February 10, 1874.

THOMAS E. HARRISON, President,
in the Chair.

No. 1,376.—“On the Construction of Harbour and Marine Works with Artificial Blocks of Large Size.” By BINDON BLOOD STONEY, M.A., M. Inst. C.E.¹

THE attention of engineers has been frequently and forcibly directed to the great cost of temporary works in engineering operations under water. In numerous cases, especially when the foundations are laid within coffer-dams at a considerable depth below the surface, the cost of the temporary works is found to equal, or even to exceed, that of the permanent structure. It occurred to the Author, many years since, that a large share of this expense might be saved by using artificial blocks of such magnitude as rapidly to bring a pier or quay wall above low-water level. In this way coffer-dams, staging, pumping, and all the incidental expenses connected with the old system of getting in foundations under water, might be dispensed with. Similar advantages should follow where setting masonry by means of divers has been the practice; for the great expenditure of time and labour involved in this method of building under water would be avoided. Indeed, one large block might be laid in little more time than would be occupied in setting a stone of a tenth of its bulk, and with the certainty, as far as the large block is concerned, that there would be no open joints or irregular beds to cause anxiety about its future permanence. Each monolith would be self-contained, and would settle in mass without endangering the stability or cohesion of neighbouring blocks, whilst its great weight would guarantee it against disturbance from waves. Where the ground is naturally level, only one special appliance is required for the new method of construction, namely, floating shears to lift the blocks off their building wharf, and convey them, when afloat, to their destination. If, however, as in the case of the quay walls which the Author is at present constructing, it is necessary to have an artificially-levelled foundation in order that the blocks may range accurately, and lie in close

¹ The discussion upon this Paper extended over portions of two evenings, but an abstract of the whole is given consecutively.

contact with each other, a second special appliance is required, namely, a diving-bell for excavating and levelling the ground. Thus only one, or at most two special appliances are required, and the simplicity of the method is one of its greatest recommendations.

The quay walls now in progress in Dublin form a portion of a large tidal basin and other works connected therewith. They were designed by the Author in 1861, and with various interruptions and suspensions from causes unconnected with engineering, have been slowly progressing from that date until recently, when more activity has been shown. The floating shears and diving-bell were constructed in 1864-65, but were not used until the spring of 1871. The basin is rectangular, with an entrance opening into the river at the south-east corner. The range of tide in Dublin seldom exceeds 10 feet, and gates therefore are unnecessary. The water area of this basin will be nearly 50 acres, its proposed length and breadth being 2,500 feet and 850 feet respectively. The blocks, when laid in place, reach from 24 feet below to 3 feet above equinoctial low water, their total height being 27 feet. They are 21 feet 4 inches wide at the base, and 12 feet long in the direction of the wall; and when set in place, 12 lineal feet of the quay are laid at one operation up to ordinary low-water level. Each block contains nearly 5,000 cubic feet of material, and weighs 350 tons. The upper portion of the wall above low-water level is built in the usual manner by tidal work, and is faced with granite ashlar, to give a smooth bearing for ships. It is coped with granite, each block of which weighs from 2 tons to 4 tons. The total height of the wall is 42 feet 10 inches. Vertical grooves, 3 feet wide and 18 inches deep, are formed in the sides of each block; and when two blocks are placed side by side these grooves make a long rectangular tube, 3 feet square, one half in each block, into which concrete is thrown, which acts as a dowel, and effectually plugs up the small interval between block and block. These concrete dowels are introduced as an element of safety rather than as an essential matter, as, no doubt, the blocks would act very satisfactorily if the dowels were omitted. The blocks are built on a timber wharf (Plate 15, Figs. 1, 2, 3) on the north side of the basin, about $\frac{1}{3}$ mile from the new quay. This wharf is 461 feet long, and is constructed of whole balk sheet piles with a double row of whole balk wales in front, which are strongly tied back by 2 $\frac{1}{2}$ -inch round iron tie-bars to a parallel row of 3-inch sheet piles driven about 22 feet in the rear. The interval between the rows of piling is filled with gravel and clay dredged from the bed of the river.

This wharf has proved perfectly capable of sustaining the enormous weights placed upon it. A layer of 3-inch planks is secured to sleepers imbedded in the top of the filling to form a level platform on which the blocks are built, and as spring tides overflow the wharf, these planks prevent the filling from being washed away in rough weather. The outer face of each block next the shipping is formed of calp limestone, found in the neighbourhood of Dublin, which has smooth quarry joints, and is tolerably easily squared. These face stones are set in mortar composed of 4 parts of sharp sand, and 1 part of Portland cement. The hearting of the block is chiefly done by unskilled labour; and is a class of work successfully used by the Author for many years in quay walls and similar massive masonry. It consists of stones weighing from 2 tons downwards, just as they come from the quarry, and placed, not on their flat beds as masons prefer, but on their ends as starts, or on their edges like slates when stacked upright in a yard, and bonding in every direction without any regular coursing. Especial care is taken not to lay any stone with the hollow side beneath, like a saucer upside down. On the contrary, a stone is placed with its convex side down, or on its pointed end and every interval is filled up with concrete, into which smaller stones are rammed to form a compact mass. For this purpose tamping irons, with small T heads something like a pavior's slice, and wooden rammers and shovels, are used in preference to trowels. Nothing can exceed the soundness and closeness of this work, which has been proved wherever a mass of it was broken out. This is always done with the greatest difficulty, the large stones generally fracturing in preference to the concrete, owing to the cohesion and toughness of the latter, and the broken surface presents the aspect of amygdaloidal conglomerate. The concrete is made of 1 part by measure of Portland cement to 7 parts of ballast dredged in the harbour. The ballast is a limestone gravel, with a large proportion of sand, and is not as coarse as could be desired. If it were coarser, a proportion of 1 part of cement to 10 parts of ballast would be strong enough. The sides and rear of each block are defined and kept in shape by wooden panels, which are removed when the block is built, and used over again. A block takes from three to four weeks to build, and is considered sufficiently consolidated to move after ten weeks. The length of each block, as already stated, is 12 feet, and this size is preserved for 2 feet in from the face. It then tapers about 2 inches on each side to the rear, to give a little latitude in squaring the blocks at the time of setting, and thus to insure the range being accurately maintained without having an open joint on the face. Two cast-iron

girders, weighing 11 cwt. each, are laid on the platform, and built into the bottom of each block. These girders act as washers to spread the local pressure of the suspender-bars, which support the block, and connect it with the lifting chains, over a large area of the masonry (Plate 16, Figs. 3 and 4). The suspender-bars are of wrought iron, 5 inches in diameter, and 31 feet long, with T ends at both the top and the bottom. Two rectangular holes are formed in each girder, and over each hole a tube of boards is placed vertically, round which the masonry is built; so that there are four rectangular tubes, each 20 inches broad by 11 inches wide, passing vertically through the heart of the block. When the block is ready for lifting the suspender-bars are dropped down through the tubes, and turned at right angles, so that their T ends catch in the girders below, and thus take the bearing of the block. After the block has been set in place the suspender-bars are turned round 90°, and withdrawn, to be used for other blocks as before. Each of these bars was proved to a tensile strain of 150 tons, or nearly 8 tons per square inch. The aggregate proof strain of the four bars is therefore 600 tons, and, as their calculated breaking strain is about 1,600 tons, the coefficient of safety is 4.5.

