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EDWARD WOODS, President,
in the Chair.

(*Paper No. 2198.*)

"Concrete-Work under Water."

By WALTER ROBERT KINIPPLE, M. Inst. C.E.

IN 1856, the Author commenced a series of experiments, which were extended over several years, with the object of finding out some means by which Portland cement might be employed with equal success below water as above, in the construction of monolithic works without the aid of heavy and costly plant, to which reference was made in the discussion on Mr. Grant's Paper on the strength of cement in 1865.[1] The Author thinks that the practical results gathered from his experiments, and from depositing concrete under water in various important works which he has carried out since 1856, may assist in determining the best method of employing Portland cement under water so as to obtain thoroughly reliable work at a moderate cost. He considers that the present methods of constructing submarine works with Portland cement do not accomplish these objects, owing to the cost of the excessive proportion of cement required for concrete deposited *in situ* when freshly mixed, or the expensive plant needed for large concrete blocks.

In his early experiments in 1856, the Author's attention was attracted to the property possessed by partially-set concrete of uniting under water into a solid mass, though passed through the water in lumps sufficiently set to resist a current of water and some action of the sea. Since then he has constantly used this plastic concrete, as he has termed it, for concrete-work under water, both in large and in small works.

The portion of the south-west pier quay-wall at the Garvel

[1] Minutes of Proceedings Inst. C.E., vol. xxv. p. 125.

Basin, Greenock, below low-water, was formed of plastic concrete deposited behind a facing of greenheart piles (Plate 1, Fig. 1). The concrete next the piling, for a thickness of 3 feet, was composed of 2 parts of cement to 7 of sand and ballast, and the remainder of 1 of cement to 6 of sand and ballast; the former was left to set for nearly three hours, and the latter for nearly five hours before being deposited; but a longer time was allowed for slow-setting, and a shorter time for quick-setting cement. The condition also of the atmosphere, and the quantity of water used in mixing, affected the rate of setting. The best results were obtained when the ingredients were mixed with the smallest possible quantity of water, and then at once rammed into the boxes, and deposited under water as soon as the concrete had set to the consistency of stiff clay. If the concrete was deposited too soon after mixture, a loss of cement resulted, and if left to set till nearly hard, it was unfit to unite with the mass of the concrete after deposition. Where there are currents or much disturbance of the water by waves, it is advisable to add a small quantity of quick-setting cement to the plastic concrete just before deposition, as this stiffens the concrete considerably, and materially helps it to resist currents or wave-action, whilst not interfering with its property of setting and uniting with the mass of concrete previously deposited. The work was very satisfactorily executed in depths of from 8 to 38 feet below high-water, at a cost of 30*s.* per cubic yard for the front concrete, and 21*s.* for the back.

At the entrance to the West Harbour, and along the face of the Steamboat Quay, Greenock, a concrete wall, 1,150 feet long and from 3 to 17 feet thick, was formed between two rows of sheet-piling, in depths of from 15 to 30 feet below high-water, and raised 6 feet above high-water. The work was carried on at all states of the tide, with plastic concrete composed of 1 part of cement to 6 parts of sand and ballast, at a cost of 15*s.* per cubic yard. The work between high- and low-water could be daily inspected at low-water, when it was seen to be perfectly sound; and the Author considers that this was entirely due to the care taken in letting the concrete set partially before being deposited. The divers reported that the part of the wall under low-water was as sound as that above. A bed of 6 to 1 concrete, 220 feet long, 26 feet wide, and $4\frac{1}{2}$ feet thick, was also deposited at the entrance to the West Harbour, at a depth of 20 feet below low-water, as a foundation for the roller-path of the movable bridge spanning the entrance. It proved thoroughly sound, and cost 18*s.* per cubic yard. In both these works, the concrete was rammed thoroughly into the boxes and allowed to set for two or three hours before being deposited, as at the Garvel Park Dock.

