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“Improvement of the Entrance to Otago Harbour, New Zealand.”

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THE harbour of Otago, situated on the south-east coast of the Middle Island of New Zealand, has for the last thirty years been the principal port in the colony for imports, though it is now closely followed in that respect by Auckland and Wellington, while Lyttleton far exceeds it in exports. This port is an arm of the sea, bearing north-east and south-west, $15\frac{1}{2}$ miles long, and averaging $1\frac{1}{4}$ mile in width. Two islands about the mid-length divide it into the “upper” and “lower” harbour, upon the former of which, at its southern extremity, stands Dunedin, the chief town of the district of Otago, and at the inner end of the latter is Port Chalmers. In the earliest days of the settlement, all large vessels anchored inside the Heads near Harrington Point; next they were accommodated at Port Chalmers, and, since 1884, a large proportion of the ocean sailing-vessels, and almost all the inter-colonial steamers, have berthed at Dunedin; but the large steamers trading between the colony and Britain still load and discharge at Port Chalmers. The increase in the shipping at Dunedin since 1884 has resulted from improvement works in the upper harbour, A, (Plate 2, Figs. 1 and 2). This Paper, however, deals especially with the natural condition of the entrance, and the works carried out for its improvement.

Physical Features.—The harbour is bounded on each side by volcanic hills, reaching an altitude of 2,200 feet on the north-western side, and 1,500 feet on the opposite side. Its south-west extremity is separated from the South Pacific Ocean by a stretch of flat, low-lying land, 1 mile wide at its narrowest part, bounded at the ocean beach by a fringe of sandhills, rising in parts to 50 or 60 feet above the water-level; but at other places, the ground is so low as occasionally to be inundated by the sea during high tides with heavy gales. This flat land is due to ancient deposit, which is of considerable depth, indicating that, at some remote epoch, the “Peninsula” was an island, and the site of the present

harbour was a tidal strait. Probably the chief agencies of the closure of the south-west extremity of the strait, instead of the north-western one, were (1), the exposure to stronger seas, which would drive the sand, borne by the flood-tide, into the deeply recessed and well-sheltered bay lying between Forbury Head and the site of Dunedin, where it would remain; (2), the contiguity of soft sandstone cliffs on the west; and (3), the discharge of large quantities of gravel, boulders, and clay, the waste of the high lands, brought down by the water of Leith stream.

All the circumstances of this locality suggest that the formation of the flat lands, marked B (Plate 2, Fig. 1), which are all alluvial, was commenced at a very early time, and also that the formation of the bar in its recent position was mainly due to the presence of that portion of land. Both before and after the closure of the south-western extremity, there would be a tendency towards accumulation of sea-drift at that position, for it would be carried on to the old beach, at the base of the volcanic rocks, by the direct force of the waves. A flat of similar formation exists at Purakanui Bay, about 5 miles to the north, which has been formed at the mouth of a deep indent in the volcanic hills, and which could not have had another opening. There is, however, no off-shore bar at Purakanui similar to that at Otago, probably because the amount of tidal water issuing from the bay, which is only about one-hundredth of that passing Otago Heads, is too small to arrest solids in suspension at any distance outside the line of the beach. This flat, B, has been formed upon a gravel beach, similar to what is found at many parts of the harbour, a portion of which was disclosed when the sand was cut into in clearing for quarrying. Once this began to form as a projection from the western cliffs, the stream would tend to keep towards the concave side at the peninsula, and thus leave the convex side in comparative quietude, when the tendency to further deposit would be strengthened. Thus the sand point would continue to stretch across the channel, until it reached a point beyond which it could not advance without reducing the cross section for the passage of the tidal waters to a limit necessitating a rate of current so strong as to scour the sides and bottom. But whatever were the stages of its growth, by the time it had attained its present shape, it had brought the tidal currents into such a direction, and had given them such a strength, as to favour the formation and growth of the bar. By stretching seawards, it had pushed the balancing line between the strength of the tide and the ocean wave further in that direction, and at the same time it would co-operate with the rocky formation on

the opposite side of the channel, in giving that oblique direction to the ebb current which has been a powerful factor in shaping the bar.

The prevailing winds are from the north-east and south-west, the result probably of the general direction of the Middle Island. The register of Dunedin for ten years, and also for the exceptional year 1886, is as follows:—

Period.	N.	N.E.	E.	S.E.	S.	S.W.	W.	N.W.	Calm	Gales.	
										N.E.	S.W.
Average per annum from 1876 to 1885 .}	8	66	13	10	11	102	38	7	110	5	22
1886	12	93	7	21	13	114	13	12	80	14	5

It is high-water at the Heads at two hours fifty minutes full and change, and about one and a half hours later at Dunedin, under ordinary conditions of weather. The winds greatly influence the tides, both as regards their height and their rate of travel. The level at Dunedin frequently differs by a few inches from that at the Heads; and on one occasion, when the current of the flood was impeded by a severe south-west gale, the deficiency at Dunedin compared with Port Chalmers was 13 inches. Under ordinary circumstances, however, the tide rises to the same height at the southern and northern ends of the harbour; but as the ebb has commenced at the Heads before it is high-water at Dunedin, the estuary is never quite full, being deficient by a wedge 6 or 8 inches thick at the one end. The range of an ordinary spring-tide is $6\frac{1}{2}$ feet, and of a neap-tide $4\frac{3}{4}$ feet; but under the influence of strong easterly winds, a neap-tide may reach the height of an ordinary spring-tide; and, with the opposite winds, a spring-tide may be much below the standard level, whilst with westerly winds it occasionally rises to 8 feet.

