted to for all portions except the erection, working, and repairs of engines and machinery, and the construction and maintenance of railway lines.

After the promotion of Captain (now Major) Merewether, R.E., in October 1870, to the charge of the Bombay Defence Works, the staff on the breakwater works consisted of Mr. George William Lowe, foreman of masonwork; Mr. William Sangster, foreman engineer; Mr. Bhumaya Saenna, supervisor, and Mr. John Humby, sub-engineer. The completion of the work was favourably noticed by the Secretary of State for India, the Governments of India and of Bombay, and the Commissioner in Sind. The Author proceeded on furlough to Europe in April 1874, and Mr. J. H. E. Hart, M. Inst. C.E., now holds charge.

### 13. CONCLUDING REMARKS.

In conclusion, it is submitted that the results, as to time of execution, stability, and cost, have been such as to warrant the construction and the means adopted. The absence of bond, and the inclination of the blocks, while facilitating execution and repair, enabled the structure to accommodate itself to the action of the sea and of settlement without fracture or serious dislocation; and the Titan proved an efficient and speedy means of setting, without the expense and difficulty of staging. Excepting the outer end, which ought undoubtedly to have been secured in a special manner, no damage whatever has occurred during the two monsoons to the outer half-length, which was founded on a regular base in deep water. The damage to the shoreward half on the irregular bottom might probably have been obviated by the employment of much larger masses so as to dispense with a centre joint; but only at an extra outlay which would have been far beyond the advantage gained.

No serious displacement has occurred below the top course, and even in that no gap has been made in the sea-side row; so that the cost of repairs has not been heavy, and will probably be lighter when settlement shall have ceased, though even if the superstructure were to lose its present regular form, it would still be efficient for shelter.

The communication is accompanied by a series of diagrams, from which Plates 1 to 4 have been compiled.

[APPENDIX..

## APPENDIX.

## DETAILS OF COST.

Materials and Works.	Quantities. Tons.	Amount. £.
Rubble base . . . . .	96,693	17,196
Foreshore rubble in angles . . . . .	5,059	841
Shore end and 'stable' . . . . .	—	1,963
Diving work, Note A . . . . .	Sup. yds. 3,903	2,491
Concrete block-making, Note B . . . . .	Cub. yds. 29,179	25,471
Block-setting, Note C . . . . .	28,970	6,303
Repair of sea damage, Note D . . . . .	—	1,314
Total . . . . .	—	£55,579
Plant and Auxiliary Items.	£.	
Preliminary, miscellaneous, and after expenses, Note E	4,179	
Plant, Note F . . . . .	16,667	
Buildings, Note G . . . . .	8,869	
Approaches, Note H . . . . .	3,335	
Concrete-mixing station, Note I . . . . .	1,103	
Block-ground . . . . .	2,399	
Experiments on cement, lime, and concrete . . . . .	231	
Share of surveys and observations . . . . .	1,203	
Total . . . . .	—	£37,986
Grand total . . . . .		£93,565

NOTE.—The above does not include engineering and office expenses, which were borne in a general account for all the harbour improvement works.

## NOTE A.—DIVING WORK.

The current working expenses during the three seasons were respectively 16s. 11d., 13s. 8d., and 8s. 6d. per superficial yard.

## NOTE B.—CONCRETE BLOCK-MAKING.

After the work had been fairly established, the cost of each block of 16 cubic yards, for current expenses of materials and manufacture, also repair (but not first cost) of plant, was 122 rupees, or about 15s. per cubic yard. In the earlier stages of the work, however, the rate was considerably higher, owing to greater cost in working and materials, and to the larger proportion of cement used.

## NOTE C.—BLOCK-SETTING.

The current working expenses during the three seasons were respectively 4s. 10d., 4s. 6½d., and 3s. 6d. per cubic yard.

## NOTE D.—REPAIR OF DAMAGE BY THE SEA.

Of monsoon of 1871 . . . . .	£185
„ 1872 . . . . .	512
„ 1873 . . . . .	199
„ 1874, of which about one-half was for refixing and alterations of the beacon on the outer end . . . . .	418
Total . . . . .	<u>£1,314</u>

## NOTE E.—PRELIMINARY, MISCELLANEOUS, AND AFTER EXPENSES.

This item includes pay and travelling expenses of the foremen and divers from and to England, their pay and other losses during suspension under the “deficit” orders in 1869–70; also charges for medical attendance, hospital, water supply, conservancy, police, and other miscellaneous expenses beyond those of the actual working seasons.