FLOATING SHEARS (Plate 16, Figs. 1-5).

The hull of this vessel is rectangular in section (Fig. 1), 48 feet wide, and 14 feet deep. It is rectangular also in plan, with the exception of the bow, which is semi-circular (Fig. 2). The forefoot has a rise of 2 feet, to enable the vessel to approach the block-wharf at or near low water without touching the ground. The length over all is 130 feet. A tank at the stern occupies 30 feet, the deck of which is 3 feet higher than the rest of the vessel, and presents the appearance of a low quarter-deck. The hull is strengthened by two transverse bulkheads of the ordinary construction, 24 feet from each end. Two double-webbed plate girders, each 3 feet wide and 18 feet asunder, run fore and aft from end to end of the hull, dividing it longitudinally into three parts, and distributing the great pressure of the shear legs over the whole length of the vessel, the iron deck and bottom of which act as flanges to the longitudinal girders. The ends of the hull and the transverse bulkheads also transfer a portion of the shearing strains to the sides, and bring them and the adjoining parts of the deck and bottom plates also into action as girders. The hull may thus be regarded as a powerful tubular girder with several vertical webs, which distribute the shearing strains over its whole area. The bottom plates are $\frac{1}{2}$ inch thick, with butt joints throughout, the cross joints having inside

covers, and the longitudinal joints outside strips, which lie in the direction of, and therefore take a share of, the longitudinal strains. The floors are formed of $\frac{3}{8}$ -inch plates, 15 inches deep, and 2 feet apart from centre to centre, with 3-inch by 3-inch by $\frac{3}{8}$ -inch angle iron at the top and bottom. The sides of the hull are $\frac{3}{8}$ -inch plates, clincher built, and the frames are 5-inch by 3-inch by $\frac{1}{2}$ -inch angle iron, 2 feet apart from centre to centre. The bilge angle iron, connecting the sides and bottom, and the gunwale angle iron, connecting the sides and deck, are $3\frac{1}{2}$ -inch by $3\frac{1}{2}$ -inch by $\frac{1}{2}$ -inch angle iron. The deck plates are $\frac{3}{8}$ -inch thick, flush on the top, with longitudinal and transverse straps underneath the butts. The deck beams of the side compartments are 4-inch by 3-inch by $\frac{1}{2}$ -inch angle iron, and those of the centre compartment are 6-inch by 3-inch by $\frac{1}{2}$ -inch, secured to the frames and to the longitudinal girders by $\frac{3}{8}$ -inch gusset plates. The transverse bulkheads are formed of $\frac{3}{8}$ -inch plates, stiffened with angle-iron frames, 5-inch by 3-inch by $\frac{1}{2}$ -inch, 2 feet apart from centre to centre.

The tank has the same beam as the hull, and is 30 feet long and 17 feet deep. The floors run fore and aft, and are formed of $\frac{3}{8}$ -inch plates 2 feet deep, with double reverse angle irons, 3 inch by 3 inch by $\frac{3}{8}$ inch. Four of these floors, which are in the line of the longitudinal girders, have $6\frac{1}{2}$ -inch by $\frac{1}{2}$ -inch flange plates riveted to the reverse angle irons, so as to strengthen the upper flanges of the floors, and give them greater strength as pillars, to withstand the horizontal component of strain in the suspenders which connect the end of the tank with the aft shear legs. A considerable quantity of concrete in the bottom of the tank overcomes its displacement when the water is pumped out, and concrete is also placed as ballast between the floors of the hull, to increase the stability of the vessel.

The framework above the deck consists of two pairs of shear legs, with powerful backstays reaching diagonally from the top of each pair to the feet of the other pair (Fig. 3). The forward shears support the block hanging from the chains, those aft support the tank. It will be observed that the centre of the block is 15 feet from the bow of the vessel, and that the centre of the tank is also 15 feet from the stern of the hull. If, therefore, a block be suspended at one end, and water to balance it be pumped into the tank, and the vessel floated on an even keel, the total weight supported by the hull will be twice the weight of the block. The peculiar arrangement of a double set of shear legs may require explanation. First, if a pair of shear legs is the most efficient arrangement for supporting the block at one end, a similar pair seems an equally good plan for supporting the tank at the other end; secondly, the local pressures

in this machine are of an unusual character. For instance, when a block is hanging from the chains, there is a thrust of about 700 tons passing downward through the forward pair of shear legs, tending to punch them through the bottom of the vessel. The vertical component of strain in the second pair of backstays, being in the opposite direction, balances a considerable portion of the downward thrust in the legs, and so far relieves the great local pressure at their intersection on the deck. The shear legs are rectangular tubular pillars, with double angle irons, 4-inch by 4-inch by $\frac{3}{4}$ -inch in each corner, as the Author's investigations have led him to conclude that the strongest form of rectangular pillars is one in which the great mass of material is placed in the corners, the chief duty of the sides being to act as a web, and to keep the corners in the line of thrust and preserve them from flexure. The legs are 3 feet square at the foot, and 3 feet by 2 feet at the top, the taper being on the outside, to keep the insides parallel. The sectional area at the top of each of the fore legs is 126 square inches, and the compressive strain is very nearly $2\frac{3}{4}$ tons per square inch. As three-fourths of the whole section of each leg is concentrated at the corners within a distance of 10 inches measured from the angle, the mass of the material has been placed as far as practicable at a distance from the axis of the pillar. Each pair of legs is braced together by cross struts and diagonal ties, which stiffen them sideways, and any tendency to sag from their own weight in the fore and aft direction is prevented by light tie-bars.