The area of the estuary is a little over 12,000 acres, of which 3,200 are beach and bank, dry at low-water. Making allowance for these banks, and also for the wedge by which the level of the flood-tide is deficient throughout the harbour, 113 million cubic yards of water travel out and in with a standard spring-tide, and rather more than $82\frac{1}{2}$ millions with a neap-tide; 240 acres of the beaches have been reclaimed, principally in Dunedin, but partly along the western side in the upper harbour, and to a small extent at Port Chalmers, amounting to one-fiftieth of the water area, or

about one-hundredth of the cubic contents of a spring-tide. In 1870 the Author reported to the Provincial Government of Otago, when the area reclaimed was about 42 acres, reducing the volume of a spring-tide by about one six-hundredth, and, while expressing the opinion that this could not prejudicially affect the bar, he insisted upon the limitation of these operations to what was absolutely necessary. Since that date the Colonial Government has reclaimed about 60 acres for a railway station, and the Harbour Board has reclaimed 100 acres for revenue purposes; but there is nothing to show that the exclusion of the tidal waters by these works has reduced the scouring agencies of the tide to an appreciable extent.

The heaviest seas come from the east and south-east, often with light winds, and sometimes with calm weather, so that the waves which reach the coast must be the propagation of storms far out at sea. They come direct on to the beach, and not with the oblique action so noticeable further north at Timaru. A north-east wind, to which the harbour entrance is exposed, brings a short lumpy sea with little force, and the south-west, being off the land at the Heads, makes a smooth bar. The easterly seas of August-September, 1886, reduced the beach to the west of the training wall, and also at the ocean beach near Dunedin, while it made up the bar to some extent, and also caused large accumulations of sand on the beaches to the south-west of Heyward Point.

Natural Changes, 1850 to 1891.—The earliest survey of the harbour was made by Captain Stokes in 1849-50; and the next was by Mr. D. L. Simpson, M. Inst. C.E., the upper harbour in 1875, and the lower in 1879. A comparison of these two shows that the low-water levels adopted at the different times were practically the same; and it does not disclose marked changes, except at one or two places. In the upper harbour, a cross section in front of Dunedin shows an average shoaling of 12 inches, a not unlikely occurrence in thirty years. In the lower harbour, the first survey showed a sandy shoal about a mile inside the Heads (known as the inner bar), with only 15 feet of water over it at low tide; while the second survey gave, at the same spot, a good channel with $27\frac{3}{4}$ feet of water. Between that and Port Chalmers, Captain Stokes showed a limiting depth of 20 feet, and Mr. Simpson $23\frac{3}{4}$ feet. This shoaled up again to 20 feet within the last five years, and has been temporarily improved by dredging. On the outer bar, the Admiralty chart showed 16 feet, and the later map 15 feet on the line of leading beacons; but taking the average of the soundings along the ridge, the two surveys agree. Comparing the

breadths, however, at the different times, the distances between the 18 feet contour lines are slightly greater in the more recent survey; and the western point of the bar has travelled about 24 chains nearer to the beaches in the interval. The limiting depths in the north channel fell from $22\frac{1}{2}$ to $20\frac{1}{4}$ feet, and the average from 29 to $26\frac{1}{4}$ feet, indicating a period of deposit during these thirty years. The close similarity between the bar soundings of these two surveys, is more a coincidence than a representation of the general depths during the intervening time, for the records kept by the harbour-master's staff show that large variations were experienced. For instance, there were $19\frac{1}{2}$ feet of water in August and October, 1872, on the line of the leading lights; but in 1879, the depth fluctuated between 15 and 16 feet; and in other years, the soundings were between these extremes. Between 1879 and 1881, when dredging was commenced, the depths ranged from $15\frac{1}{2}$ to $16\frac{1}{2}$ feet. The bar was generally better with a prevalence of strong south-west winds, which brought high tides, and also made a smooth bar.

On the 13th August, 1868, there was a severe earthquake in Peru and Ecuador, which, on the 15th, caused a violent disturbance of the sea on the coast of New Zealand. At Otago Heads the wave rose 1 foot higher, and fell 18 inches lower than the mean high- and low-water, or about 18 feet in all; and it kept swelling and receding with diminishing range for about twelve hours. At Port Chalmers the vertical oscillation was 15 to 18 inches; while at Dunedin there was only a slight throbbing. The extra currents reduced the northern part of the bar, from an average depth of about $15\frac{1}{2}$ feet down to 22 feet at low-water, and probably displaced about a million cubic yards of sand from that part, while it heaped up immense quantities on the part to the eastward; so that, in the line of leading lights, the depth was suddenly reduced to $11\frac{1}{2}$ feet, and consequently vessels had to approach and leave the harbour by the north channel. In about two years, the bank had resumed its old shape, showing that whatever agencies had built it up in the first instance, the forces which produced its modern form were still in existence. These disturbances of the waters did not affect the inner bar.