## NOTE F.—PLANT.

*Plant procured specially for the Breakwater, including freight from England.*

	Cost.
‘Titan,’ including erection . . . . .	£2,879
‘Goliath,’ „ . . . . .	1,010
Rails, 54 lbs. per yard, 4 miles, with spikes, chairs, twenty sets of points and crossings, and four turntables . . .	4,667
Tank locomotive, including erection and spare gear . . .	2,126
Ten trucks for blocks . . . . .	1,298
Balk timber, squared sleepers, planks, and blockings, for breakwater roads . . . . .	2,033
Diving apparatus . . . . .	378
Sundry materials and stores for repairing old plant, and for general purposes . . . . .	1,356
Total first cost . . . . .	£15,747
Deduct, value after completion, one-fourth . . . . .	3,937
A. Net cost of special plant . . . . .	<u>£11,810</u>

*Plant transferred from other Works.*

	Original Cost.
Workshop engine, 20-HP., and machinery . . . . .	£2,453
Five hand-travellers, including erection and alterations . .	1,627
Tip-wagons for stone and earth, platform, break and water- trucks, also trollies . . . . .	9,550
Portable cranes, two 8-ton, two 4-ton . . . . .	815
Derrick cranes, two 10-ton . . . . .	498
Crane and sling chains, blocks and gin wheels . . . . .	594
Railway sleepers . . . . .	1,715
Diving apparatus . . . . .	172
Weighbridge and turntable . . . . .	148

Carried forward . . . . . £17,572

		Original cost.
Brought forward . . . . .	£17,572	
Piling engines and hand-pumps . . . . .	229	
Quarry, smith's, and platelayer's tools . . . . .	841	
Miscellaneous plant and tools . . . . .	785	
Total, first cost . . . . .	£19,427	
Deduct, value after completion, one-fourth. . . . .	£4,856	
And two-thirds of the loss, which is chargeable to the previous works . . . . .	9,714	
	<u>£14,570</u>	
B. Net cost of transferred plant . . . . .	£4,857	
Total of A and B . . . . .	<u>£16,667</u>	