The sectional area of the aft shear legs which support the tank is a little less than that of the fore legs, being 102 square inches at the top. The diagonal backstays are H-shaped, formed of $\frac{1}{2}$ -inch side plates, 34 inches wide, with a T-iron, 6 inches by 4 inches by $\frac{1}{2}$ -inch, running along the inside of the centre of each, and braced across with light internal lattice bars, $2\frac{1}{2}$ inches by $\frac{3}{8}$ inch. Theoretically no stiffening is required for these stays; but it is requisite to prevent them from vibrating with the wind. The gross cross section of each stay, omitting the internal lattice bars, is 50 square inches; the net section is about 41 square inches, and the working strain is nearly $4\frac{1}{2}$ tons per square inch of net section. The suspender stays which support the tank are similar in general design, but lighter than the diagonal back stays. A strong double-webbed cross girder rests on the top of the forward shears, and supports the upper sets of pulleys through which the chains are reeved. This cross girder has to sustain a severe transverse strain, due to its own weight and that of the block, chains, pulleys, and suspender bars, &c., amounting to over 450 tons, or, approximately,

[1873-74. N.S.]

the weight of eighteen ordinary locomotives piled on the top of each other. The total height from the deck to the upper flange of this cross girder is $53\frac{1}{2}$ feet, and the horizontal distance from the bow of the vessel to a vertical dropped from the centre is 15 feet, so that the centre of a suspended block is 15 feet from the vessel when the latter is on an even keel. The lifting chains are pitch chains, formed of one and two flat links alternately, and weigh 46 lbs. per lineal foot; they are controlled independently of each other by powerful crab winches bolted to the deck. The sectional area of the links is $6\frac{3}{4}$ square inches in the waist, and the pins are $2\frac{1}{2}$ inches in diameter; the length of the link, measured from centre to centre of the pins, is 11.48 inches, and the length of each chain is 645 feet; they were tested to a proof strain of 35 tons, and their breaking strain is 112 tons. The breaking weight of the bar iron of which the chains were made was 22 tons per square inch, and its ultimate elongation, or set after fracture, was a little over 17 per cent. Each chain has eight parts, or sixteen parts in both chains together, so that each part has theoretically to carry only $\frac{1}{16}$ th of the total suspended weight, or nearly 24 tons; but, with an additional allowance of $\frac{1}{4}$ th for moving friction, the maximum working strain will be 28 tons, or $\frac{1}{4}$ th of the breaking weight. Each chain is reeved through two sets of four-sheaved pulley-blocks, 4 feet in diameter (Fig. 4). The upper set of blocks rests on the top cross-girder, the lower set hangs beneath in the air, and has a pair of forged cross-heads bolted to the lower part of the wrought-iron plates forming the cheeks of the sheaves. The suspender bars, which pass through the block of masonry as already described, can pass freely in one direction between these cross-heads; but when turned at right angles their T ends catch on the upper surface of the cross-heads, and are raised along with them when the chain is hauled in. The downfall of each chain passes from the upper set of pulley blocks to a toothed barrel on the main shaft of a powerful crab winch placed on deck, and thence over a guide pulley, from which it descends beneath the deck, where the slack would soon kink and become an inextricable tangle if it were allowed to pile up like an ordinary chain in a chain bunker. To prevent this, the slack chain is wound backwards and forwards over two sets of sheaves attached to the extreme ends of the engine room. This coiling operation is effected by a separate donkey engine and crab winch for each chain, which coils up on a drum a $\frac{3}{4}$ -inch close-linked chain attached to the free end of the large pitch chain, and drags it backwards and forwards over the fixed pulleys as fast as the slack comes in from above. The donkey engines accommodate them-

selves to the varying speed of the pitch chains, running fast when there is much slack, and going slowly, or stopping gradually, when the chains come in slowly or are stopped. This gradual stoppage of the coiling engines is effected in the following manner: the pitch chains descend from the deck to the floor of the engine room with a catenary curve, which acts like the spring of a cable, and pulls up the little engines gradually and without jerk to any part. When the large chains are going outboard the coiling barrels are thrown out of gear, and the spare chain below is uncoiled and hauled up again by the reversed motion of the large crab winches on deck. With this exception, all the work is done by an ordinary horizontal high-pressure engine of 14 nominal HP., placed in the central compartment of the hull, which drives the large crab winches on deck, a centrifugal pump in one of the side compartments for filling or emptying the tank, and six large surging heads on deck for hauling in the ropes by which the vessel is warped from place to place. The boiler is in the aft part of the engine room, and is an ordinary multitubular boiler, 14 feet long and 5 feet 9 inches in diameter, the steam pressure being about 45 lbs. per square inch.

DIVING BELL (Plate 15, Figs. 4-7).

The second special appliance used in the works under consideration is the diving bell. The chamber is 20 feet square at the bottom, 16 feet square at the roof, and $6\frac{1}{2}$ feet high inside, formed of twenty-five massive castings, with planed joints, bolted together with $1\frac{1}{2}$ -inch screw-bolts, spaced 8 inches apart from centre to centre. From the centre of the roof rises a tube or funnel of $\frac{3}{8}$ -inch plate iron, 3 feet in diameter and $37\frac{1}{2}$ feet high, with a hand-rail round the top. The total height of the chamber and funnel is 44 feet; and this is the greatest depth of water in which the bell can be worked at present, though, by adding to the length of the funnel, it might be used for greater depths. The upper end of the funnel forms an air-lock $6\frac{1}{2}$ feet high, with suitable cocks for admitting the compressed air from the chamber into the lock, or for letting that in the lock escape into the external atmosphere. The door-frames of the air-lock are of cast iron, 2 feet in diameter in the opening, and bolted to angle iron rims riveted inside the funnel. The doors are of $\frac{1}{2}$ -inch plate iron, with india-rubber rings where they bear against the circular lip of the frame; and each door has in the centre a round light of thick plate-glass 8 inches in diameter. There are also three rectangular side lights near the top of the

funnel, each 12 inches long by 4 inches wide. In addition to these deck and side lights, which transmit a certain share of daylight down through the funnel, there are sixteen rectangular plate-glass lights in the roof of the chamber itself. When at work in deep or muddy water, paraffin candles are used inside the chamber; but the eye gets so accustomed to the dim twilight, that the men occasionally dispense with artificial light, and thus avoid the smoke which hydro-carbons produce in a greater degree under pressure than in the ordinary atmosphere. Ladder-rungs are fixed on both the outside and the inside of the funnel. A flexible air-pipe of $2\frac{1}{2}$ inches bore leads from the air-pump on board the barge, and is coupled, below the bottom of the air-lock, to the nozzle of a 3-inch wrought-iron pipe, which passes down the inside of the funnel, then along the ceiling, and down one corner of the chamber to within about 10 inches of the bottom. Supposing an accident were to occur, such as the rupture of the flexible air-pipe, or the stoppage of the air-pump, the water would rise inside the bell only as high as the lower end of the iron pipe, which would then be sealed, so that the water could not rise higher, and the men would have time to come up the funnel at their leisure, and pass out of the bell. The clerk of the works can also pass in or out at any time while the men are working, to see what progress is being made. Inside the chamber two large sheet-iron trays, 11 feet long, 4 feet wide, and 18 inches deep, are suspended by chains from the roof. These trays are hung on gimbals, and on knocking up a detent they tilt and discharge their load. A dial on the outside of the top of the funnel, with a pointer and a bell to call attention, corresponds with a dial and pointer inside the roof of the chamber; the two pointers are connected by a vertical shaft of thin gas-tubing, passing through a stuffing-box in the roof. The signals required are, "Raise," R.; "Lower," L.; "North," N.; "South," S.; "East," E.; "West," W.; and full stop "•." The operation of excavation is simple. The bell rests on the bottom, and the men shovel the stuff into the trays. When these are filled the ganger below turns the signal-handle to the letter R., and the bell is lifted a few feet off the ground; the barge is then hauled some yards to the rear of the wall, into the proper position for discharging, and the deck man gives a knock on the side of the funnel as a signal to the man below to release the detents and discharge the stuff. The barge is then hauled back to its original position, and the bell is lowered again. The bell, which weighs $80\frac{1}{2}$ tons, is suspended by two $1\frac{3}{8}$ -inch close-link chains, rove through two sets of pulley-blocks placed on the top of a pair of shear legs projecting over the stern of the barge. Two