No part of the harbour has shown so many changes from natural agencies as that portion lying between the Kaik jetty and Harrington Point. The ebb-tide runs strongly towards the concave eastern beach, causing the spit on the opposite side to stretch in the same direction, until the bend becomes so acute that the main strength of the flood-tide makes a shorter cut for

itself across the projecting tongue. Then two streams flow by different routes with an area of almost still water between them, where the deposit of sand forms a bank in mid-channel. Probably that is the history of the inner bar, which, being little more than a knoll, must have been the remains of a larger shoal, and has its existing representative in a bank near the old locality, which has been created in this manner within the observation of the Author.

In 1850, the channel was very crooked, and the inner bar formed a serious obstacle to navigation; but there were narrow gullets of 18 and 19 feet on each side of it. An attempt to remove this by harrows about 1864, only resulted in the reduction of a few unimportant knobs; and when the Author inspected it in 1870, there was only 15 feet on it at low-water. However, in 1872-4, nature diverted the main volume of the water towards the east, causing the ebb-tide to scour away the obstruction to a depth of $27\frac{3}{4}$ feet by 1879. From this date, the spit was travelling eastward, and by January, 1887, the flood-tide seemed likely before long to take a more direct course; and this appeared so imminent in June, that the Author drew the attention of the Harbour Board to the circumstance. In 1888, the flood channel developed still further, and simultaneously a bank grew up in the area between the two streams with only $16\frac{3}{4}$ feet, where five years earlier there was a depth of 30 feet; and by April, 1890, the depth was only 14 feet 5 inches, whilst the flood channel still deepened on the west, and the ebb current followed the eastern side. The sailing course consequently became exceedingly difficult for the outward passage of long vessels; and the Harbour Board dredged a channel in the line of the flood current, which, by April, 1891, gave a low-water depth of 20 feet; but the bank had shoaled to 13 feet 5 inches at one point, with larger areas ranging from $14\frac{3}{4}$ feet to $15\frac{1}{4}$ feet, producing a somewhat similar channel to that of 1850 to 1872, but not quite so bad. On the eastern side, there has always been a back channel, with a bank between it and the main one, having depths at low-water of 17 to 30 feet in the channel, and 2 to 6 feet on the bank in 1850; 16 to 20 feet, and 8 to $10\frac{1}{4}$ feet respectively in 1883; and $15\frac{3}{4}$ to $24\frac{3}{4}$, and 4 to 6 feet respectively in 1891, and between these depths in other years. The principal depths did not appear to vary much between 1850 and 1871; but about 1871 a scouring action commenced at the bank, probably due to the same cause as the scouring away of the inner bar. The cross section Y Z (Plate 2, Figs. 4 and 7) shows the alterations between February, 1885, and April, 1890, and indicates the form and posi-

tion of the channel being formed towards the west by the flood-tide. In this period, the average low-water depth had increased by $3\frac{1}{3}$ feet, its width had decreased 693 feet, and its area had increased 329 square feet.

From 1879 to February, 1885, along a line 500 feet seaward of Y Z (Plate 2, Fig. 1), the average low-water depth had increased 6 inches, its width had decreased 211 feet, and its area had decreased 1,470 square feet. This reduction in the sectional area, though larger than between 1885 and 1890, is still only 3 per cent.; whilst between 1850 and 1879, there was an increase of only $3\frac{1}{2}$ per cent. Therefore, whatever differences arise in regard to the widths and depths, the areas of the cross sections keep fairly constant. Sir John Coode, Past-President Inst. C.E., pointed out that one effect of the construction of the two break-water moles, recommended by him, would be the reduction of the eastern margin of the north spit, by the flood-tide being made to act more strongly upon it; and possibly the formation of this new flood channel has been promoted to some extent by the portion of the scheme which has been carried out; but the Author is of opinion, that even if these works had not been commenced, the time had arrived when the flood current would have cut across the spit, in preference to travelling by the longer and more tortuous channel of the ebb. It is not unlikely, however, that the movement of the outer part of the spit further in towards the harbour in 1887, was caused by the new strength given to the flood current. Once established in its new position, the power of the flood to scour its channel would probably be about the same as in the old position, but a little further seaward.

The Author anticipates that the ebb-tide and the north spit will cause the dredged channel to be silted up; and he has advised the construction of a rubble training wall approximating to the 18-foot contour line, going north-eastward from about the Kaik jetty, so as to force the ebb over to a position nearly coinciding with the route of the main body of the flood. A groyne is also suggested about $\frac{1}{2}$ mile further south, for the purpose of blocking off the water from a back channel which has low-water depths of 20 to 32 feet, and which ought to be continued to join the longitudinal wall if funds will allow.

SCHEME FOR IMPROVEMENTS.

In May, 1880, the Author pointed out the conditions of the currents near the Heads, and urged the desirability of blocking up

the north channel for the purpose of deflecting these; but the first recommendation in this direction put before the Harbour Board was in a report from Sir John Coode, received in June, 1880. In that report, the expectation of getting an improved permanent channel by dredging alone was discouraged, and the general principles of improvement by induced scour were laid down; and plans showed the direction of two breakwater moles, and of an improved line of channel inside the Heads; but in the absence of information upon the currents and the composition of the bar, no details were given (Plate 2, Fig. 7).