## NOTE G.—BUILDINGS.

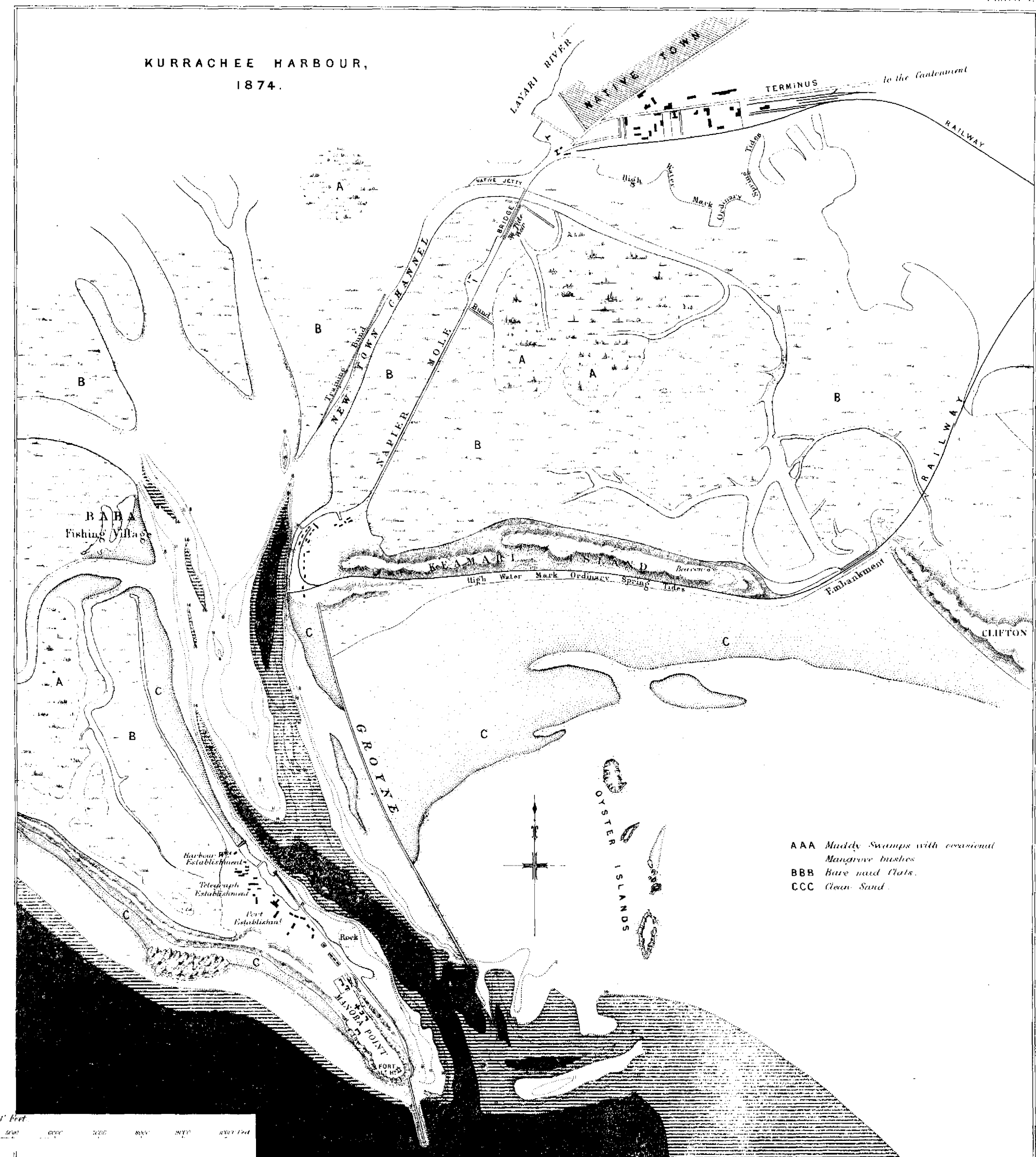
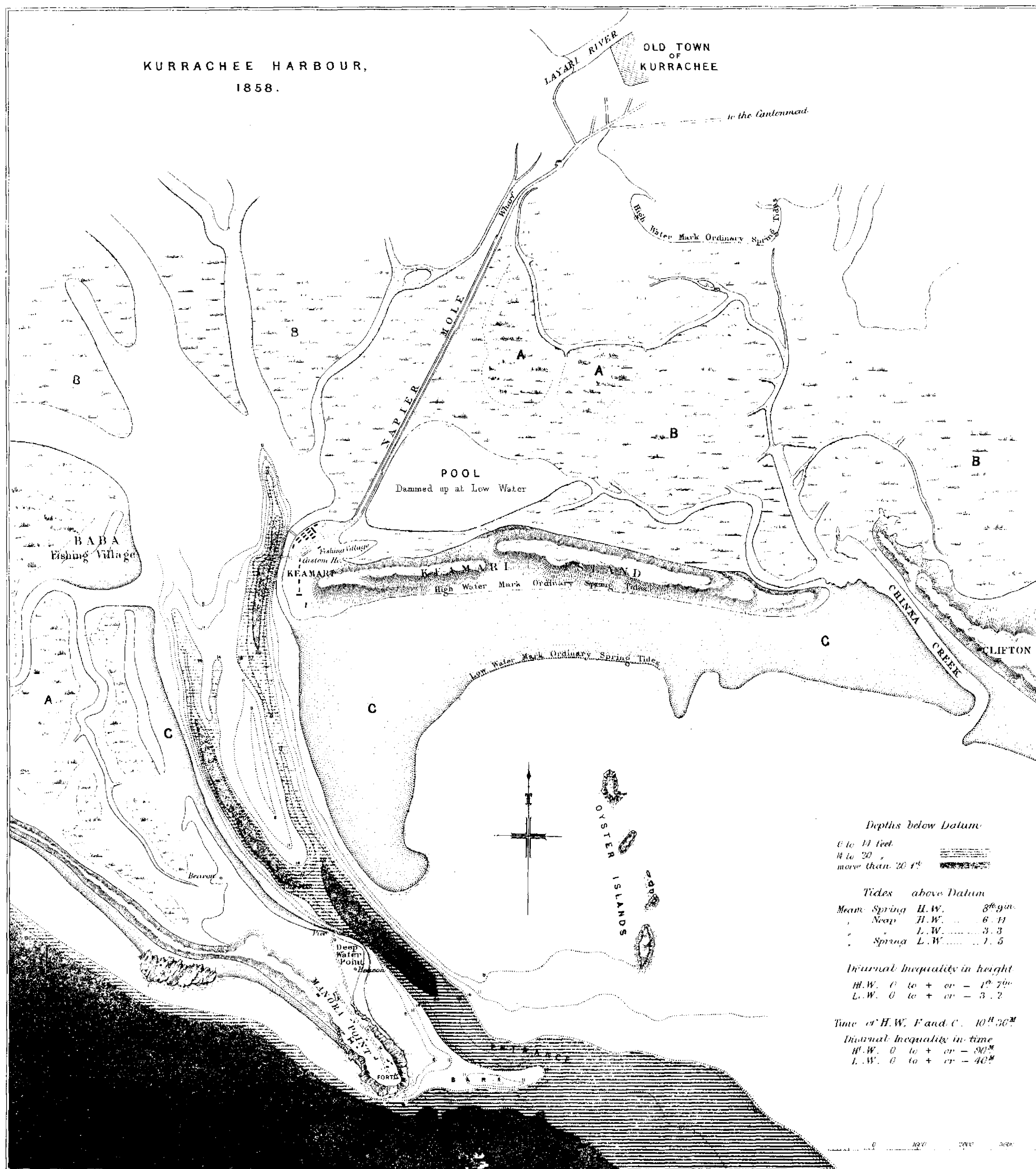
Office, workshops, and store buildings, landing pier, quarters for staff and workmen . . . . .	£9,711
Repairs to the foregoing . . . . .	558
	<u>£10,269</u>
Deduct, value of buildings, &c., as above, or of their materials, after completion . . . . .	1,400
Net charge for buildings . . . . .	<u>£8,869</u>