other sets of pulley-blocks are attached to the ends of a cross-head of plate and angle iron, riveted outside the funnel, and connected by strong iron stays to the chamber of the bell. When the bell is hanging in the air each part of the chain sustains (omitting friction) 10 tons, or less than half the Admiralty proof strain; but when the bell is in the water, and full of air, the strain on each part of the chain probably does not exceed 4 tons or 5 tons, even when the trays are quite full of excavated material. The bell-barge is rectangular in plan, 80 feet long, 30 feet wide, and 8 feet deep, with two longitudinal single-webbed girders running fore and aft in the line of the shear-legs; these girders are latticed amidships for about half their length, and are plated at the extremities. A quantity of concrete, at the end remote from the bell, balances the weight at the other end, and leaves a safe free-board at the stern when the bell is out of water. A horizontal engine, with a cylinder 8 inches in diameter, and a length of stroke of 18 inches, drives the air-pump, which is a horizontal cylinder, parallel and similar to the steam-cylinder, but 9 inches in diameter, the piston driving the air in place of being driven. The compressed air is cooled when passing through a short metal pipe leading under the deck to the coupling of the flexible hose, and again in the hose and inside of the funnel, as also in the chamber itself, which is kept cool by the surrounding water, so that no annoyance is felt in the bell from overheated air. When the pump is working at its usual rate of thirty-six double strokes per minute, the temperature of the contained air is about 102° F., while that of the air in the bell-chamber varied, in the observations which have been taken, from 50° to 59°, and that of the external atmosphere from 44° to 57½°.

The water-surface inside the chamber is quite calm in all weathers, and when on level ground is only about ½ inch deep, so that it gives a plane surface of 400 square feet, which enables the bottom to be levelled with the greatest facility and accuracy. The funnel has a scale of feet marked on the outside, and acts as a sounding-rod or level-staff; thus the proper depth of excavation is readily obtained by comparing its indication with that of a standard tide-gauge fixed a few yards distant. Nothing can exceed the simplicity and satisfactory way in which this works. A double cylinder engine, each cylinder being 6 inches in diameter, with a length of stroke of 8 inches, actuates two crab-winch on the deck, which hoist the bell. Six men and a ganger work inside the chamber together, four hours at a spell. There are two gangs, and each gang works one spell every second day, and two spells on the

alternate days, averaging six hours' work per day, except on Saturdays, and in winter, when the hours are somewhat shorter. The Author is indebted to the late Mr. George Strype for the design of the horizontal air-pump, and the air-tube passing down the inside of the funnel of the bell. Mr. Strype's analysis of the working of the pump is given in the Appendix (p. 354). The remainder of the machinery and works was designed by the Author. Messrs. Harland & Wolf, of Belfast, were the contractors for the hull, Messrs. Courtney, Stephens & Co., of Dublin, were the contractors for the machinery of the floating shears, and Messrs. Grendon & Co., of Drogheda, were the contractors for the diving-bell and barge. Some portions, however, of the foregoing plant were constructed, and the works now in progress are being executed, by the Author, for the Dublin Port and Docks' Board, without the intervention of a contractor.

LIFTING AND SETTING A BLOCK (Plate 16, Figs. 3 and 4).

The operation of lifting and setting a block is as follows:—The floating shears is brought bow on to the block wharf during the flood tide, and the suspender bars, already in position in one of the large blocks, are attached to the cross heads of the lower set of pulleys. The chains are then hauled in by the crab winches, and the centrifugal pump is started to fill the tank, but as its action is slower than that of the winches the vessel soon dips at the bow a few feet more than at the stern. As soon as this is considered sufficient, hauling in of the chain ceases, and the final lift of the block is done by the quiet action of the water filling the tank, and bringing the vessel on an even keel. So quietly is the operation performed, that a person on board is unconscious, unless he is looking at the block, of the moment when it parts from the wharf. The machinery is quite competent to lift the block off the ground, but the *modus operandi* described has the advantage of not putting so severe a strain on the chain as if it were hauling in when all the weight is on, for the increased strain due to moving friction is thus avoided. The block is grasped on either side by a pair of timber booms hinged near the feet of the fore shear legs, and lowered down like the arms of a man, one on each side of the block, and a diagonal chain and tightening screw to each boom enables them to grasp the block tight, and keep it from swaying from side to side. As the block is hung from a point 53½ feet over the deck there would be a powerful leverage to capsize the vessel if the latter took a serious list. The booms, however, prevent anything of this sort, for if the vessel had a

small list to one side, this list would be removed by causing the boom on that side to bear hard against the block and press it a little over to the other side; or if desired, a list in the opposite direction could be created by pressing the block still further over. The centre of gravity of the block might also from inadvertence not lie exactly midway between the chains, and thus cause a few tons more pressure on one set of chains than the other. This would tend to produce a list of the vessel to that side, but the boom on that side being made to bear hard on the block will move it a little over and bring the centre of gravity to agree with the central line of the vessel. In addition to this, water can be let into either of the fore-side compartments, and 1 ton of water in one compartment will balance an excess of nearly 4 tons on one set of chains over the other. These things are mentioned to show the perfect control which exists in case an error should occur in finding the exact centre of gravity. In practice, however, there has been no difficulty in doing so accurately, by the well-known method of finding the intersection of two plumb lines hanging in front of a model profile of the block, cut out of a thin board of yellow pine to the scale of 1 inch to the foot. As soon as the block is afloat, the vessel is warped a little off from the wharf, and the block lowered in the water to about half its height (depending on the local depth of water), merely to relieve the chains and other parts of the structure by the partial displacement, which amounts to from 80 tons to 100 tons. If lifted in the forenoon, the block is generally laid at low water in the afternoon; if lifted in the afternoon, it is laid at low water the following morning; yet it has occasionally been left hanging on for several days together. As already mentioned, there are powerful surging heads on deck for warping the vessel, but sometimes it is towed to its destination by a tug steamer, which seems desirable when the distance exceeds $\frac{1}{3}$ rd of a mile. The vessel is then moored in position, and the block lowered to within a few inches of the bottom, and close to the block previously set. The exact adjustment of the block in place is simply managed, for massive though it may be, yet from the length of the chains it hangs freely like a plumb bob, and can be readily moved within a limited range. The following is the method adopted for bringing it accurately into position. Short timber posts or bollards, about 11 inches square, are temporarily wedged into the grooves in the sides of each block. Two of these bollards are in the block already in place, and two in the block being set in position, all ranging in the length of the wall. On either side of the bollards a short piece of balk timber is placed horizontally, and a couple of screw bolts