Experiments made at the Garvel Park dock works by Mr. Daniel Macalister, Assoc. M. Inst. C.E., show that $3\frac{1}{2}$ to 1 concrete, after setting out of water for eighteen hours, and then rammed into moulds, will form a monolithic mass when afterwards placed in water; but that the strength of this mass will very much depend upon the time allowed for setting before deposition. If only eight hours elapse between mixing and deposition, there is practically no reduction in strength; but with a longer interval, the strength is gradually reduced, until at about eighteen hours it is little more than one-half.

At the Girvan Harbour extension works in Ayrshire, designed and carried out by the Author, a pier, groyne, and quay-wall were constructed of concrete deposited in a plastic state (Plate 1, Figs. 2, 3, 4, and 5). The face-work of the pier above low-water was at first constructed within temporary sheet-piling, which, even when lined with grooved and tongued boarding, proved unsatisfactory; and subsequently a facing of dove-tailed concrete blocks, 21 inches long and 12 inches deep, bonding into the concrete hearting, was adopted with success where the wash was very great (Plate 1, Figs. 6 and 7). As the blocks only weighed about 180 lbs. each in air, and 80 lbs. in water, they were easily handled without a crane. These blocks extended from low-water level to the underside of the coping at 6 feet above high-water (Plate 1, Fig. 2); they were made of 1 part of Portland cement to 4 parts of sand and fine gravel; and their exposed faces and arrises were rendered with a $\frac{1}{2}$-inch coat of 1 to 1 Portland cement mortar. Small semi-dovetailed grooves all round the outer arrises of each block made (when the blocks were laid in position) complete dovetailed grooves with the adjacent blocks, which, as each course was laid, were filled up with clay or quick-setting cement, making the blocks into a water-tight dam, behind which the plastic concrete was deposited to within 6 inches of their tops. Thick cement grout was then poured down the circular holes in the centres and end joints of the blocks, which spread over the hollowed-out beds, and flowed into the hearting, firmly cementing it to the facing blocks.

The pier was constructed by enclosing lengths of 15 feet by 3 feet high with these blocks, and filling these lengths with plastic concrete. The surface of the concrete in these compartments was effectively protected, at the close of each tide or day's work, by a covering of closely-packed pitching, grouted with fine concrete, and finished off with a grout composed of 3 parts of Portland cement to 1 part of a quick-setting cement.

In the construction of the groyne (Plate 1, Figs. 3 and 4), a movable shield was used, formed of wrought-iron plates and angle-irons, with two sides and one closed end, or nose, and one open end. It was about 40 feet long, and extended from the foundation, at 1 foot above low-water, to the coping at 3 feet above high-water; it fitted closely to the groyne, and enclosed about 33 feet of the newly-formed work, leaving a space, about 7 feet long, between the nose of the shield and the end of the groyne, in which the plastic concrete was deposited almost independently of the state of the weather. When the shield was in good order, 120 lineal feet of groyne were completed in a fortnight. This shield was rendered useless during a severe gale, having been constructed by the contractor rather as an experiment than to withstand heavy seas. The Author had suggested the shield to the contractor, and was so well satisfied with its capability during the construction of the groyne that he subsequently designed a large one adapted for the construction of a breakwater (Plate 1, Figs. 16 and 17). The remainder of the groyne was carried out more slowly, partly by means of a facing of close piling, and partly by dove-tailed facing blocks. The average cost of the concrete in the pier and groyne, including the facing-blocks, was 13*s.* 6*d.* per cubic yard.

At Wick, the Author, in rebuilding the head of the South Pier, which had been destroyed during the storm of February 17, 1880, formed blocks of 60 to 140 tons in position in sailcloth, which protected them from the waves till the mass was firmly set. A piece of sailcloth, of sufficient size to enclose the block, was turned up to form a sort of bag, in which plastic concrete was deposited; and when full, the edges were folded over, and kept down with heavy iron weights till the concrete had set. The whole of the rubble base of the South Pier was encased by this means in a mass of 6 to 1 concrete, and has resisted the gales of several winters without the slightest damage. The concrete cost about 18*s.* per cubic yard. On one occasion, a 60-ton block formed in position on the end of the pier, 2 feet above low-water, resisted a most severe storm within twenty hours after its completion, although the sailcloth was wholly removed by the waves.