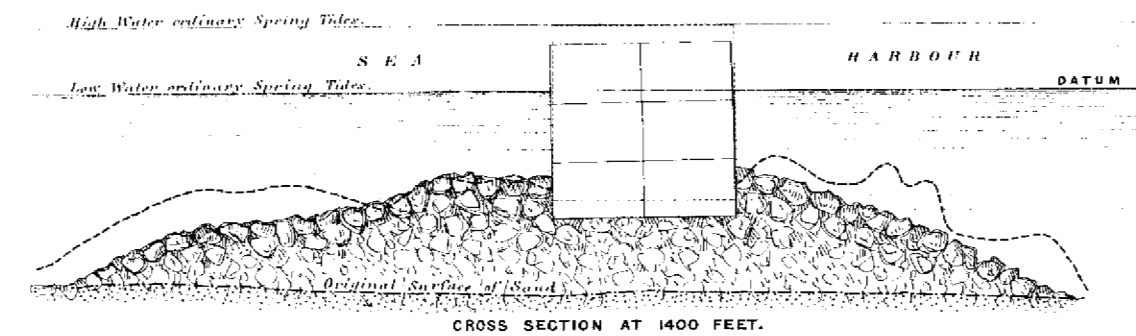
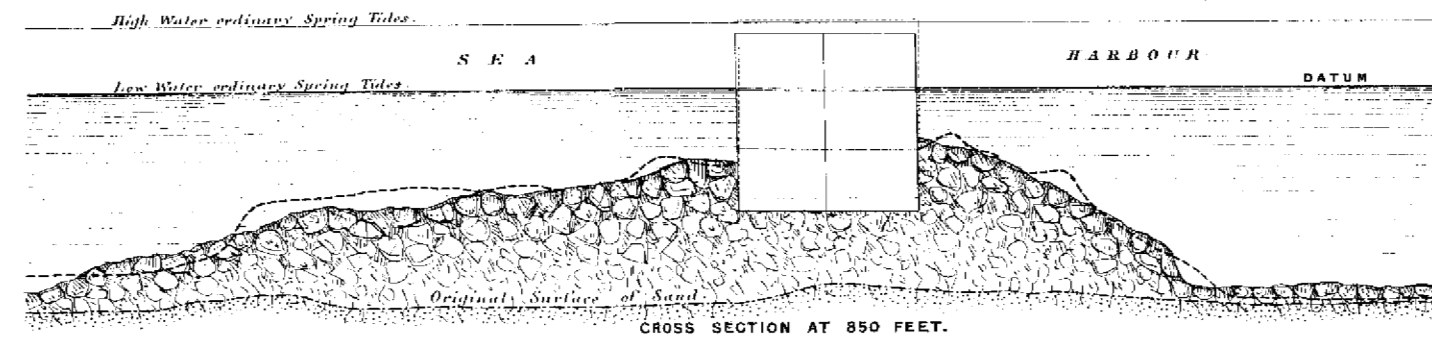
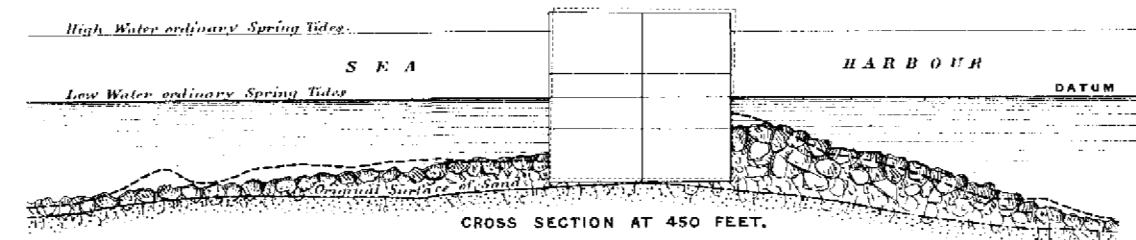
