MINUTES OF PROCEEDINGS.

8TH APRIL, 1886.

Walter Shellshear, President, in the chair.

The following candidates were balloted for and duly elected as

MEMBERS:

W. M. NOAKES.

WM. PAISLEY.

Mr. WALTER SHELLSHEAR then read the following paper, the discussion on which was held at a special general meeting on the 29th April. During the reading and discussion of the paper, Mr. Trevor Jones, Member of Council, occupied the chair.

ON THE CONSTRUCTION OF BREAKWATERS AND TRAINING JETTIES.

WORKS for providing shelter to ships in time of storms, and for facilitating trade must at all times be of interest to a country whose chief source of wealth is to be found in commerce, and with our extended seaboard and rapidly developing trade, a paper on the subject of the construction of breakwaters and training jetties should be of some little public interest, and it is to be hoped that the discussion of this subject may be of practical utility.

It is proposed, firstly: To consider the different forms of breakwaters that have been constructed for the protection of bays and the formation of artificial harbours. Secondly: To describe the various forms of training jetties that have been used for the improvement of river entrances, with a view to showing how far the valuable experience gained in other parts of the world may be profited by in New South Wales when works of this class are taken in hand with the object of improving the shelter of our bays, and the removal of the sand bars from our river entrances.

The object to be attained by the construction of a breakwater is to provide shelter to ships in time of storms, and still water where the operation of loading and discharging cargo can be carried on without danger or inconvenience.

Before considering the various details of construction, it may be well to examine the forces that are brought into play by the waves.

If this part of the subject is carefully studied, the author is of opinion that the cause of many of the failures that engineering history records may be understood, and the inherent weakness that has proved to exist in these cases can be guarded against, and the chances of success to a great extent insured.

The following description of wave-motion in water is founded chiefly on the theoretical investigations of Mr. Airy (now Sir George B. Airy) and others, and the observations of the Messrs. Weber and of Mr. Scott Russell, with a few additions founded on later researches :—

Rolling waves in water are propagated horizontally, the motion of each particle takes place in a vertical plane, parallel to the direction of propagation; the path or orbit described by each particle is approximately elliptic, and in water of uniform depth the longer axis of the elliptic orbit is horizontal, and the shorter vertical; the centre of the orbit lies a little above the position that the particle occupies when the water is undisturbed; when at the top of its orbit the particle moves forward as regards the direction of propagation, when at the bottom, backwards.

The particles at the surface of the water describe the largest orbits; the extent of the motion, both horizontally and vertically, diminishes as the depth below the surface increases, but that of the vertical motion more rapidly than that of the horizontal motion, so that the deeper a particle is situated the more flattened is its orbit; a particle in contact with the bottom moves backwards and forwards in a horizontal straight line.

In water that is deep, as compared with the length of a wave (or distance between two successive ridges on the surface of the water) the orbits of the particle are nearly circular, and the motion at great depths is insensible.

The period of a wave is the time occupied by each particle in making one revolution, and is also the time occupied by a wave in travelling a distance equal to its length. Thence we have the following proportion :—

$$\frac{\text{Mean speed of a particle}}{\text{Speed of the wave}} = \frac{\text{Circumference of particle's orbit.}}{\text{Length of wave.}}$$

The speed of the waves depends principally on their length and on the depth of water, being greatest for long waves and deep water.

When the depth of water is greater than the length of a wave, the speed is not sensibly affected by the depth, and is almost exactly equal to the velocity acquired by a body in falling through half of the radius of a circle whose circumference is the length of a wave. In water that is very shallow, compared with the length of the waves, the velocity is nearly equal to that acquired by a heavy body in falling through half the depth of the water added to three-fourths of the height of a wave.

Two or more different series of waves moving in the same, different, and contrary directions, with equal or unequal speeds, may traverse the same mass of water at the same time, and the motion of each particle of water will be the resultant of the respective motions which the several series of waves would have impressed upon it had they acted separately. This is called the interference of waves.