At the Quebec harbour works, the Author formed the quay-walls of cribwork, filled with plastic concrete (Plate 1, Fig. 8). The conditions under which works are carried out at Quebec differ considerably from those of this country, for the working season is confined to about half the year, and all plant or temporary works must be removed at its close, as only substantial works can resist the breaking-up of the ice in spring. The cribs were constructed during the winter of 1878 and the following spring, and between May and November, 1879, were floated into position, and sunk on the tops of bearing-piles, 24 feet below low-water. The cribs, extending over a length of 1,250 feet, were each 40 feet long, 33 feet wide at the base and 23 feet at the top, and 27 feet high; and their front cells were filled from bottom to top with plastic concrete in the following proportions, namely, the front 2 feet of concrete in the proportion of 4 to 1, and the remainder 8 to 1, and costing respectively 26*s.* and 19*s.* 9*d.* per cubic yard. The floating out of the cribs forming the entire length of 1,250 feet of work, dredging out the trench, sinking cribs into position on the bearing-piles, filling up the front cells with concrete, and the back cells with clay and stones, occupied about five months, being at the rate of 1 lineal foot of complete work up to 3 feet below low-water per working hour.

Plastic concrete was used by Mr. W. Smith, M. Inst. C.E., at Aberdeen Harbour, on the Author's advice, for the substructure of a new quay-wall founded 24 feet below high-water spring-tides, having a height of 14 feet, and a thickness of 10 feet, which was increased to 12 feet at the base by a sloping toe in front (Plate 1, Fig. 9). Three complete frames, formed of timber strengthened with angle-irons, and placed 10 feet apart, were first filled with concrete; and three intermediate frames, with only back and front, were subsequently filled (Plate 1, Fig. 10). The concrete in the first compartment was composed of 1 part of Portland cement, 3 parts of coarse sand, and 4 of granite chips; and in the other compartments, for one-third of the height, of 1 part of Portland cement, 2 parts of sand, 3 of granite chips; and for the remainder, of 1 part of Portland cement, and 7 parts of sand and chips, with about 12 tons of rubble in each compartment. The concrete for the first compartment was allowed to set twelve hours after mixture before being deposited in the frames, the cement being old and slow-setting. The concrete was found perfectly hard on the removal of the framing after three weeks. In constructing another quay-wall somewhat similarly, Mr. Smith allowed only from one to two hours before depositing concrete made with quick-setting cement. Both these walls were carried on at all states of the tide.

Some experiments were carried out by Mr. Smith at Aberdeen, and Mr. H. G. H. Spencer, Assoc. M. Inst. C.E., at St. Heliers, Jersey, at the Author's suggestion, under the belief that the system of grouting, adopted by him for joining the face blocks at Girvan, might be advantageously extended. At Aberdeen, a timber box, 6½ feet long, 1 foot wide, and 4 feet deep, was filled with round smooth stones of basalt and whinstone, from 1 to 4 inches in diameter, and was lowered to the bottom of the tidal harbour in a depth of 18 feet at high-water spring-tides. At high-water, a thick grout of 4 parts of Portland to 1 part of Sheppey cement was poured down a wrought-iron pipe, 3½ inches in diameter, reaching down 12 inches into the box, and rising a few feet above the water-level; and this grout filled the interstices between the stones. After twelve days, the box was lifted out of the water by means of the pipe, which had become firmly cemented into the concrete; and on removing the sides of the box, the concrete was found to have a smooth surface, and to be perfectly solid throughout. At Jersey, two experiments were made. First a box, about 6 feet cube, was filled with shingle, and a 1½-inch gas-pipe was inserted 18 inches into it, and when the tide had risen 20 feet above the box, thick neat cement grout was poured down the pipe; on opening the box afterwards, its contents were found united into a solid mass, with the grain of the rough-sawn timber of the box imprinted upon the surface of the concrete, so completely had the grout filled up all the interstices of the box. Secondly, a box, 2 feet cube, filled with shingle, was suspended 60 feet under water in the strong tide-way of the Little Roads. A thick grout of Portland cement was poured through a tube reaching down to the box, which united with the shingle into a single concrete block. The block was not so perfect as in the first experiment, owing to the bottom zinc tubing being crushed by the weight of the iron tubing above, which allowed the grout to escape; but the failure was only partial, for one-half of the block was thoroughly solid and had sharp arrises. These experiments confirm those made by the Author in 1858, in proving the feasibility of cementing shingle in foundations at great depths, grouting up fissures, and repairing works undermined by the sea or scour.