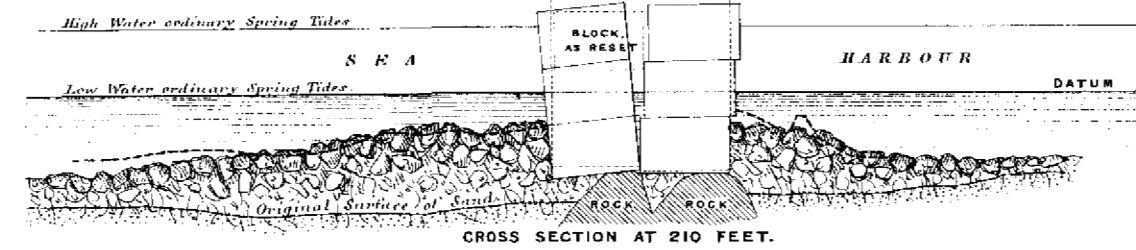
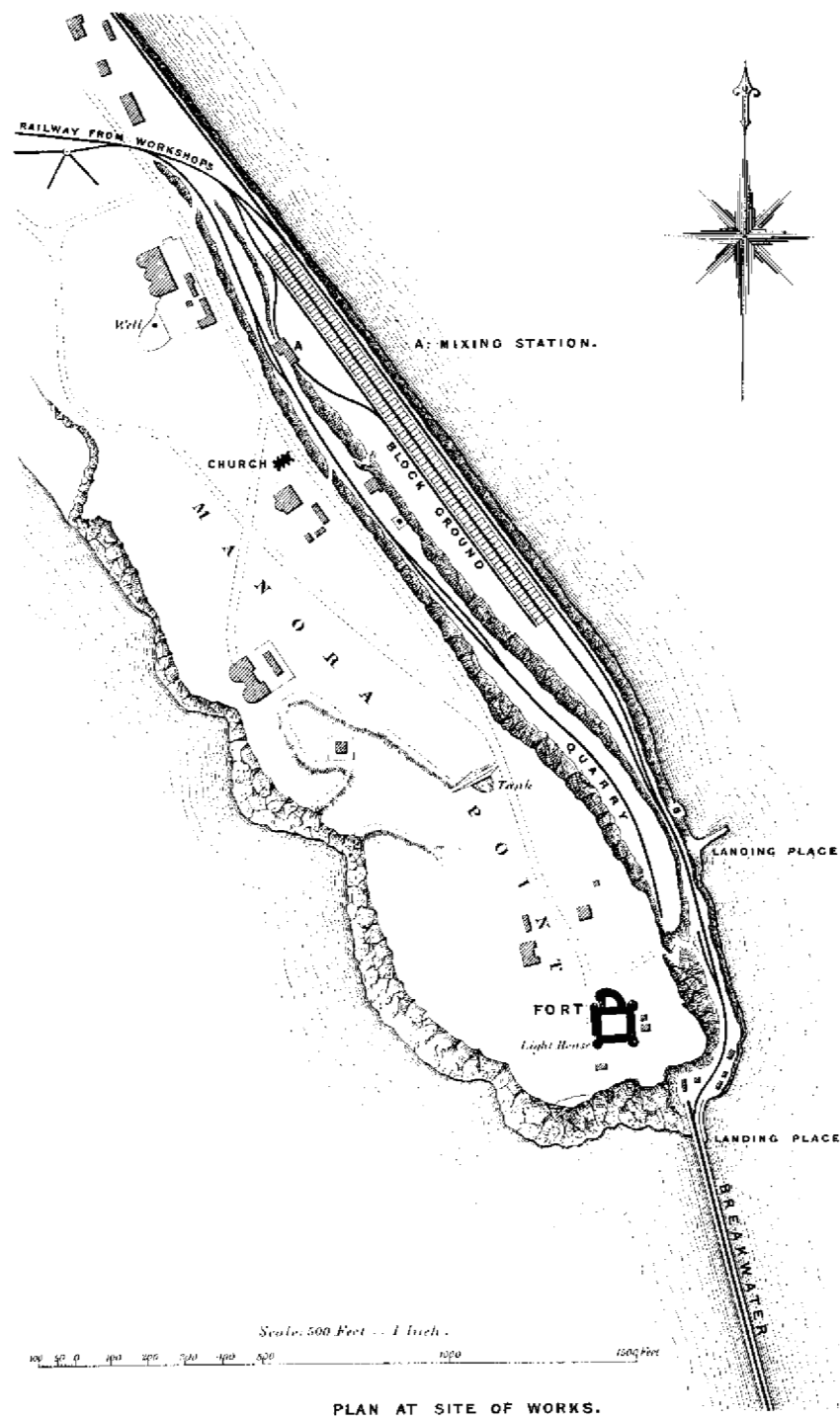
## NOTE H.—APPROACHES.