The Author having become engineer to the Harbour Board in May, 1882, immediately urged the desirability of building the western wall across the north channel, believing that while the complete scheme of Sir John Coode was beyond the capability of the Board at the time, this work would turn the currents into a better direction, and with the rocky headland on the eastern side, would concentrate the tidal forces within reasonable compass. A survey of the harbour entrance was accordingly made in January, 1883, including a series of soundings over the lines of 1879; and these were repeated at frequent intervals till November, 1888, when the works were stopped, and the Author ceased to be engineer. Since then, these soundings have been continued on the same lines, and in the same manner, by the inspector of works.

Conditions in January, 1883.—While the flood-tide enters the harbour with its main force in the most favourable direction for the channel across the bar, the strongest ebb runs almost due north, obliquely to the bar, and therefore, favourably for counter-acting the heaping-up agency of the ocean wave. The greatest velocity of the flood was $1\frac{1}{4}$ knot per hour, and of the ebb 2 knots per hour. The deepest water followed a somewhat tortuous line along the North Channel, which had the serious disadvantage of taking a vessel beam to sea; and at one part, the channel was dangerously close to the beach. Besides these currents, one ran constantly from the north-west, parallel to the beach, about ten chains wide, apparently independent of the tides, but probably running towards the main body of the ebb as it left the harbour, or of the flood as it entered. When this was stopped by the construction of the training wall, the beach began to extend upon the north-west side, owing to the increased deposit in the quieter water.

The 18-foot contour line of the bar had a convex outline towards the sea on the northern part, and a concave form next the beach;

but adjoining the line of leading lights, close in upon the shelter of Taiaroa Head, parallel to the strongest ebb, but directly across the strongest flood as it comes sharply round the headland, the concavity is on the ocean side. The narrowest point of the bar was also in the line of beacons, where the flood was relatively stronger than the ebb. At this part, the distance between the outer and inner 18-foot contour lines was 400 links; while further north, on the line of the strongest ebb, the distance between the same lines was slightly over 20 chains. In this latter position also, the least depths, of only $12\frac{1}{2}$ feet, were found, when there were depths of 16 feet of water in the sailing channel. Where the bank tapers off and merges into the North Channel, neither tide preponderates.

The inner slope of the bar, between the rocky face of Howlett Point and the line of beacons, is decidedly steep (Plate 2, Fig. 3). For 6 or 7 chains it is flatter, and then again much flatter. The abrupt face is probably the result of the ebb-tide acting tangentially in paring off the face of the bank; while at the other parts it comes upon the sand more in front, thus causing the bank to be more like a beach. The face opposed to the ocean is naturally flat. Before works were commenced, the ocean was labouring to build up the sand all along the bank; but within a short distance of Taiaroa Head, the most powerful part of the ebb was cutting off and transporting the sand brought from the outside, and whenever its carrying power was lessened by the joint opposition of the waves, and of the ebb tide coming down the coast, the solids would be precipitated. Hence the higher and wider condition of the bank at the northern part. During flood-tide, also, with a disturbed ocean, quantities of sand would be brought into the harbour, some of which would permanently lodge; but much of it would be picked up by the ebb and deposited on that northern area, which had fluctuations in depth like other parts of the bar, and when it was at its shallowest the channel in the line of beacons was at its best. This action of the ebb sufficiently accounts for the extension of the bank, and the accumulations in the north channel between the years 1850 and 1879, for the resultant of the inward wave force and the ebb current, would have an inclination northwards and shorewards.

To ascertain the nature of the bar, thirty-six probings were executed within 70 chains of Taiaroa Head in sixty-five hours' work, the larger number of tests being in the neighbourhood of the proposed channel and wall, being effected by a 3-inch tube, down which water was forced by the feed-pump of the hopper

dredger. The deepest sinking was 44 feet, and the least 30 feet below low-water, giving depths into the bank of from 7 to 21 feet. These tests showed that the body of the bank was sand, with little variation, though the topmost 3 or 4 feet are less firm than below. The flat also to the south proved to be of similar composition.

In 1880 the Harbour Board contracted with Messrs. Simons and Co.¹ for the construction of a hopper dredger, which arrived in the colony early in 1882.²

Dredging, 1882-84.—The result of dredging on the bar, before the commencement of the training wall, was not satisfactory. In 1882 the dredger lifted 7,080 cubic yards of stuff in eighteen operations, and deposited it 3 miles out at sea, being an average load of only 393 cubic yards. An increase in depth of $2\frac{1}{2}$ feet was gained for a short time; but, as there was no indication of permanency, the Author again urged the adoption of other means for the attainment of better depths on the bar. In 1883 the dredger removed 34,017 cubic yards in fifty-nine operations, or an average of 576 per trip, being a little over two-thirds of her full complement. In October, however, 11,650 cubic yards were removed in fifteen days' work, or an average of 777 cubic yards per day. During that steady work the low-water depth in a narrow trench was nearly 21 feet; but the return of less favourable weather, and the consequent stoppage of dredging, was immediately followed

¹ Minutes of Proceedings Inst. C.E., vol. lxxxix. p. 40.

