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"The Foundations of the River-Piers of the Tower Bridge."

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General Description.

This Paper is limited to a description of the foundations of the two river-piers of the Tower Bridge and does not deal with the superstructure, which is still under construction. It is advisable, however, to refer briefly to the general design of the completed work, to give a correct notion of the necessity for the massive foundations to be described.

It will be seen from the general elevation, Fig. 1, Plate 4, that the bridge has 3 spans; the middle one is 200 feet in the clear, and those on either side of it 270 feet each. The middle span is constructed to open on the bascule system, to admit of the passage of vessels through the bridge; the water-way being spanned by two movable platforms, each projecting 100 feet beyond the pier-faces. Above the movable road-way is a pair of fixed footways, accessible by stairs and hydraulic lifts and placed at such a height as to allow the movable platforms to be raised into a vertical position. The weight of the opening road-way, added to that of the high-level foot-ways and the towers supporting them, renders the load upon the foundations unusually heavy for a bridge of such moderate spans—so much so that for a load of 4 tons per superficial foot the dimensions of the foundations worked out to 100 feet in width by 204½ feet from end to end of the cutwaters.

It was essential to adopt caissons of some kind for laying the foundations, because timber cofferdams were specially prohibited by the Act of Parliament. The ground to be passed through was London-clay, the reliable nature of which rendered it possible to effect a considerable saving by contracting the limits of the caissons within the outside line of the foundations; the full dimensions of the latter being attained by under-cutting beneath the caissons to the extent of 5 feet horizontally. Thus the outside limits of the caissons measured 90 feet across by 194½ feet in length. Instead of sinking large caissons extending right across the pier, a system of smaller ones around it was adopted. Figs. 4, 5, 7 and 8 show that there was a row of 4 caissons, each 28 feet square, on both the north and the south sides of the pier; and at each end of these rows was a pair of triangular-shaped caissons formed approximately to the shape of the cut-waters. The spacing between all the caissons was 2 feet 6 inches; this dimension being adopted as the minimum in which workmen could be effectively employed. The caissons enclosed a rectangular space, 34 feet by 124½ feet, which was not excavated until the permanent work forming the outside portion of the pier had been built continuously within the caissons, and in the narrow spaces between them, to a height of 4 feet above Trinity high-water level.

Temporary Staging (Figs. 7 to 10).

To avoid the obstruction of the water-way of the Thames more than was necessary, the extreme limits of the staging were restricted to a breadth of 130 feet and a length of 335 feet from point to point of the cut-waters. The piles surrounding the pier were in 2 rows, about 13½ feet apart, with additional rows at the cut-waters. The inner row was driven 6 feet away from the outside line of the caissons, in order to clear the toe of the under-cutting. These piles were about 57 feet long, and were driven about 20 feet beneath the river-bed. Those in the outer rows were some 5 feet shorter. The piles in both the inner and the outer rows were spaced about 15 feet apart, and were connected together by walings and bracings, both longitudinally and transversely. The planking was laid upon bearers spaced 3 feet apart, at a height of 5 feet above Trinity high-water. The staging in the central space between the caissons had 3 rows of piles, spaced the same distance apart as those already described. Before the erection of the caissons, beams were laid across between the central and the outer stagings a short distance above low-water, so as to form a low-level platform for the erection of the caisson immediately over the site it was to occupy.

THE CAISSONS (Figs. 11 to 16).

Both the square and the triangular-caissons were similar as regards the scantlings of the iron, the methods of joining their lengths together, and in most other particulars; so that a description of one type will apply generally to the other. The caissons were in two portions—the permanent caisson, 19 feet in height, and above this the temporary caisson, 38 feet high. Each portion consisted of a single skin of wrought-iron plate, $\frac{1}{2}$-inch thick at the bottom of the permanent caisson and diminishing to $\frac{1}{4}$-inch at the top of the temporary caisson. The cutting-edge was of rolled steel, Fig. 14, Plate 4, weighing 25 lbs. per lineal foot. It was riveted on the outer side of the skin, projected $\frac{3}{4}$-inch beyond the latter, and formed in its descent a passage through the clay somewhat larger than the caisson above. The friction was thus reduced and the descent of the caisson consequently facilitated; and at the same time the natural swelling of the clay made good the space above the cutting-edge sufficiently to prevent the water from passing down the outside and so into the caisson. The cutting-edge was stiffened every 3 feet by vertical rolled-iron joists; which were in turn supported by two horizontal frames of 15-inch pitch-pine balks, with diagonal struts of the same material at each corner. To give additional stiffness, wrought-iron diaphragms were inserted between the joists at the back of each horizontal frame. It was necessary to keep the lower frame some distance above the cutting-edge, to give the excavators room to work when removing the clay. To prevent the external pressure from forcing the cutting-edge inwards, the joists were carried to a considerable height above the bottom frame; so that the pressures on the parts above the frame exceeded those below it. The joists answered the purpose of covers to the skin-plates, which were laid with their long-edges vertical, and butted along the middle of each joist.