This item comprises the cost of the formation of through lines of approach and communication, 8,070 lineal feet, including a stone embankment along the sea-face of the block-ground, but not the cost of railway material, which is charged to Plant.

## NOTE I.—CONCRETE-MIXING STATION.

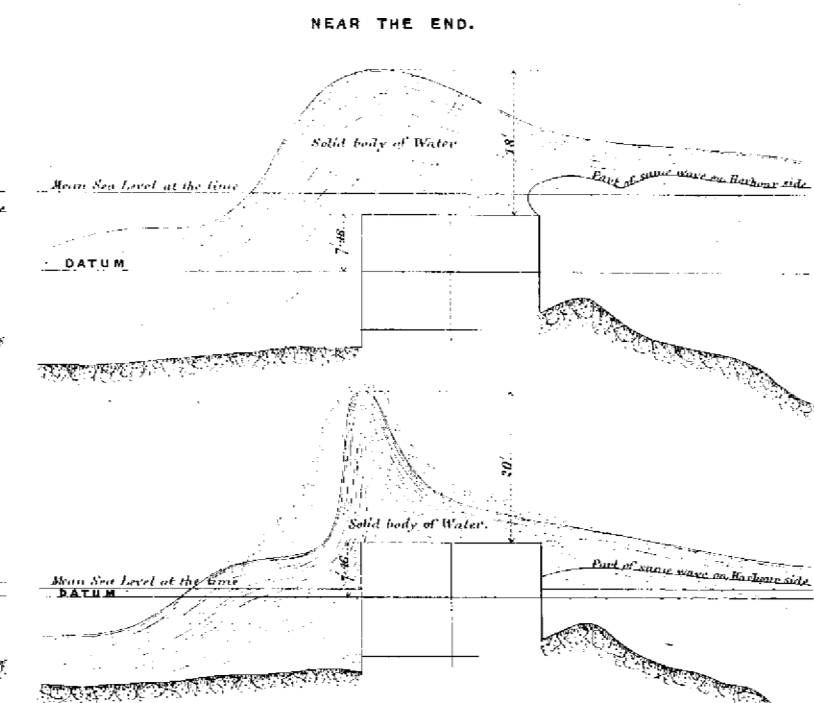
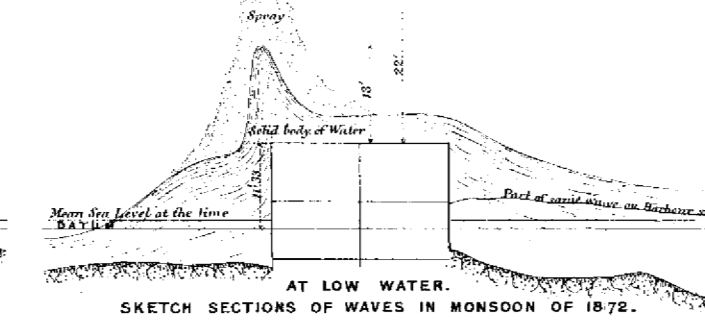
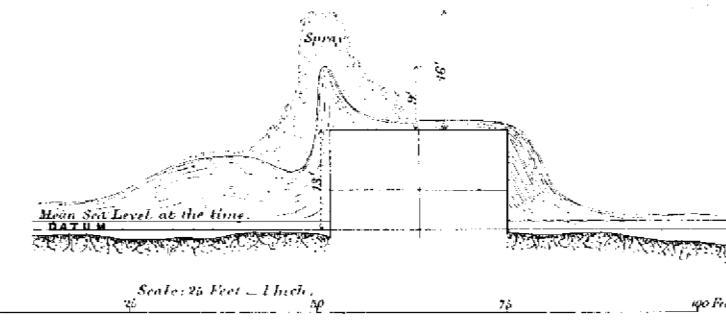
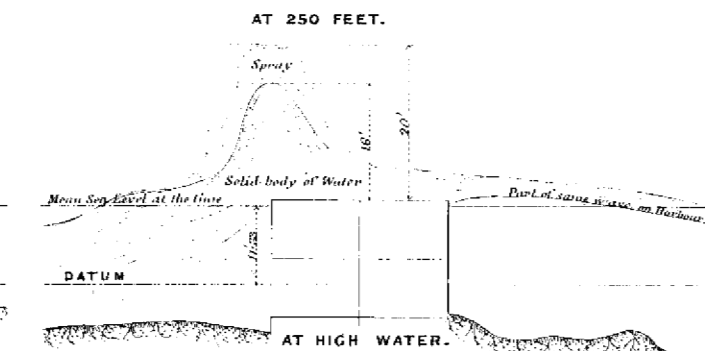
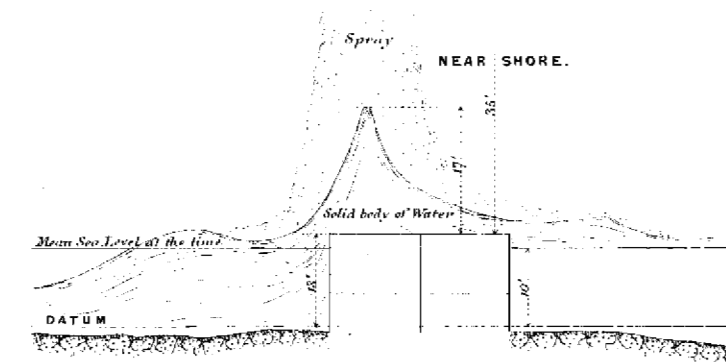
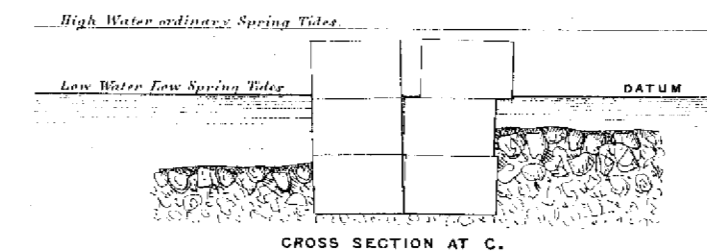