Portland cement grout was successfully used by the Author, in 1882, in stopping considerable leakages at No. 1 Graving Dock in the West Harbour, Greenock, which had given so much trouble for some years as to lead to proposals for reconstructing or removing the dock. Bore-holes were made, 1 foot to 2 feet apart, through the masonry behind the heel-posts into the sand for several feet below the foundations, and also through the inner and outer aprons near the pointing-sill, on which latter holes stand-pipes were set up. A thick grout of neat Portland cement was poured down these holes, which permeated the various fissures and open joints to a distance, in some cases, of 18 feet from the bore-holes, virtually joining the bore-holes together, and thereby forming a water-tight sheeting of cement; and about 5 tons of cement were used in grouting up the holes. The grout was only poured down the stand-pipes when the water was at the same level inside and outside the dock; and it carried down the water-level inside the pipes 6 feet below the water-level outside. Before these operations were carried out, an 18-inch pump was constantly working to keep down the leakage; whereas subsequently, only one hour's pumping was required in forty hours.

Grouting might be extensively used in forming the hearting of piers and quay-walls by packing small grooved blocks (Plate 1, Fig. 11), composed of concrete consisting of 12 parts of gravel to 1 part of cement, behind a facing of blocks like those at Girvan pier (Plate 1, Figs. 6 and 7), and then grouting them together into a solid mass by neat cement poured down through tubes from the surface of the water. Large hearting-blocks deposited by a crane might be economically substituted for hand-blocks in large works; for the saving in cement and diving work would more than compensate for the cost of the plant.

Some of the various methods of constructing monolithic piers in the sea with plastic concrete, proposed by the Author, are shown in Plate 1, Figs. 12 to 17. One system of construction is by means merely of sand-bags and sailcloth. A trench must first be dredged for a foundation, and its irregularities filled up with plastic concrete, forming a fairly level surface upon which concrete blocks can be cast in position. The facing blocks are first cast in a mould, formed by piled-up sand-bags lined with sailcloth, whose sides and ends are then folded over the concrete and weighted down, protecting it completely from the action of the sea; as soon as the block is sufficiently hard, the weights and sand-bags are removed, and the loose sailcloth is cut away. The adjoining blocks are then formed in a similar way, the side of the previous block serving for one side of the mould instead of a pile of bags. The blocks can be cast of any size and shape; but there is little need to make them break joint, as being concreted together they form a monolithic mass, thus differing from the ordinary dry block and bag systems which depend upon the weight of each block and the proper breaking of joint throughout the work. The facing above low-water may consist of small dove-tailed blocks, similar to those used at Girvan pier, or of various other forms of facing; and the hearting between the facing blocks can be formed by concrete blocks cast in position, like the lower portion of the pier. By the above method, a monolithic pier or breakwater can be formed with the minimum amount of plant. The system is well suited for constructing works in exposed localities above low-water level; and even though its cost below low-water would be increased by diving work, it might be advantageously adopted where expenditure on special plant is unadvisable.