clamp these together, and keep all four bollards in range, just as fish plates hold rails in line. This adjusts the range of the blocks, and they are then drawn up into close contact by a small tackle, one end of which is attached to one of the suspender bars, and the other end to one of the blocks previously set. These operations are completed when the block is within 3 inches or 4 inches of the bottom; it is then finally lowered gently into place by pumping water out of the tank. On one or two occasions, when the adjustment was not quite correct, the block was lifted again for a few minutes, readjusted, and again lowered into place. The control over it is so complete, that if there were any object in doing so, it would be quite possible, after a number of blocks have been set in place, to lift them one after the other, and put them back on the block wharf again. The average width of each joint, obtained by measuring a length of more than 300 feet of the wall, is only $\frac{3}{8}$ ths of an inch—a proof of the accuracy with which the blocks are laid in place. As already explained, this opening is subsequently plugged by the concrete dowel, between block and block. The two following tables give the cost of the work:—

TABLE 1.

COST OF PLANT.		£
Diving bell and barge,		5,454
Floating shears,		18,783
Block wharf,		4,610
Cranes, concrete mixer and engine, chain-testing machine, rails, lorries, weighbridges, panels for blocks, moorings, stone barge, &c.		5,000
		<u>£33,847</u>

TABLE 2.

COST OF QUAY WALL PER FOOT RUN.		£	s.	d.
Excavating and levelling foundations with bell, including maintenance of bell and bell barge,		3	0	0
Block standing on the wharf, including erection and maintenance of panels, casing of tubes for suspender bars, girders and masonry,		16	0	0
Lifting and setting block, including maintenance of floating shears,		2	10	0
Filling side grooves with concrete,		0	10	0
Superstructure above block, faced and coped with granite ashlar,		11	2	0
Shifting the moorings, maintenance of wharf and sundries,		1	0	0
		<u>£34</u>	<u>2</u>	<u>0</u>
Interest on plant at 7 per cent., supposing 400 feet per annum laid,		5	18	6
Cost of wall, 43 feet high, complete, per foot run,		<u>£40</u>	<u>0</u>	<u>6</u>

The total cost of the wall is in round numbers £40 per lineal foot, or less than one-half what it would be if built in the usual manner inside a cofferdam with double sides in a depth of 40 feet of water, including the expenses of pumping, and the consequent saving has already much more than paid for the whole cost of the special plant. It should be borne in mind, that Portland cement is about 20 per cent. dearer in Dublin than in London; that stone and labour are much more expensive in Dublin than in the country parts of Ireland; and that wages and materials of all kinds are far dearer than they were a few years since. The progress of the work depends chiefly on the rate at which the divers can prepare the foundations. When the depth of cutting is 4 feet, each block 12 feet in length requires $46\frac{1}{4}$ cubic yards of excavation, and when, as has hitherto been the case, the ground is tenacious clay, the preparation and levelling of the foundation for each block occupy sixty-two hours, or an average week's work for two gangs of men working in spells, each gang consisting of six men digging and one ganger directing, or seven men in the bell at one time. This is equivalent to $\frac{3}{4}$ cubic yard of tough clay excavated per hour, which may appear a small quantity; but about one-sixth of the whole time is spent in discharging the trays and spelling the gangs; and a considerable, but indeterminate time is required for levelling the bottom accurately, as the men cannot excavate so boldly when within a few inches of the final depth as at a higher level. The cost of the bell-work, including maintenance, but not interest on plant, is about 15s. per cubic yard of excavation. The necessity of accurately levelling the ground, as already explained, and the tenacious character of the clay, make this item of expense greater than it would be in a rougher kind of work or in freer ground. Allowing for the time spent in repairs and painting, the special plant in Dublin is sufficient to lay from 500 to 600 lineal feet of quay per annum; but the rate of progress for the first two years was only 300 feet each year; first, because at the commencement of such a novel work it was deemed prudent to proceed gradually; and, secondly, because the bell was engaged for several months each year in another part of the harbour, drawing the stumps of piles which had been broken off at a depth of from 15 feet to 20 feet below low water. In this operation it proved exceedingly useful: the men first excavated round the head of each stump to get room for grasping it with one end of a chain, the other end of which was fastened to a powerful ring bolt in the roof of the bell, and when the latter was lifted by the engine on board the barge, it readily drew up several stumps at one

time. If the floating shears alone were required, say for a break-water, where accurate levelling of the ground and nice adjustment of the blocks are unnecessary, the progress of the work would depend on the weather. Supposing two days on an average were spent in depositing each block, and there were only two hundred sufficiently fine working days per annum, a length of from 1,000 to 1,200 lineal feet of blocks could be laid with one floating shears each year. Of course, in extensive works such as harbours of refuge, several floating shears might be used at the same time, and thus expedite the work. The weather does not interfere with the bell-work, and seldom with the lifting of a block; but it is not desirable to move about the floating shears on a stormy day, especially if vessels happen to be lying in its course.

CONCRETE BEACON.