² Hull of iron, 210 feet long and 41 feet beam. Ladder, 76 feet long with thirty-six buckets; one set of 8 and the other of 10 cubic feet. General speed in working, fourteen buckets per minute. Hopper capacity, 850 cubic yards. Loaded draught, $10\frac{1}{2}$ feet forward, and $14\frac{1}{2}$ feet aft. Twin screws, and two pairs of compound engines, with cylinders 22 and 39 inches diameter. Two tubular boilers with working strength of 60 lbs. per square inch. When dredging, one pair of engines, with 50 to 55 revolutions per minute, was sufficient, but when in motion, both engines were used, consuming 5 cwt. and 15 cwt. of coal respectively per hour. The coal was obtained from the west coast of the Middle Island, where there are immense deposits of a bituminous character, with about $7\frac{1}{2}$ lbs. evaporative power. The dredger was provided with heavy harrows, but neither in the upper harbour, nor on the bar, were they efficient, as there was no strong current to carry away the sand when it stirred up. In November 1884 one of the cast-steel bucket-backs broke during work on the bar, and the whole chain of buckets slipped from the ladder and sank. When recovered after a few days, the accident was found to be due to air-blows in the metal. In the following year, they were replaced by malleable iron ones, at a cost of £909. In January 1887 the dredger sank after collision with a steamer at the islands, but was speedily recovered, and repaired at a cost of £1,626 6s. 10d.

by a reduction in the depth to $18\frac{1}{4}$ feet. In 1884 the dredger was thirty-three times on the bar, and removed 21,585 cubic yards, or an average of 654 per trip. Still, no greater depth than $18\frac{1}{4}$ feet could be depended upon.

Training Wall.—The Board having become convinced that other means than dredging must be resorted to, the Author, early in 1883, prepared designs for the construction of the Western Mole, on the line recommended by Sir John Coode, which were duly approved by the Colonial Marine Engineer. Before being sanctioned by the Governor in Council, they were submitted to Sir John Coode for his opinion, especially as to whether the execution of the portion within the capacities of the Board's funds would be likely in any degree to operate against the success of his complete design, if at any future time it could be carried out. That scheme provided for two walls, the western one starting from the land, and extending into 28 feet depth at low-water on the outer slope of the bar, with a length of 6,200 feet; and the eastern one, 1,700 feet long, commencing at the extreme point of Tairaroa Head (Plate 2, Fig. 2). He replied that the western wall should not be extended further than 4,000 feet, unless the eastern one was also gone on with, and that though a certain amount of fluctuation in the depths on the bar would still be experienced, the degree of improvement obtained from this portion of the work would be worth the expenditure incurred.

A good supply of stone, suitable for a wall of random work, being available within $\frac{1}{2}$ mile of the root of the proposed work, the Author proposed that method of construction (Plate 2, Figs. 5 and 6). The cliffs, 300 feet in height, consist mostly of a hard basalt, but partly also of a volcanic breccia, lighter than the basalt, but capable of easy quarrying in large blocks. There was also a heavy and extremely hard variety of rock at the northern end, which was used, to a limited extent, towards the end of the work; but it was costly to work on account of the extreme difficulty in drilling. There was a considerable falling off in the quantity of 6 to 8-ton blocks, at a time when an endeavour was being made to raise the work above low-water, where the wave force was particularly severe, and consequently a large quantity of the rubble was carried to leeward, unnecessarily spreading out the width of the wall.

In the absence of suitable hard wood in the colony, piles of iron bark,¹ red gum, blue gum, and turpentine, from Australia, in

¹ Minutes of Proceedings Inst. C.E., vol. lxxxix. p. 313.

lengths of 26 to 70 feet, and diameters of 18 to 21 inches, were obtained for the staging for constructing the mole.¹ For the superstructure, native timber alone was employed. On the first section, 524 feet in length, black pine (*podocarpus spicata*) was used,² but thereafter a red pine was substituted, for economical reasons, and it was also found to have the advantage of giving a better grip for the feet of the workmen. The distance between the piles longitudinally was made 22 feet, as timber beams strong enough for that span could be got in the colony, whilst a larger span would have required costly under-bracing of iron (Plate 2, Fig. 5). Six longitudinal beams carried three lines of rails, from each of which stone was tipped as required. The piles sank about $\frac{1}{4}$ inch per blow of a 30-cwt. monkey with an 8 or 10-foot fall. They were driven 12 to 18 feet into the ground, the greater depth being in the seaward portion. Vertical wrought-iron bracing was placed at the piers, and was moved forward as soon as enough stone was placed to secure the piles. In accordance with Sir John Coode's recommendation, the rails were placed 18 feet above high-water; but as there was a tendency to fall going seawards, the outer two-thirds of the lengths were built with a rise of 0.15 foot per 100 feet, which raised the rails 22 feet above high-water at the outer extremity, a height not at all too great as experience proved. Three feet above low-water was the limit of height first proposed for the rubble; but Sir John Coode recommended high-water as the level for the first 500 yards, and 2 feet lower, or $4\frac{1}{2}$ feet above low-water, for the remainder. Only a part of the inner end is up to the proper height, and the remainder falls short of even the lowest limit proposed (Plate 2, Fig. 6). The higher part at the

¹ As the structure was only required for the deposit and consolidation of the rubble, the employment of jarrah from West Australia was not considered, as its cost is much greater than that of these other timbers; but, apart from this, the Author can endorse the statement of Mr. Ohaimer, that in several cases its use has been a disappointment on account of its yielding within a few years to the attack of the teredo. Such experiences are not uncommon in the colony with timber of good repute, probably in many cases caused by differences in the locality of growth, but often it may be suspected from mistakes in the names of the timbers, for some of very similar appearances have quite different characteristics. In the matter of durability in either air, earth, or water, few colonial timbers can excel the heartwood of New Zealand totara (*podocarpus totara*); but it is deficient in strength, and decidedly brittle when large and old.