In sheltered situations, and during calm periods, the sailcloth and bags of sand may be dispensed with, and the plastic concrete hearting deposited behind the facing blocks without any protection. The facing blocks may be similar to those of Girvan pier; or much larger blocks might be deposited by cranes; or a facing of concrete blocks cast in position might be adopted. The plastic concrete is deposited in a series of cells formed by cross walls of blocks; and by keeping the outer walls above the level of the hearting, the wave-disturbance over the surface of the hearting is reduced.

Another simple inexpensive method of constructing breakwaters without special plant is shown in Plate 1, Figs. 12 and 13. Mounds of plastic concrete are deposited in two trenches excavated along the lines of each face of the breakwater; and round wrought-iron piles are driven into the soft concrete, along the top of each mound, through the eyes of distance-bars, and their heads are held in position longitudinally by similar bars, and transversely by wire ropes anchored out on each side of the breakwater, and connecting them across the breakwater, and provided with adjusting shackles to keep the piles in line (Plate 1, Fig. 12). Oak planking is secured to the piles at the back by loop bolts, so that the planks, fastened in groups of two or three, are free to slide down (Plate 1, Fig. 13). Openings in the joints of the planking are covered with sailcloth before the fine plastic concrete is placed against the faces; and the work is advanced in steps by help of partition walls at intervals, formed of plastic blocks or sand-bags; and sailcloth with weights may be used to cover up each day's work.

Concrete caissons, forming a modification of the system of crib-work blocks adopted by the Author at Quebec, might be extensively used in constructing considerable lengths of breakwater at a time (Plate 1, Figs. 14 and 15). The caissons may be built on launching-ways on shore, and, when thoroughly seasoned, may be towed into position in favourable weather, and sunk by admitting water, either by means of pipes (Plate 1, Fig. 14), or by pumping over the side. A foundation for the caisson may be formed by excavating a trench and filling it up level with concrete, or with gravel, subsequently grouted with cement poured down stand-pipes through the caissons. Bearing surfaces are formed on the bottom of the caissons, either of concrete (Plate 1, Fig. 14), or of timber bedded into the concrete. On sinking the caissons, the projecting bearing surfaces rest upon the prepared foundation; and the intervening spaces are afterwards filled up solid with Portland cement grout, poured down through stand-pipes. At the junction of two caissons, dove-tailed grooves filled with oakum, tallow, clay, or quick-setting cement, serve to form water-tight partitions, and prevent any cement from washing out of the joints. The interior of the caissons may be filled with plastic concrete, and large stones, which, when raised nearly to the top of the caisson, can be protected for a time, if necessary, by weighted sailcloth, or with a paving of small grooved blocks grouted with quick-setting cement. The caissons may either be made strong enough to be floated out to withstand the waves before being filled with the hearting; or they may be strengthened by angle-iron framing built into the concrete, as shown by Plate 1, Figs. 14 and 15. The strengthening was carried much further in caissons designed for a proposed extensive breakwater, where as much buoyancy as possible was desired. In this case each caisson consisted of a framework of angle-iron having a facing of concrete; in fact, an iron caisson plated with concrete instead of iron was proposed, thus combining considerable strength and buoyancy. The caissons were to be constructed on launching-ways down which each was to be launched into a large circular barge or pontoon, and, in suitable weather, conveyed to the site of the works, sunk, and filled up with plastic concrete and large stones. A temporary wooden platform, secured to the top of each caisson, prevented water getting into the caisson when launched from the barge near the site of the works. The platform is provided with manholes, through which the concrete is lowered into the caisson; and it is not removed, to serve for another caisson, till the concrete hearting of the caisson has set hard.

A modification of the above system, specially applicable to great depths of water, consists of a base, or mound, formed of a facing of large concrete bags with a hearting of plastic concrete, raised to a suitable level below low-water, on which a concrete caisson is placed and filled up with concrete; or a rubble mound might be formed, kept below the disturbing action of the waves, as a foundation for the concrete caisson.