When a series of waves advances into water, gradually becoming shallower, their periods remain unchanged, but their speed, and consequently their length, diminishes, and their slopes become steeper. The orbits of the particles of water become distorted, as at B C D (Plate 10, fig. 1), in such a manner that the front of each wave gradually becomes steeper than the back; the crest, as it were, advancing faster than the trough. At length the front of the wave curls over beyond the vertical, its crest falls forward, and it breaks into surf on the beach.

As the energy of the motion of a given wave which advances into shallowing water, or up a narrowing inlet, is successively communicated to smaller and smaller masses of water, there is a tendency to throw these masses into more and more violent agitation; that tendency may either take effect, or it may be counteracted, or more than counteracted by the loss of energy which takes place through the production of eddies and surge at sudden changes of depth, and through friction on the bottom.

When waves roll straight against a vertical wall as in Plate 10, fig. 2, they are reflected, and the particles of water for a certain distance in front of the wall have motions compounded of those due to the direct and reflected waves. The results are of the following kind :—The particles in contact with the wall, as at A, move up and down through a height equal to double the height of the waves, and so also do those at half a wave length from the wall, as at C; the particles at a quarter of a wave length from the wall, as at B, move backwards and forwards horizontally, and intermediate particles oscillate in lines inclined at various angles.

In order that a surface may reflect the waves, it is not essential that it should be exactly vertical. According to Mr. Scott Russell, it will do so even with a batter of 45 deg.

A vertical or steep surface which is wholly covered by the water, reflects the wave-motion of those layers of water which lie below its level, and thus a sunken rock or breakwater, even though covered with water to a considerable depth, causes the sea to break over it, and so diminishes the energy of the advancing waves.

The greatest length of waves in the ocean is estimated at about 500 feet, which corresponds to a speed of about 53 feet per second, and a period of 11 seconds. Their greatest height is given by Scoresby as about 43 feet, and this, with the period just stated, gives 12 feet per second as the velocity of revolution of the particles of water.

In smaller seas the waves are both lower and shorter, and less swift; and, according to Mr. Scott Russell, waves in an expanse of shallow water of nearly uniform depth never exceed in height the undisturbed depth of the water. But the concentration of energy upon small masses of water, which occurs on shelving coasts in the manner already stated, produces waves of heights greatly exceeding those which occur in water of uniform depth, as the following examples show. Pressures of waves against a vertical surface, at Skerryvore, as observed by Mr. Thomas Stevenson :—

	Summer average.	Winter average.	Storms.
In lbs. per square foot... ...	611	2086	6083
In feet of water...	9.8	33	97

Greatest height of breakers on the south-west coast of Ireland, as observed by the Earl of Dunraven, 150 feet.

Recent investigations tend towards the conclusion, which is in accordance with observation, that every wave is more or less a "wave of translation," setting down each particle of water, or of matter suspended in water, a little in advance of where it picked that particle up, and thus by degrees producing that heaping up of waves which gather on a lee-shore during storm. This property of waves accounts for the facts that, although they tend to undermine and demolish steep cliffs, they heap up sand, gravel, shingle, or such materials as they are able to sweep along, upon every flat or sloping beach against which they directly roll, that they carry such materials into bays and estuaries, and that when they advance obliquely along the coast they make the materials of the beach travel along the coast in the same direction.

The action of waves against a vertical wall is well illustrated in the case of the new breakwater at Wicklow. The waves never strike this breakwater a blow; they rise strongly and pile up against the breakwater, the rebounding wave annihilating the incoming wave. The extent to which waves acting obliquely along a coast cause the materials of the beach to travel is well illustrated along the coast of New South Wales, where at almost every inlet sand spits are found forcing their way across the entrance by this action.

The effect of a wave rising up against a breakwater is to cause a considerable difference of pressure against the two sides of the wall, and if the wall is not solid, or founded on loose material, the hydraulic pressure due to the differences of height will cause the water to be forced through every joint with a great velocity, thus tending to wash out the materials from the foundation. Again, as the wave recedes the action will be reversed, and when it is remembered how great this difference of pressure may be in time of storms it is not difficult to imagine that considerable displacement may take place in the foundations when these are constructed of loose rubble, and that the various parts of the structure will sooner or later be ground to shingle by the motion imparted to them by undulations of the waves.