The Author constructed an 80-ton block of concrete in the years 1863-4, and carried it between a pair of iron lighters about 2 miles down the river, where it now forms the base of a beacon tower for marking the navigable channel. This was at the time probably the largest block of concrete that had been moved in this manner. The beacon was required near the side of the river, in a depth of $5\frac{1}{2}$ feet at low water of spring tides, and as the money to be spent was limited—for it was to compete in cost with a timber beacon—it was obviously impossible to make a coffer-dam, or adopt any plan entailing costly temporary works. The base of the tower was a ring of 19 feet external and 9 feet internal diameter, the thickness at the base being 5 feet, with a batter on the outside of 1 inch in the foot. The height of the ring was 6 feet 2 inches, and its weight slightly exceeded 80 tons. This was built on a platform of 3-inch planks laid on the strand, which was dry at low water, in the vicinity of the block wharf. Four small cast-iron washers, having a bearing area of 1.5 square foot each, were built into the base, and vertical tubes were left in the ring over each washer, in the same way as already explained in the large blocks. When the ring was consolidated, two iron mud barges, belonging to the dredging department, were placed one on either side about 20 feet apart, and barks of timber were laid across their decks spanning the intervening space where the ring lay. Four suspender-bars of 2-inch round iron, with screwed ends above and T ends below, were then lowered between the barks into the tubes formed in the concrete, and the bars were turned at right angles so that their T ends caught below; the nuts above were

then screwed down over iron plates which rested on the barks, and the whole was floated off as the tide rose, and carried down the river. At low water the ring took the ground, the nuts were unscrewed, the suspender-bars were withdrawn, and the barges went back to their regular work. A few days after the ring had been set in place it was found that some of the planks on which it had been built, and which had been merely laid as a platform on the strand, adhered to the bottom, and prevented excavation within. Accordingly the barges were sent down to lift the block as before, and when this was afloat, a few blows with a pole knocked away the planks, and the ring was again set in place. This annular wall was raised several feet with concrete, and shortly after the operation of sinking commenced, as described in a diary kept by Mr. Conolly, the chief foreman of works:—

“1864. *June 10th.*—Three hand-pumps, 11 feet long and 4 inches bore, set to work and lowered water in well 8 feet, or within 2 feet of the bottom, when the water burst in from beneath and overpowered the pumps. Put some clay round outside of base.

“*June 20th.*—Three pumps set to work and drained out well in one hour; after that one pump sufficed until the tide rose over the top of the ring; in $3\frac{1}{2}$ hours excavated 18 inches deep and 2 feet 6 inches underneath ring: ring sank 8 inches on south and 4 inches on north sides; ground full of shells with a small quantity of pebbles.

“*June 21st.*—Repeated same operations as yesterday, but worked only two hours in well; sea very rough; ring sank 10 inches and quite level; total sinking 1 foot 4 inches. Sand came into excavation equally all round and more uniformly than yesterday.

“*June 22nd.*—Three and a half hours' work; sank 9 inches quite level; total sinking 2 feet 1 inch.

“*June 23rd.*—Same operations repeated, $3\frac{1}{2}$ hours' work; average sinking 9 inches, most on east side; total 2 feet 10 inches.

“*June 24th.*—Three and a half hours' work; ring sank 10 inches and very level; total sinking 3 feet 8 inches.

“*June 25th.*—Three and a half hours' work, sank 6 inches; total 4 feet 2 inches. Bottom very fine woolly sand.

“*June 27th and 28th.*—Raised top of ring 4 feet 2 inches with concrete; total height 14 feet 6 inches.

“*June 30th.*—Lengthened three hand-pumps to 15 feet; dried out well in $1\frac{1}{2}$ hour, got a quantity of excavation out, and the tower sank 5 inches, when the bottom burst in at N.E. point, where the clay outside had been wasted by the heavy wash of the sea. A quantity of clay was forced under the foundation and into the well by the rush of water.

“July 2nd.—Got 120 tons of clay put round base of tower; total clay used 305 tons.

“July 4th.—Pumped out well in $2\frac{1}{2}$ hours; 3 feet of sand and clay in well from burst of 30th ult.; got it and a quantity of the bottom out. Leakage greater than on any previous day: tower sunk 4 inches; total 4 feet 10 inches.

“July 5th.—Pumped out well in $1\frac{1}{2}$ hour; finished excavation and tower sunk to final level, 5 feet under surface of ground and about 10 feet 6 inches below low water zero.”

The superstructure was then completed at intervals in eight working days. The height of the concrete tower is 38 feet. It is surmounted by a timber beacon, 6 feet high, fixed on a short mast 3 feet high, making the total height 47 feet, the elevation over high-water level being about 24 feet. The core of the tower is filled with ballast, which, as well as the clay, was dredged in the harbour. The cost was under £200, exclusive of payment for the use of the barges.

CONCRETE MIXER (Plate 15, Figs. 8, 9).

The method adopted by the Author for making both concrete and mortar differs in several respects from the custom elsewhere. The gravel or sand, according as concrete or mortar is required, is tipped from barrows into large rectangular trays of rough deals without ends, generally of the following dimensions: length 20 feet, breadth 6 feet to 8 feet, height of sides 2 feet to 4 feet. As soon as the tray is filled with ballast, a straight edge is passed along the top to strike the ballast to a uniform level with the top of the tray, and battens of a definite thickness are then laid on the top to gauge the due proportion of cement, which is spread evenly over the ballast, its surface being levelled with the straight edge as before to coincide with the upper surface of the battens. Thus, if the tray be 3 feet high and the battens 6 inches deep, the proportion will be 6 of ballast to 1 of cement; if the battens be $4\frac{1}{2}$ inches deep, 8 of ballast to 1 of cement, and so on. Two men to each tray then shovel the dry material into the mixer, pushing their shovels along the floor of the tray, whereby the cement sheds itself uniformly down the slope of the gravel and becomes mixed with it to a certain degree.

The mixer is an open trough of cast or wrought-iron, from 7 feet to 9 feet long, and $3\frac{1}{2}$ feet wide. The lower half is semi-circular, and the top sides are slightly splayed out. A wrought-iron shaft, $3\frac{1}{2}$ inches square, with wrought-iron blades, passes through the centre of the trough, the blades being arranged to

screw the concrete forward as the shaft revolves. The pitch of the blades can be adjusted at will by turning them more or less in their sockets, and the travelling movement is accelerated by inclining the trough in the direction of its length, so that it may have a fall towards the delivery end. The motion may be communicated either by a belt or gearing from an engine of 2 HP. or 3 HP. The method of working is as follows:—The gravel and cement, in their proper proportions, are shovelled from the tray alongside directly, without hand-mixing, into the upper end of the trough, where the first three or four blades toss over and incorporate the dry ingredients thoroughly. They then pass under the water-rose, about one-third of the length of the trough from the upper end, and from thence to the delivery end the mixture of gravel, cement, and water is perfected, and the mortar or concrete comes out quite uniform in colour and homogeneous in quality. The machinery is of the simplest character; all the operations are open to view, and the friction and consequent useless expenditure of labour are reduced to a minimum; and large stones pass through it which would destroy any ordinary mortar mill. After several months the ends of the blades become shortened by wear, a small interval being left between them and the lower half of the trough; the latter gets coated with hard set mortar forming a lining to the trough, and when the blades are lengthened again, which is done by simply welding a scrap of iron or steel to their ends, the coating of mortar is chipped off, and the machine restored to its original condition. The great advantage of this machine over hand labour consists in the facility it affords for mixing the ingredients thoroughly and with a small quantity of water. It never flags, and requires little attention, whereas labourers are apt to add an excess of water to relieve the toil of turning over a stiff mass, or they add water in irregular quantities, and rarely incorporate the principal ingredients in a thorough and uniform manner. As already stated, this concrete mixer is equally efficient for making mortar. Indeed, the Author thinks it preferable to any mortar mill with which he is acquainted, especially the pan with edge-runners, which tend to grind and triturate the sand, thus reducing its sharpness, and doing useless work. In the manufacture of hydraulic mortar the proper mode of proceeding seems to be: First, to have the cement or lime reduced to a state of fine powder. Secondly, to incorporate the sand with the cement or lime in the dry state. Thirdly, to temper the mixed ingredients rapidly with a moderate amount of water let on gradually as required. When lime is not ground, and when, therefore, lumps