A system of constructing breakwaters by means of a travelling shield or casing, similar to that used at Girvan, but on a much larger scale, is shown in Plate 1, Figs. 16 and 17, inside which work may be carried on in the most stormy weather. A level concrete base is first formed for the travelling casing, into which short iron stakes or bearing-piles are driven at convenient intervals; transverse sleepers are placed on the top of these stakes, and kept in position by plastic concrete surrounding them. On these sleepers, rolled beams or other guides are laid down, along which the casing moves, either on rollers or on timber bearings. The cellular casing, formed to the cross section of the breakwater, is provided with hinged interior side linings, moved by screws to and from the face of the newly-finished work, and also with a movable end, to which hydraulic rams are attached by which the whole casing, except the movable end, is pushed forward. The casing encloses a considerable portion of the completed breakwater, thus protecting the more recent work, and steadying the casing during stormy weather. The work is constructed in lengths (Plate 1, Fig. 16); and for forming a fresh length, the hinged sides are moved back by the adjusting screws from the face of the work, the casing is pushed forward the required distance by the hydraulic rams, which, with the movable end, are then drawn back close up to the fixed diaphragm, and the hinged sides are brought tight up against the last finished length and the movable end. Water-tight joints are then formed between the hinged sides and the concrete, by india-rubber or leathern pipes let into grooves and swelled out by water under pressure so as to fill up the irregularities in the face of the work. Sailcloth may be used along the bottom of the hinged sides to protect the newly-deposited concrete from any wash. Plastic concrete can then be deposited in the space between the casing and the end of the work, where the water is so still in the roughest weather that the work can be carried on continuously. Two small tunnels could be formed in the breakwater, along which self-emptying skips could be conveyed and brought back by an endless rope, depositing their contents in the space at the end, in which the water rises and falls with the tide outside by means of sluices (Plate 1, Fig. 17). A crane at the end of the casing, fitted with a dredging bucket, serves to excavate the foundation trench in front, and may also assist in depositing the concrete. The crane can be lowered on to the top of the casing when not in use (Plate 1, Fig. 16). The casing can be floated into and out of position, and be ballasted in place by filling up the whole of the cells of the structure with water; or pig-iron may be used, to give it greater stability in rough weather.

Though the proposed casing described above constitutes expensive plant, it might prove very economical in exposed situations by enabling sea-works to be constructed independently of the state of the weather, for which purpose the Author believes it to be well suited.

Breakwaters might also be expeditiously constructed of huge concrete blocks without staging, by forming the blocks on a travelling incline, by aid of a 3-ton revolving derrick crane[1] at the upper end of the incline, down which incline the blocks would be launched, when finished, in a slanting position, into place on a bed of plastic concrete. Each block might be made 135 feet long, 46 feet wide, and 20 feet high, weighing about 6,000 tons, so as to form a complete section of the breakwater, about 66 feet in length, in a depth of 23 feet at low-water and with a range of tide of 20 feet. The main body of the concrete block might be composed of 10 parts of ballast to 1 part of cement, with an outer coat of masonry or of concrete, of which one-third was cement; and if the block was strengthened by a skeleton steel framing braced longitudinally and transversely, it could be launched without fear of fracture soon after completion. The blocks being on a slope of about 3 to 1, or only a little less than the angle of repose, could be launched with a small amount of force; or the launching-ways could be at an inclination of $2\frac{1}{2}$ to 1, and the blocks lowered down into position by brakes. The sliding down of the block, below high-water level, along the top surface of the previously laid block, would be facilitated by timbers built into the under surface of the upper block sliding on the timbers in the upper surface of the under block. By filling up adjacent recesses, left along the centre of the upper and under surfaces of each block, with plastic concrete and Portland cement grout, the successive blocks could be connected together into a monolithic mass. If the block, instead of being formed complete before launching, was constructed and launched in successive stages, so as to have only a third or fourth of the block above water at one time, the travelling incline might be made smaller. By this system, work could be carried on almost continuously throughout the year, at the rate of 2 feet a day or 600 feet per annum.

The communication is illustrated by a series of tracings, from which Plate 1 has been compiled and engraved.