The consideration of the above action leads to the question of foundations and the security of this part of the work is of the first importance. The bottom at the site of a breakwater may be rock, clay, gravel, or sand, and it is evident that the plan of securing the foundations will have to be modified to suit the nature of the bottom. In describing the different types of breakwaters, the various plans for securing the foundations will be considered as they may be applicable to the class of work under discussion.

The range of tide is an important factor when considering the cost and strength of a breakwater, as the greater the range of tide the larger the surface of the works exposed to the maximum effect of the waves. With these few preliminary remarks it is next proposed to describe the various types of breakwaters protecting harbours in various parts of the world.

Breakwaters may be classed under three heads:—Firstly: Those constructed of loose blocks of stone or concrete, and deposited without regard to bond, the materials taking their natural slope under the action of the waves. This system is known as the *pierre perdu* (literally "stone at random") system. Secondly: Those constructed with a *pierre perdu* base up to near low water-mark surmounted by a solid superstructure of masonry or concrete. Thirdly: Those constructed with solid masonry or concrete throughout.

Of the first system of constructing breakwaters, namely: the *pierre perdu* or random block system, the breakwater at Plymouth (Plate 10, fig. 3), is a good example. It is formed in a bay sheltered on three sides by land rising to a considerable height, and only open to the south. Several banks or natural reefs of rock exist, between which and the shore there were three principal passes towards the east, the west, and in the centre. The breakwater is erected on the banks situated the nearest to the interior of the harbour, and closes the centre passage. The banks situated more towards the open sea serve to break the fury of the waves before they arrive upon the breakwater. The main body of the breakwater is placed perpendicularly to the south-south-east, from which quarter the severe storms assail the Plymouth roads. The total length is 1,700 yards, and the two arms, forming on either side angles of about 135 deg. with the centre, occupy respectively 350 yards each. A surface of about 1,120 acres is, by means of this work, rendered available for large vessels.

Originally it was intended to make the width of the top of the breakwater only 11 yards, and the bottom about 55 yards; but during the execution of the works the width of the top has been increased to 15 yards, and that of the bottom to 133 yards. At the level of the low water at spring tides a set-off 22 yards in width is formed, and the slopes from this point upwards, on the sea side, are paved with large stones 4 feet by 3 feet 6 inches, by about 3 feet thick, laid with an inclination of 5 base to 1 height and bedded in Roman cement; and it is proposed to continue this paving below low water line by means of the diving-bell. The height of the crown is only 2 feet above the level of high spring tides.

It appears to be beyond question that the long slope of the Plymouth breakwater is less exposed to be injured by violent shocks of the sea than in the case of Alderney (to be hereinafter described) where a vertical wall surmounts the rubble mound; but at the same time it is equally beyond question that the latter destroys far more effectually the agitation and undulation of the open sea, and offers a greater resistance to their transmission into the inner harbour, because the waves in Plymouth Sound during violent storms break over the slope; whilst in the case of works built on the system adopted at Alderney all their effect is destroyed by the wall. In the latter case, however, the descending motion of the return wave is materially interfered with. The vertical wall at the top of the long slope transforms it, in fact, into a horizontal motion, whose velocity is highly dangerous to the stability of the foundation of the wall. It is also found that the large blocks of stone detached from the outer slopes are driven against the outer face of the wall with extraordinary violence during great storms, whilst upon the long paved slope of the Plymouth breakwater the waves not meeting with any abrupt resistance, break in precisely the same manner upon the incline that they would do upon a natural shore, and with a considerably diminished degree of violence. It is true that, in consequence of this form, they acquire an increased horizontal velocity in their original direction; but as the top of the slope is rendered as smooth as possible, there are no salient points in the masonry able to attract, as it were, the destructive action of the waves. Notwithstanding the precautions observed in the execution of the top slope of the breakwater, it is by no means of rare occurrence that blocks weighing from 2 to 5 tons are carried over from the sea to the land side; and in February, 1848, considerable damage was caused to the upper parts, showing that even with special precaution of paving the slope with large blocks set in cement, it is by no means uncommon for the mound to be considerably disturbed in time of storms. The cost of this work was very considerable, being no less than £300 per foot run. The average cross section of the breakwater is about 10,920 square feet.