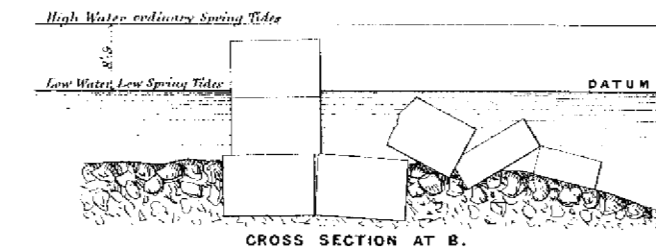
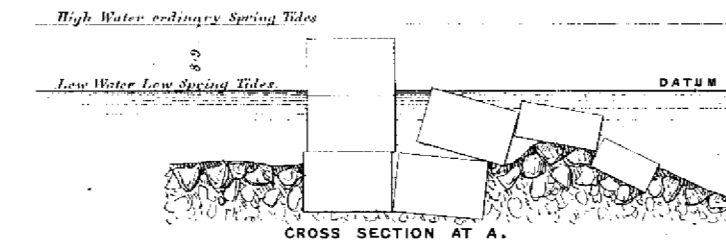
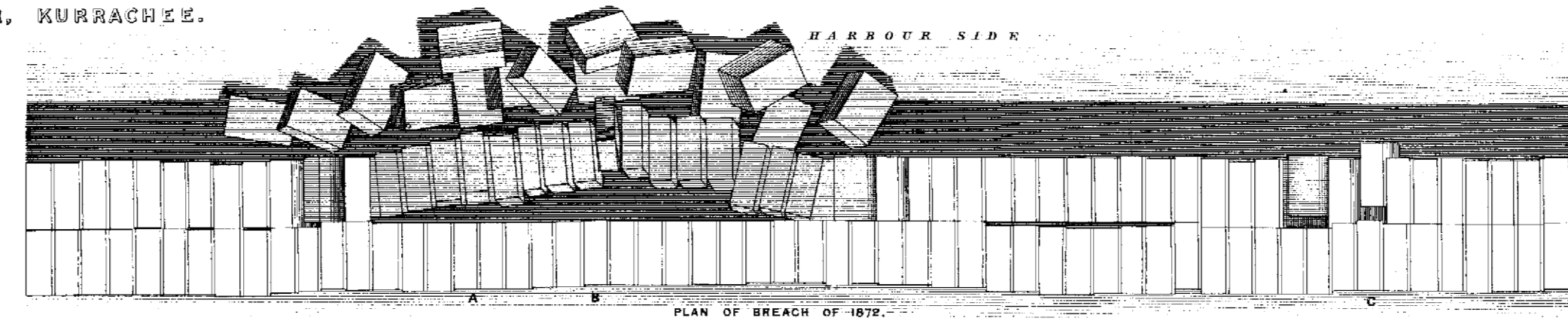
Cost of four mixers, 8-HP. engine and boiler delivered at Manora . . . . .	£683
Cost of masonry, platform, roof, well, and setting up and fixing boiler, engine and machinery . . . . .	688
	<u>£1,371</u>
Deduct, value of engine and machinery after completion, one-fourth first cost . . . . .	£170
Deduct, value of materials of roof, building, and platform . . . . .	98
	<u>£268</u>
Net charge for concrete-mixing station . . . . .	<u>£1,103</u>