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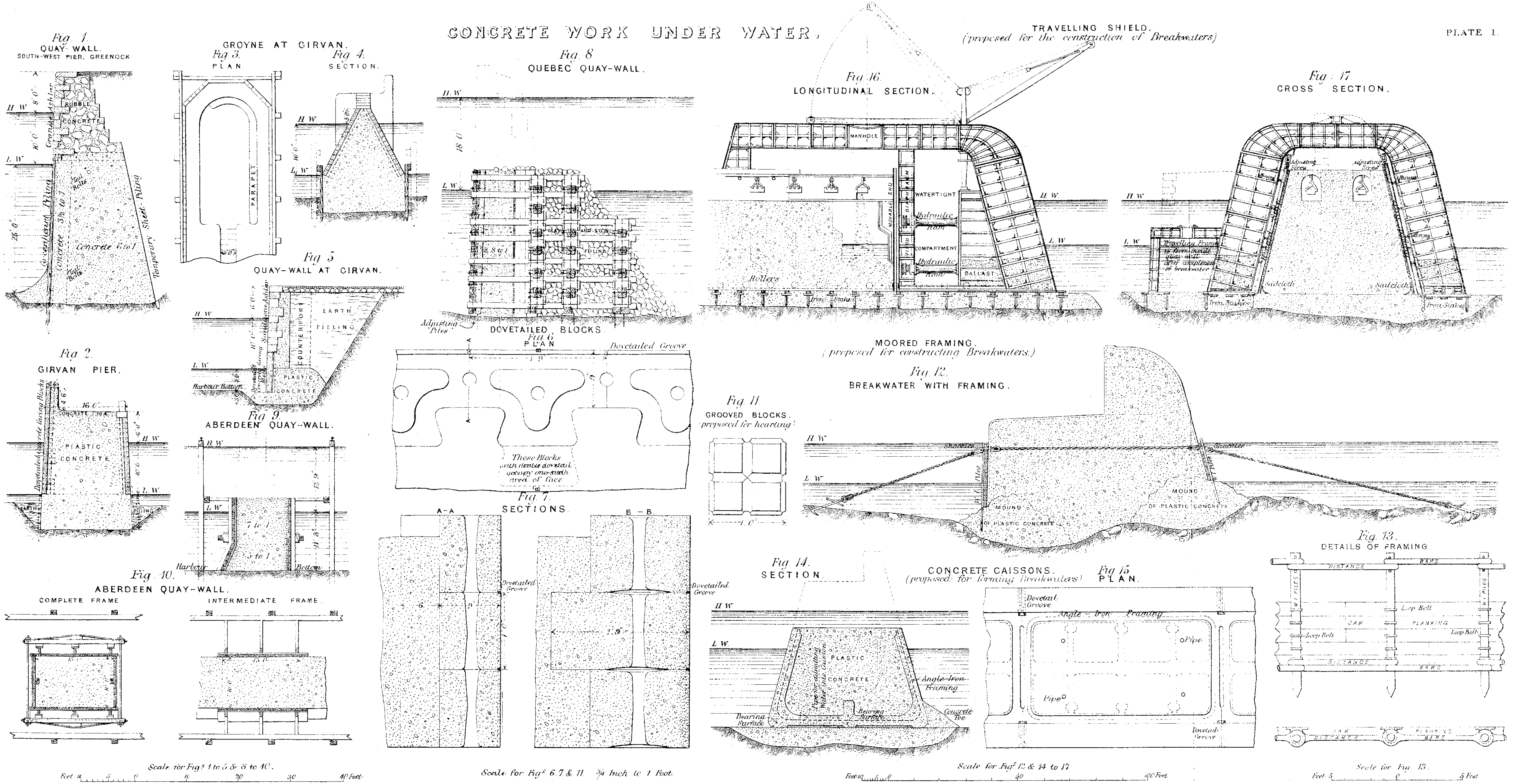
[1] Minutes of Proceedings Inst. C.E., vol. lxxiii. Plate 12.

CONCRETE WORK UNDER WATER.



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