² This wood is slightly stronger than oak, but is sometimes uncertain, owing to coarseness of grain. The heartwood has often shown great lasting qualities; but there is a danger of a timber of less durability, and very similar in appearance when sawn up, called miro (*podocarpus ferruginea*), being taken instead. The red pine is rather weaker.

beach end, by impeding the sand in its course from the westward, has fulfilled the purpose intended.

Contracts were obtained for the supply of piles, squared timber, malleable and cast-iron, and workmanship of the staging; and the quarrying, the carriage, and the deposit of the stone were effected by day labour. By this means everything was got at about its first cost; and as the Board accepted the responsibility for the stability of the structure as soon as the stone wagons were run upon it, and as these followed close upon the piles, the contractors' risk was very small. Had the whole been put in one contract, the item for risk and probable losses would have been very high; but these did not cost the Board over £100.

The average cost of the staging, exclusive of maintenance, light at the outer extremity, and a few minor items, was as follows:—

		£	s.	d.	
1st section, 524 feet		8	3	6	per lineal foot
2nd " 506 "		7	18	6	" "
3rd " 990 "		7	14	10	" "
4th " 990 "		7	9	6	" "
5th " 1,078 "		7	1	1	" "

The reduction in rate, as the structure extended from the beach, was partly due to the cheaper labour and material, consequent upon the relaxation of Government works, and partly to increased familiarity with the operations, and the freedom from serious accidents in the earlier part of the undertaking. The handling of the stone by the Board's own workmen, secured perfect control by the engineer over the sizes and qualities of the material put into the work. For about half the time, one of the quarries was worked by prison labour, the cost of which, compared with free labour, was slightly in favour of the former. The convicts cost the Board 3s. a day, made up of 2s. 6d. paid to the Government, and 6d. per man as the cost of carrying them and their stores between Dunedin and the works. The free labourers were paid 7s. per day of eight hours. Disadvantages in the employment of prisoners were their fluctuating numbers, and the inexperience of many of them.

The total quantity of stone put into the wall, between January 1885 and November 1888, when the work was stopped owing to the failure of funds, was 283,341 cubic yards; and the cost, including the formation of railways from the quarry to the mole, and to the landing place, was £35,831 3s. 2d., or 2s. 6½d. per cubic yard. The railways, however, are included, which are available

for future use, either in maintenance or extension. The actual working expenses were 1s. 11d. per cubic yard in 1885, when the stone was easily got, up to 2s. 4d. in 1888, when circumstances were not so favourable. Up to the stoppage of the work, in November 1888, the cost had been :—

	£	s.	d.	=	£	s.	d.	
Staging	31,272	7	0	=	7	13	0	per lineal foot
Mole and railways . . .	35,831	3	2	=	8	15	0	„ „
Total	67,103	10	2	=	16	8	0	„ „

Adding £1,836 6s. 3d. as the cost of 18,513 cubic yards of stone deposited in 1890, the cost of the wall amounts to £37,667 9s. 5d., or £9 3s. 9d. per lineal foot; and the total expenditure upon staging and wall has been £68,939 16s. 5d., or £16 16s. 3d. per lineal foot (see Appendix). In an estimate put before the Board by the Author, in June 1883, for the larger wall, the average rate was £16 18s. 10d. per lineal foot. The rubble is higher at some parts, and lower at others, than was at first proposed; and the staging is wholly higher, so that the actual cost was very close to the estimate.

The Table on the next page shows some of the principal points regarding the improvement of the bar, and the results produced.

From May 1882 to November 1887, the dredger, operating on the bar 186 times, carried away 108,994 cubic yards, or an average of 586 per trip, equal to 0·69 of her hopper capacity, the short filling being due in most cases to an increase of the wave-motion before her full complement was dredged. She worked bow on to the sea, with only bow and stern moorings, because side ones would have been too great an obstacle in the way of vessels. She was, therefore, very unsteady, but with the short seas from the north, she could work with waves 4 to 6 feet high; whereas with the long swell from the south-east, the motion became too great with waves half that height. Her ladder is of the box-girder pattern, very buoyant, offering a large surface to the sea, so that its heavy surging caused much damage to the buckets by their knocking against the bottom and sides of the cut. The large buckets proved unsuitable for this work, so that the smaller ones had to be used; and as it was impossible to shift them each time she changed her locality, the work done in smooth water was less than it otherwise would have been. Within the same period, the dredger removed 763,904 cubic yards from Port Chalmers and the upper harbour; so that of her whole dredging, only 12·4 per cent. was that for

OPERATIONS AND ALTERATIONS ON OTAGO BAR, MAY 1882 TO APRIL 1891.