The breakwater at Algiers is another example of this system of construction. This work was at first constructed wholly of large blocks of concrete, about 13 cubic yards in volume, weighing about 25 tons each, in water averaging 50 feet deep. But in prolonging the mole, since 1847, a less costly system was adopted according to Plate 10, fig. 4. Small rubble was deposited on the bottom, up to a level 33 feet below the water line, to the natural slope of 1 to 1, so economising, to a great extent, the cost for the sub-structure. Upon this base the remainder of the work, consisting of blocks of concrete, was deposited to a slope of $1\frac{1}{4}$ to 1 on the seaward side, and of 1 to 1 landwards, finishing at the water line at a width of 46 feet. The cost of the breakwater amounted to £122 per lineal foot. The average cross section of this breakwater is about 5,000 square feet.

But, comparing this with Plymouth, it must be remembered that there is practically no tide at Algiers and a range of about 15 feet at Plymouth. The principal disadvantages of the *pierre perdu* system are the great quantity of material required in their construction, and the liability of being gradually converted into banks of shingle by the continual motion of the various stones, of which they are constructed, grinding each other firstly from angular blocks to boulders, and then from boulders to shingle, and also the liability of considerable displacement of the material in time of storms.

Of the second system, namely: that with a rubble base deposited *pierre perdu*, and a solid superstructure, three examples may be briefly referred to. The first is the Alderney breakwator. This work was commenced in 1847 and completed in the end of 1864. The rise of spring tides is 17 feet, and the depth at low water increases from 45 feet near the shore to 133 feet at the head of the pier. The total length of the breakwater is 4,700 feet. On a long slope base of *pierre perdu*—hard stone from Manney quarry—large and small, the superstructure for the most part consists of a sea-wall and a harbour wall, with filling in the intermediate space, surmounted by a promenade. It was constructed with a few modifications of structure as the work advanced. The last 2,000 feet were constructed to the section Plate 10, fig. 5, the final length of 66 feet constituting the head of the pier was somewhat stronger. It was presumed that the rubble stone would not be disturbed by waves at a greater depth than 12 feet below low water, and the foundations of the superstructure were carried to that level. The quay is 20 feet wide, and the promenade is 14 feet wide, making together a width of 34 feet. The faces were built with a batter of 4 inches in 1 foot. The quay stood 6 feet above high-water level, and the promenade was 10 feet higher. Great disturbances were experienced in the rubble mound. It was found impossible, even with the large quantities deposited for renewing the foreshore, to maintain the level of the mound close to the sea-wall at the level of low water. The disturbance extends to a distance as much as 80 or 90 feet from the seaward wall, at the maximum depth of 20 feet. The great distance and depth of the disturbing action are attributable, no doubt, to the recoil of the waves from the wall, as each wave, during a storm, rises to a great height above the breakwater, then falls and rushes down the slope to the mound, opposing an overpowering resistance to everything in its course till it rebounds some height into the air on meeting the next wave, at a distance of about 70 or 80 feet from the wall. It was estimated that at least 25,000 tons of large stone would be required to be deposited each year in order to maintain the sea-slope of the mound, and prevent the superstructure from being undermined. Breaches were made in the superstructure at various points—mostly in the deeper water. The rubble was dashed against the seaward wall, and, no doubt, helped to open the breaches. The superstructure subsided unequally at different portions, longitudinally as well as transversely, and cracks and openings were formed in the interior; so that the action of the water entering these openings, in conjunction with the confined air, under the pressure of the waves, aided in producing cracks. That subsidence, in a considerable degree, should have taken place under the weight of the superstructure on such an unprecedentedly deep base of rubble might have been expected. The settlement amounted to about one-twentieth of the height of the mound, though it was not uniform. At the head the superstructure settled at least six feet. The nature of the settlement is illustrated by the Plate 10, fig. 6. The total cost of the works of construction and maintenance, extending over a period of twenty-five years, amounted to £1,274,200. Of this sum £57,200 was expended in repairs of damages caused by the sea to finished and unfinished work, leaving the net cost, £1,217,000, at the rate of £259 per lineal foot, for a depth averaging probably about 90 feet below low water. The average cross section of the breakwater is about 13,000 square feet.