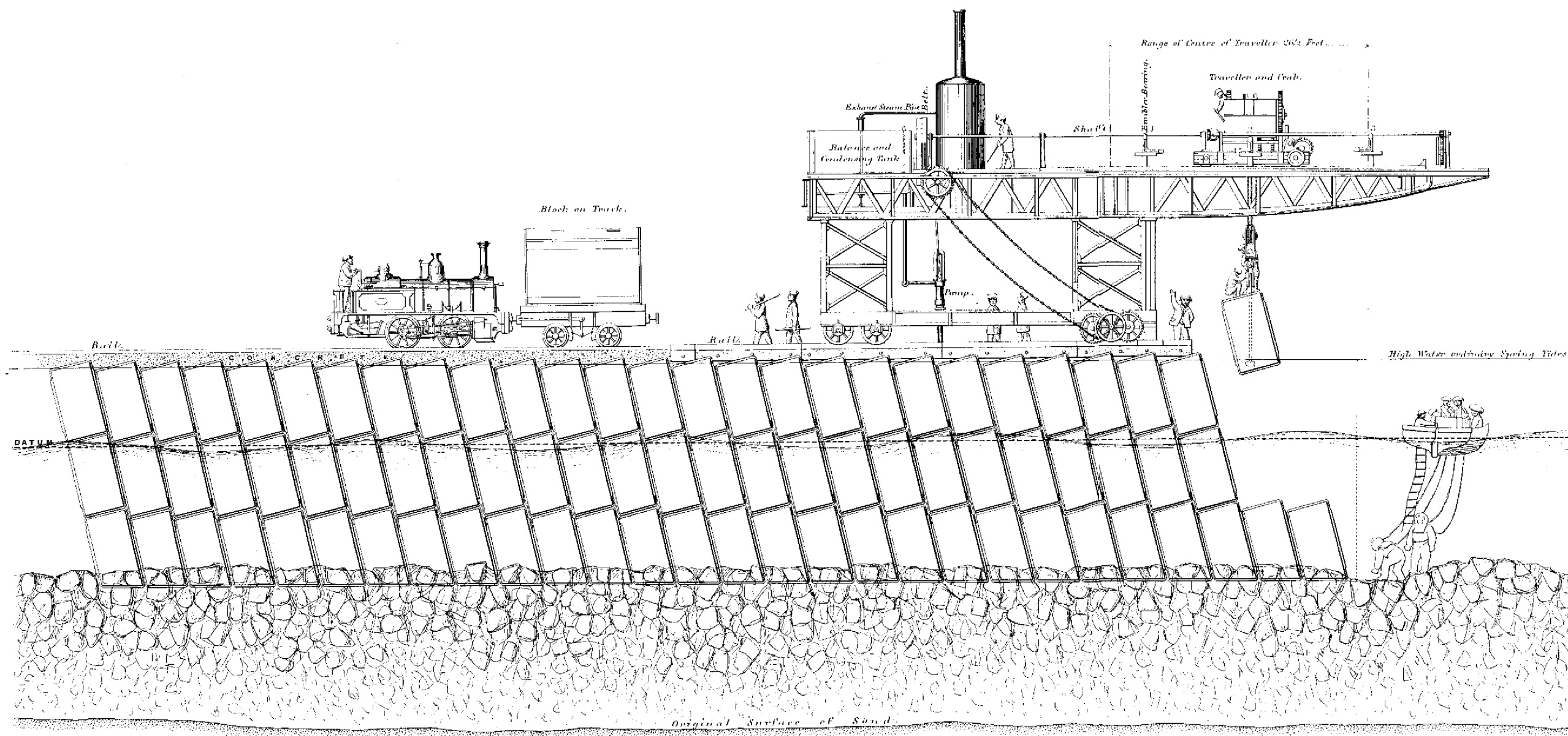


NOTE: The dotted lines show the Sections as originally formed.  
The full lines show the Sections as left by the action of the Monsoon Seas.

Scale: 25 Feet = 1 Inch.



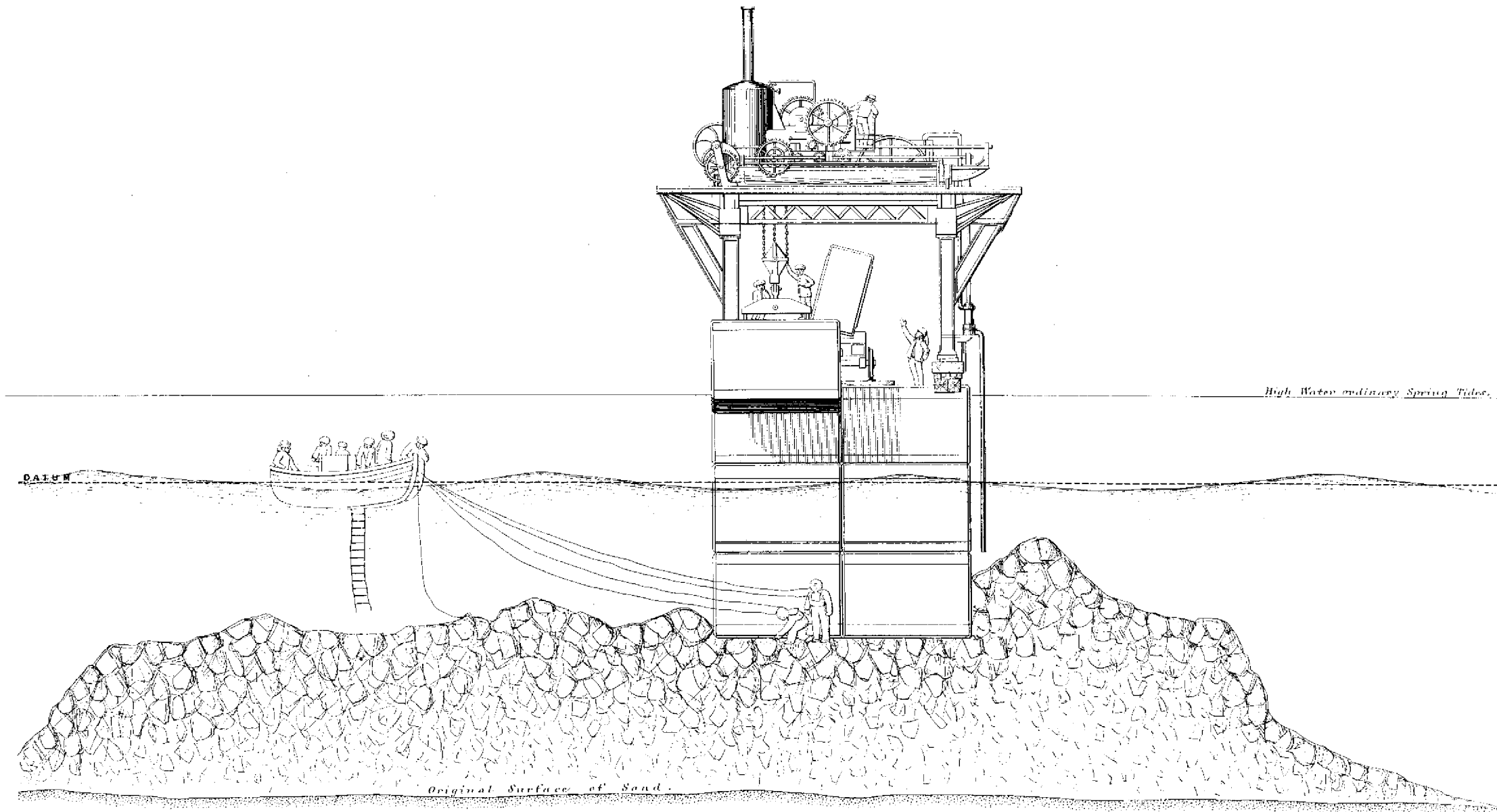
THESE SECTIONS WERE DRAWN BY CAPTAIN GORDON



SIDE ELEVATION OF BREAKWATER AND TITAN.

Scale: 18 Feet = 1 Inch.

0 10 20 30 40 50 60 70 80 Feet.



END VIEW OF BREAKWATER AND TITAN.