Period.	Dredging Occasions.	Dredging.	Navigation Channel.			Length of Staging at End of Period.	Stone deposited in Mole.	Breadth of Bar at 26 Feet below Low-Water.	Amount of Bar above 26 Feet below Low-Water for Length of 2,100 Feet.	Travel of Ridge seawards since January 1883.	Travel of Centre of 26 Feet below Low-Water Contours seawards since January 1883.	Average Low-Water on Ridge of Bar, for Length of 2,100 Feet.
			Water Depths.	Low-Water Depth at End of Period.	Feet Inches.							
		N ^o .	Cub. Yds.	Ft. Ins.	Ft. Ins.	Feet.	Cub. Yds.	Feet.	Cub. Yds.	Feet.	Feet.	Feet. Ins.
1882 May to 31 Dec. ¹	18	7,080	16 6 to 19 6	19 0	{Temporary}	..	..	920	636,300	..	..	14 5
1883 1 Jan. to 31 Dec.	59	34,017	19 0 " 21 0	18 3	..	400	..	990	..	60	90	16 10
1884 " " "	33	21,585	18 3 " 19 6	18 3	..	1,420	42,828	..	..	630	410	16 10
1885 " " "	42	27,080	18 3 " 20 3	20 3	..	3,022	74,830	990	..	860	520	16 10
1886 September.	..	..	..	..	..	4,088	102,740	750	..	560	560	18 3
1886 1 Jan. to 31 Dec.	8	4,806	21 3 to 19 3	19 6	..	4,088	62,943	620	151,750	1,020	590	21 0
1887 " " "	28	14,426	19 3 " 22 1	22 1	..	(Anarrow gut with 26ft. 2ins.)	18,513	..	134,980	730	820	22 7
1888 1 Jan. to Nov. ³	..	..	21 6 " 23 9	23 1	..	4,088	301,854	920 to 620	636,300 to 134,985	..	..	{14 5 to 22 7}
Nov. 1888 to April 1891	..	..	23 0 " 25 2	25 2	..	4,088	301,854	920 to 620	636,300 to 134,985	..	..	{14 5 to 22 7}
May 1882 to April 1891	188 ⁴	108,991	16 6 " 25 2	25 2	..	4,088	301,854	920 to 620	636,300 to 134,985	..	..	{14 5 to 22 7}

¹ The breadth of bar is taken at right angles to its length.² The length of bar (2,100 feet) on which the average depths and cubic contents are taken, excludes about 300 feet next Tairua Head, which is subject to frequent changes independent of those affecting the main bank.³ Bar flat on top.⁴ Two occasions removing moorings.

which she was specially ordered. If her sole duty had been on the bar, a suction dredger would have been better; but as a large quantity of the material inside the heads was clay, the bucket type was the more suitable (see Appendix). The performances inside the harbour contrasted favourably with the effects on the bar; and if she had never lifted a yard of sand from the latter place, the results would have been quite as favourable. The condemnation of the dredgers for bar work would apply equally to all operations which did not include works for the training of the currents, for it was quite impossible to secure permanent improvement of such a sand bar without some alterations in the natural conditions. The dredger was excellent in design and workmanship; and since the suspension of her work in Otago Harbour, she has done good service in Melbourne, and is now doing equally well in Lyttelton Harbour.

The average interest and depreciation on the hopper dredger, from May, 1882, to the end of 1887, amounted to $9\frac{1}{2}d.$ per cubic yard, so that the whole chargeable against the bar for dredging is:—

	£	s.	d.
Working expenses	5,294	7	0
Interest and depreciation	4,314	0	0
Total	9,608	7	0

Accordingly, the slight temporary advantage gained in the three years, before the wall had made much progress, had cost about one-seventh of the expenditure on that permanent improvement. The rate for the bar has been taken the same as for the work at other parts, because, though the distance run was much less, the losses by damage to the plant, and incidental to the difficulty of work in that exposure, were much more than in smooth water.

Between January, 1883, and April, 1891, the low-water depth over the bar, in the line of navigation, has been increased from $16\frac{1}{2}$ to $25\frac{1}{8}$ feet. Though the dredging of 62,600 cubic yards, up to the commencement of the mole at the end of 1884, had practically made no difference in the permanent depth, there was a gain of 2 feet on the removal of 27,080 cubic yards of sand in 1885, the year closing with $20\frac{1}{2}$ feet. This, indeed, shoaled to $19\frac{1}{4}$ feet under the influence of the heavy storms of August-September, 1886, but as soon as these had subsided, the deepening recommenced under the influence of the tide alone. Moreover, whereas under natural conditions, the bar was occasionally unfit