occur in it, the edge-runners doubtless crush them, and thus render the mortar homogeneous. In this respect only does the pan mill seem to present any advantage over the mixer just described. The latter is far simpler, cheaper, and more rapid in its operation, a single mixer when well attended being able to turn out from 8 cubic yards to 10 cubic yards of concrete or mortar per hour with thirty revolutions of the shaft per minute; that is to say, one mixer driven by a 3 HP. engine will make as much mortar as twelve ordinary pan mills, while its cost is only from £30 to £35, and it can be set up anywhere on a couple of wooden trestles.

This machine has also been applied to pulping peat; and if a fire were placed beneath, it might be successfully used for pulverising and dessication, as, for example, drying and pulverising sewage mud or similar matters.

BREAKWATERS.

The Author has now described some of the works on which he has been engaged, but it is evident that the new method of building with large blocks is of much wider application. Its advantages will probably be more marked in the construction of piers and breakwaters, such as those of harbours of refuge, which have hitherto been a frequent source of anxiety and expense. Stone breakwaters may be divided into six classes:—Breakwaters built of rubble stone on the long slope principle, either with a paved sea face like those at Plymouth, Howth, and Kingstown harbours, or with a rough sea face formed of large rubble laid at random. Breakwaters formed of artificial blocks of from 10 cubic metres to 20 cubic metres each, laid promiscuously at an angle of about 45° , as at Alexandria, Leghorn, Algiers, Marseilles, and other French harbours, the mound being sometimes composed entirely of artificial blocks, though generally the heaving and lower part are formed of rubble with the large blocks on the sea face, the breakwater being surmounted by a roadway and parapet wall of masonry. Breakwaters like those at Cherbourg, Holyhead, and the Tyne, constructed of a mound of rubble reaching from the bottom of the sea to a little over low-water level, along the axis of which is a vertical wall or backbone of masonry, the foundations being laid in the heart of the rubble at extreme low-water level. Breakwaters like that at Alderney, which resemble the last class, with the exception that the base of the masonry backbone is laid by divers several feet below low water. The breakwater at Kurrachee

harbour may be included in this class, as the 27-ton concrete blocks of which its superstructure is formed are laid regularly, though they are not bonded together with mortar. Breakwaters of loose rubble stone held together by a cribwork of timber, as at Blyth. And, finally, breakwaters built regularly with ashlar stone or artificial blocks from the bottom of the sea vertically upwards, like the Admiralty pier at Dover.

The two systems chiefly in favour in the United Kingdom, namely, the long-slope system with paved sea face, and that in which a masonry backbone is founded on the axis of a rubble mound at low-water level, both contain the elements of destruction within themselves, unless in the one case the base of the paved slope, and in the other the base of the masonry backbone, is protected from being ripped up or undermined by the waves. When this protection is wanting, an apparently slight injury at the base eats upwards like a canker, and spreads rapidly over a large area; and unless prompt measures are taken to replace the lower courses where the mischief generally begins, and to protect them as best may be against a similar recurrence, the destruction of the superstructure of the breakwater is only a question of time. Plymouth, Sunderland, Kingstown, Howth, Tynemouth and Holyhead breakwaters have been long enough in existence to show how the evil acts. The rubble mound protecting the lower courses of the paved slope, or the base of the masonry backbone, large as its constituent stones may have been originally, is yet not massive enough to resist the action of heavy storms, and the stones are knocked about and worn away gradually till they lose their original shape and volume, and change from sharply quarried blocks into rounded boulders. These in turn are constantly rolled about till they are reduced to gravel, which, in some instances at least, is swept round the pier-heads, and forms a dangerous shoal at the entrance of the harbour, involving the necessity of employing dredging machinery to remove the débris of what a few years previously formed an integral portion of a structure apparently destined to last for ages. The same destruction sooner or later seems destined to await the breakwater formed with a long slope of rough rubble stone, unless indeed its sea face be coated with artificial blocks of sufficient size to resist the action of the sea; for though the larger blocks of natural stone may apparently resist the waves for a time, every unusually severe storm makes a greater or less change in their contour, and the stones are gradually reduced in bulk, and ultimately washed over the crest or round the end of the breakwater, which will thus in process of time more

and more approximate to the condition of a shoal. It is instructive to observe the wave-like shapes that the rubble foreshore outside a vertical wall assumes. In some parts it is piled up so that the crest of the stone wave reaches high up on the masonry, or even outtops it, in which case the stones are washed over into the harbour; in others, the hollow of the wave approaches the base of the wall, and when it goes below it, the local destruction of the latter is inevitable. After another storm the stone waves will have moved forwards, and their crests and hollows have changed places, and in time this travelling motion will generally bring a large portion of the foreshore, so far down as the action of the sea is sensible, round the pier-head as already described; though in the case of one pier under the Author's charge the travel is towards the land, and the pier-head is being rapidly stripped of its former protection. The remedy for this evil is expensive, still it seems the only one, for merely mending the breaches by throwing down fresh material of the same size as that removed by the waves is but a temporary expedient. Large artificial blocks appear to be the only final remedy, and these must be of such a size that they will not travel. The smaller stuff below and around them may be washed away, and the blocks themselves may subside locally until their base is below the level at which the waves will act on the foreshore, but when once they have reached this level further derangement need not be apprehended. Some apology may be considered due for thus freely criticising the designs of the great men of a past generation, but no apology is really required. They acted up to their lights, and according to the state of mechanical knowledge in their day; and engineers of the present day would be most unworthy successors of those eminent men if they were not to benefit by their practice, and derive that experience from their works which time alone can give.

The vertical wall, of which the Admiralty pier at Dover has been selected as the type, is free from the special sources of destruction to which the long slope or the wall with rubble foreshore are liable. Its base is laid below the disturbing action of the waves, and, if the foundations are secure, and if the individual stones are massive enough, or so bonded together that they cannot be disturbed by the action of storms, the upright wall seems to possess the desired elements of stability and durability. The cost, however, of the vertical breakwater is usually great, and its progress slow, two things which seem to have interfered with its general adoption. The Author submits that both these objections may in most localities be removed by the new method of construction.