Another instructive example of the characteristic behaviour of mixed rubble foundations of breakwaters at the surface of the sea is supplied in the case of the breakwater at Holyhead Harbour. This breakwater consists, like that of Alderney, of a mound of mixed rubble quartz-rock from an adjoining hill, upon which is erected a substantial stone superstructure, finished with a transverse head carrying a lighthouse. The breakwater, 7,860 feet in length, in a depth of water averaging 40 feet at low spring tides, with a maximum depth of 55 feet. Ordinary spring tides rise 17 feet equinoctial tides, 20 feet. The slope of the foreshore, according to the section Plate 10, fig. 7, is 12 to 1 above low water, and for a foot or two below it, where it assumes a slope of 5 to 1, to a depth of 10 or 12 feet below low water, and thence about 2 to 1 to the bottom. Landwards the slope is $1\frac{1}{4}$ to 1. The width of the mound at low water level is at least 250 feet. In 50 feet of water the width at the bottom is about 450 feet. The weight of the rubble stone in bulk is 1 ton per 20 cubic feet. The stone was deposited from a temporary wooden stage.

The rubble mound having been formed and consolidated by the action of the sea, the superstructure was erected, for the foundation of which the rubble was excavated to the level of low water. The principal object of the superstructure was to shelter the interior of the harbour, and to prevent the loose deposit from washing into the harbour. The outer wall has a total thickness of $17\frac{1}{4}$ feet at the upper part, with a batter to the base, which is 23 feet wide. The total height to the top of the parapet is $25\frac{1}{2}$ feet above high water. The inner wall, distinct from the outer wall, is formed with a vertical face to the harbour and is 8 feet wide at the base. It stands 10 feet above high-water level. The width of the quay-way is 40 feet, and the total width at the base of the superstructure is 64 feet. The hearting consists of rubble. The total cost of the breakwater was £163 per lineal foot.

The rubble on the seaward side is exposed to the force of the waves at all times of the tide, and it is stated that it is subject to shifting and drifting, and to be reduced to the condition of shingle. From the ascertained results of the action of the sea at Alderney, this effect is what might have been expected. The flatness of the exterior slope, 12 to 1, is no doubt much below the angle of settlement of rubble under the action of the sea waves; and this consideration may have formed an element in the original design in the anticipation that therefore the rubble would not be disturbed. It is on record, nevertheless, that as a matter of fact the rubble foreshore has been in some places washed away from the lower part of the superstructure, and in other places piled up to within a few feet of the parapet.

The breakwater at Marseilles (Plate 11, fig. 8) has been constructed upon a system embodying the combined experience of Cherbourg and Algiers. On the one hand, the idea of directly opposing the powerful action of the waves by enormous blocks, artificially constructed, has been taken from the mole at Algiers; while on the other the breakwater at Cherbourg suggested the employment of natural blocks of all dimensions to constitute the main body of the work. The former serve as a facing to the latter, and in the present instance both have been used simultaneously in such a manner as not to have the natural blocks exposed to the great force of the waves. As this force sensibly diminishes at a depth of about 15 feet below ebb-tides, the use of artificial blocks has been limited to about 20 feet below that level.

The value of large artificial blocks to protect the outer slope will be better understood when it is remembered that the action of the wave is in proportion to the surface struck, while the resistance of a block increases as its cube.

With the twofold view of solidity and economy, positions have been assigned to the natural blocks according to their respective dimensions. This course has been adopted in preference to the plan followed in the construction of the works already mentioned, in which the stone was used indiscriminately as it came from the quarry. From considerations of economy the small materials have not been mixed with the large in order to preserve the greatest possible void. With a view to solidity, the large blocks have been so disposed as to entirely surround the small ones.

Experience has fully confirmed the rationale of these ideas. The part of the breakwater which protects the basin of La Joliette was commenced 27 years ago, and is at the present time in an excellent state of preservation, time having, therefore, satisfactorily demonstrated the excellence of this system. The cost of this