for the passage of vessels of $18\frac{1}{2}$ to 19 feet draught, there is now $30\frac{1}{2}$ to $31\frac{1}{2}$ feet depth at high-water, giving, except under circumstances of special severity, facility for the passage of vessels of the heaviest draught. Unfortunately the condition of the channel near Kaik jetty, and also a small length near Port Chalmers, limit the capacity of the whole harbour, but these places being in smooth water, their improvement can be accomplished with a moderate expenditure. The breadth of the bar at the navigation channel, in a direction at right angles to its length, and at 26 feet below low-water, is less by 300 feet than in its original condition. The section given for 1891 is rather misleading in this respect, owing to the manner in which the line of the beacons passes along, instead of across this particular part of the bar in its new position. The reduction of the bar above a 26-feet low-water line, and for a length of 2,100 feet, represents the scouring away of at least 500,000 cubic yards; and considering the frequency with which the bank would be made up by storms, the material shifted by the currents must have been enormously greater. The crest of the bar in the navigation channel is 730 feet further seaward, and the centre of the 26-feet depth has shifted 820 feet in the same direction. The two columns of figures in the Table (p. 318) concerning the motion of the ridge and contours must be considered in relation to each other; and it must be borne in mind that the fluctuations outwards and inwards of the ridge are due to the extreme sensitiveness of the upper layers of sand, which are thus readily affected by even moderate currents or wave disturbances; but, on the other hand, the motion of the central point of the 26-feet depth is more nearly representative of the behaviour of the body of the bank, and has shown a fairly steady progression seaward in about six years.

The great alteration in the contour lines between 1883 and 1891, are shown on Plate 2, Fig. 7; and the manner in which the 26-feet contours are tending, indicates that a channel has been formed along the line of strongest ebb, different in direction from the original North Channel, but evidently taking its form from causes similar to those which developed the older course, though acting upon a line trending more seawards. Practically the bank has kept its position close to Taiaroa Head, while the more northerly point has wheeled round so as to present a face directly opposed to the south-east seas.

Between 1883 and April, 1891, there was a large extent of scour north-west of the line of wall. Some of this was caused by the ebb rushing past the toe of the rubble as it advanced, and some of

it is caused by the present direction of the currents; and no doubt if the wall had been raised to the proposed height, the more recent portion of the scour north-west of the wall would have been less, while the action near its line, and between that and Taiaroa Head, would have been greater. The deposit outside the position of the old bar is the natural result of the strengthened ebb in arresting the sand from the ocean further seaward than formerly; while the deposit inside has resulted from the settlement of the solid matter brought in by the flood-tide, so soon as it got into a position of less agitation, and of weakened current in the wide basin just inside the entrance.

The depths on the bar keep very steady. Nevertheless, it is evident, from the two clearly defined lines of deep water, that the strongest parts of the ebb and the flood streams are not yet forced into the same channel. So long as this is the case, the entrance to the port cannot be considered to be in such good condition as is desirable in a harbour intended for the accommodation of the large trading vessels of the present day.

Such is the history of the entrance to Otago Harbour, and it may be useful in showing certain points bearing upon the formation of bars which have been built up by the action of the ocean and tidal water alone, with no fresh-water stream of consequence, and no contribution of solid matter from the land. The comparison between the results of dredging and of the training wall, in clearing away the obstruction to navigation, will demonstrate the vast advantage of permanent works and induced scour over the merely temporary expedient of dredging.

APPENDIX.

RATES OF MATERIAL AND LABOUR FOR THE IMPROVEMENT OF OTAGO HARBOUR
ENTRANCE.

Labourers	7s. to 8s. per day.
Piles delivered at landing place . .	3s. 5½d. to 3s. 10d. per lineal foot.
Square timber delivered at landing place—	
Black pine	14s. to 17s. per 100 superficial feet.
Red pine	7s. 8¾d. to 10s. 3d. per 100 super- ficial feet.
Malleable iron	2½d. to 2¼d. per lb.

Work on Staging.

Piles—shoeing and placing ready for driving . . .	4s. to 25s. each.
„ driving, per foot in the ground	1s. 11d. to 5s.
Square timber, per 100 superficial feet	7s. to 18s.
Foot planks „ „ „	4s.
Coal for dredging, 1885	26s. 3d. per ton.
„ „ „ 1886	23s. 5d. „

COMPARISON OF EXPENSES OF HOPPER AND STATIONARY DREDGERS.

Comparing the work of the hopper dredger and that of a stationary dredger, with its attendant steamers, barges, and cranes, the following figures are arrived at. The stationary dredger selected is the “Vulcan,” with double ladder, of good design and make, and the year is 1885, when both dredgers had a good record of work.

*“Vulcan” Stationary Dredger, with Steamers, Barges, and Cranes on shore
for Discharging.*

	Per Cubic Yard.
	s. d.
Working expenses, 247,608 cubic yards (material carried about 2 miles), £15,088 16s. 11d.	1 2·64
Interest and depreciation, 12 per cent. on the dredger, steamers, and cranes, and 15 per cent. on the timber barges. Total capital value, £45,451	0 5·00
Total	<u>1 7·64</u>

Hopper Dredger.

Working expenses in raising, carrying, and depositing—

	Cubic Yards.		Miles.	Per Cubic Yard.
Bar	27,080	Double journey.	6	
Port Chalmers .	55,486	" "	19	s. d.
North Harbour .	123,849	" "	26	
	<u>206,415</u>	=	£6,809 15 7	= 0 8·00

Interest and depreciation—

12 per cent. on £44,290	=	£5,314 16 0	=	0 6·12
Total				<u>1 2·12</u>

So that the figures are in favour of the hopper dredger by $5\frac{1}{2}$ d. per cubic yard.

Fig: 1.

Fig: 2.

Fig: 3.

Fig: 4.

Fig: 5.

Fig: 6.

Fig: 7.

NOTE.
Walls C.D. and H.K. and centre of Channel E.F. proposed by Sir John Coode in 1880.