There may be several days in the year during which a block could not be set in exposed situations; but, supposing there are only one hundred and fifty suitable working days in each year, the rate of progress, even with but one floating shears, will exceed that of the ordinary method; and in works of such magnitude as harbours of refuge there is no reason why several such appliances should not be used simultaneously. When the depth at low water exceeds 30 feet to 40 feet, it may be desirable to use two blocks one above the other, or to raise the foundation by a mound of rubble stone extending to within 25 feet or 30 feet of low water; that is, to a depth below that at which the action of the waves is sufficient to move the stones forming the mound. A single, double, or triple row of blocks might be laid on the axis of such a mound after it has been allowed to consolidate, and even supposing that local settlement of the mound takes place, this will not affect the cohesion of individual blocks, nor will it in any way injure the adjoining blocks; and if a wide roadway is required on the top of the breakwater, rubble filling can be thrown in between a double row of blocks so as to obtain any desired width of pier.

The Paper is illustrated by a series of drawings and diagrams, from which Plates 15 and 16 have been compiled.

APPENDIX.

ANALYSIS OF THE AIR-PUMP ON BOARD THE BELL BARGE.

Pump, 8 inches in diameter, length of stroke, 18 inches; double acting. Ports, $3\frac{1}{2}$ inches by $\frac{7}{8}$ inch. Valve, $2\frac{1}{2}$ inches stroke, $\frac{3}{8}$ inch cover on exhaust side, and $\frac{1}{2}$ -inch on discharge side. Clearance of piston at the end of the stroke, $\frac{1}{2}$ inch, making with the contents of the port a space equal to 1 inch at the end of the cylinder. Since 35 cubic feet of salt water weigh 1 ton, $\frac{35 \times 144}{2240} = 2\frac{1}{4}$ feet of depth = 1 lb. per inch. The minimum depth of water to work in is assumed to be 25 feet, and $\frac{25}{2\frac{1}{4}} = 11$ lbs. per inch. The maximum working depth is 38 feet, and $\frac{38}{2\frac{1}{4}} = 17$ lbs. per inch. Assume that $\frac{1}{2}$ lb. per inch is absorbed by the friction of the air through the port, then $15 - \frac{1}{2} = 14\frac{1}{2}$ lbs. per inch, which will be the pressure on the suction side with every depth of water so long as the valve is open. With 25-foot depth of water the pressure on the discharge side will be $15 + 11 + \frac{1}{2} = 26\frac{1}{2}$ lbs. per inch so long as the valve is open. With 38-foot depth the pressure on the discharge side will be $15 + 17 + \frac{1}{2} = 32\frac{1}{2}$ lbs. per inch while the valve remains open, atmospheric pressure in each case being included.

CONSTRUCTION OF MARINE WORKS
WITH ARTIFICIAL BLOCKS OF LARGE SIZE.

BLOCK WHARF.
AND BLOCK.

CONSTRUCTION OF MARINE WORKS, WITH ARTIFICIAL BLOCKS OF LARGE SIZE.

FLOATING SHEARS.

Minutes of Proceedings of The Institution of Civil Engineers, Vol. XXXVII Session 1873-74 Part I.

THOS KELL, LITH. 40 KING ST COVENT GARDEN.

The following Table gives the pressures on both sides of the piston at various points of the stroke.

Degrees passed through by the crank.	Space passed through by the piston from beginning of stroke.	Degrees moved through by the eccentric from the middle of its stroke.	Space moved through by the valve from the middle point of its stroke.	Port open for exhaustion.	Port open for discharge.	25 feet depth of water.		38 feet depth of water.	
						Pressure of air on suction side, atmosphere included.	Pressure of air on the discharge side, atmosphere included.	Pressure of air on the suction side, atmosphere included.	Pressure of air on the discharge side, atmosphere included.
°	inches.	°	inches.	inch.	inch.	lbs.	lbs.	lbs.	lbs.
0	0	—20	—43	0.05	0	28.0	15.0	34.3	15.0
5	.04	—15	—32	0	0	27.0	15.0	33.0	15.0
10	.14	—10	—22	0	0	24.6	15.1	30.1	15.1
15	.31	—5	—11	0	0	21.4	15.2	26.3	15.2
20	.54	0	0	0	0	18.2	15.4	22.3	15.4
25	.85	5	11	0	0	15.1	15.7	18.5	15.7
30	1.21	10	22	0	0	*12.7	16.0	15.5	16.0
35	1.64	15	32	0	0	*10.6	16.4	*13.0	16.4
40	2.10	20	43	.05	0	13.5	16.9	14.0	16.9
50	3.21	30	62	.25	.12	14.5	*18.0	14.5	*18.0
60	4.50	40	80	.43	.30	14.5	*19.7	14.5	*19.7
70	5.92	50	96	.58	.46	14.5	*21.8	14.5	*21.8
80	7.44	60	1.08	.71	.58	14.5	*24.6	14.5	*24.6
90	9.00	70	1.17	.80	.67	14.5	26.5	14.5	*28.5
100	10.56	80	1.23	.86	.73	14.5	26.5	14.5	32.5
110	12.08	90	1.25	.88	.75	14.5	26.5	14.5	32.5
120	13.50	80	1.23	.86	.73	14.5	26.5	14.5	32.5
130	14.79	70	1.17	.80	.67	14.5	26.5	14.5	32.5
140	15.90	60	1.08	.71	.58	14.5	26.5	14.5	32.5
150	16.79	50	.96	.58	.46	14.5	26.5	14.5	32.5
155	17.15	45	.88	.50	.38	14.5	26.5	14.5	32.5
160	17.46	40	.80	.43	.30	14.5	26.5	14.5	32.5
165	17.69	35	.72	.34	.22	14.6	26.5	14.6	32.5
170	17.86	30	.62	.25	.12	14.8	26.5	14.8	32.5
175	17.96	25	.53	.15	.03	15.0	27.0	15.0	33.0
180	18.00	20	.43	.05	0	15.0	28.0	15.0	34.3

Note on the above Table.—On the suction side, before the valve opens, the pressure falls below the atmospheric pressure. See the pressures marked * in the suction columns.

On the delivery side, as soon as the valve opens, the air will re-enter the pump from the diving bell until, by further compression, the pressure equals that in the bell. See the pressures marked * in the discharge columns. Thus the valve opens late for the suction side and too early for the discharge side. These are weak points in the system, but it is presumed that other good points will more than compensate for them. This system, however, cannot be carried to much greater pressures without serious loss.