Above the joists, the remainder of the permanent caisson consisted of $\frac{1}{2}$-inch and $\frac{7}{16}$-inch plates, 7 feet long by $3\frac{1}{2}$ feet wide, laid with their long edges horizontal. The vertical joints were covered with T-irons on the outside and with strips on the inside. To avoid impeding the descent of the caisson by continuous projections on the outside, the horizontal joints were covered on the inside only. Angle-irons, wide enough to take a double row of rivets, were used for this purpose. The angle-irons served also to carry the timber frames which supported the skin immediately above each of the horizontal joints. These frames were of 14-inch pitch-pine balks, with diagonal struts at each corner, placed over the diagonals of the bottom frames.

The temporary caisson was generally similar to the upper portion of the permanent caisson, but of a lighter description. For instance, the skin diminished from $\frac{3}{8}$-inch at the bottom to $\frac{1}{4}$-inch at the top; and the frames, from timbers 14 inches square to half-timbers 12 inches by 6 inches. The junction between the temporary and the permanent caissons was made water-tight by a small strip of india-rubber, $\frac{3}{8}$-inch in diameter, laid in a groove at the top of the permanent caisson. The groove was formed by an angle-iron on the outside and a strip on the inside of the skin-plate, both projecting upwards 1 inch above the top of the skin-plate (Fig. 15). The bottom plate of the temporary caisson rested inside the groove upon the india-rubber. An angle-iron was riveted to the outside of the temporary caisson, near the bottom of the skin-plate, and bolts, about 2 feet apart through this and the angle-iron at the top of the permanent caisson, served to tighten the joint. As an additional precaution—which might perhaps have been dispensed with—a second strip of india-rubber, $\frac{3}{4}$-inch thick, was laid outside the skin-plates between the two angle-irons. The joints proved water-tight and after the first 5 caissons had been sunk the additional strip was omitted.

The Tower Bridge Act provided that the piers should not exceed a width of 70 feet within a depth of 34 feet below Trinity high-water; thus the width across the caissons being 90 feet, the joint between the temporary and the permanent caissons was fixed at that depth. The general surface of the river-bed was slightly higher than this; and, as it would have proved difficult to obtain access to the joint when it became necessary to unbolt the temporary from the permanent caisson, the bolts connecting the two were fitted with long projecting shanks, so that a diver, standing on the bed of the river, could easily unscrew them. For facility of erection and removal, the temporary caisson was divided horizontally into four sections. The joints between them were similar to that already described, except that the bolts were of the ordinary description.

To connect the caissons when sunk, a pair of angle-irons was riveted on at each corner, forming grooves, extending from the top of the temporary to the bottom of the permanent caisson. These sufficed to hold in position the piles which were driven, after the caissons had been sunk, for the purpose of enclosing the narrow space between each pair of adjoining caissons. Vertical joints (Fig. 16) were made in the skin-plates of the temporary caissons close to the pile-grooves; so that, on the piles being driven, the adjoining sides of the caissons might be removed. The joints were covered inside and outside by butt-strips, and a flat strip of india-rubber, $\frac{1}{8}$-inch thick, was laid beneath the outer butt-strip. The bolts also, which were spaced 4 inches apart, were furnished with india-rubber washers.

Erecting and Lowering the Caissons.

The permanent caissons were manufactured by Messrs. Head, Wrightson and Co., and the temporary caissons by Messrs. Bow and McLachlan. Each side of the former was delivered in four pieces, which were lowered upon the platform previously described as situated a short distance above low-water, where the complete permanent caisson was put together and riveted. The joints, as well as all the edges of the outside covers, were carefully caulked and made thoroughly water-tight. This was not a long operation, as all the edges of the plates were planed and butted close together. The timber frames were next inserted, and the caisson was then ready to be lowered to the bed of the river. To accomplish this, two pairs of trussed beams were placed above the caisson, with their ends supported upon the staging, as shown in Fig. 9, Plate 4. Four lowering-rods, passing between the beams, were connected with the tops of the rolled joists near each corner of the caisson. The rods were $2\frac{1}{4}$ inches in diameter, in 8-foot lengths, coupled together by link-plates and pins 2 inches in diameter. The upper length of each rod was 14 feet long, and was screwed with a 4-inch square thread for a distance of 9 feet from the top. The caisson was lifted clear of the platform by setting up the screws and at low-water the platform was removed from beneath. The caisson was then lowered until the ends of the screwed rods were brought nearly down to the nuts, when it became necessary to couple additional lengths to the rods. To effect this, the caisson was supported by large wrought-iron hooks, suspended from the trussed beams, clipping the rods beneath the connecting link-plates (Fig. 11). The screwed rods were then uncoupled and lifted, and additional rods inserted. The positions of the rods for lowering the angle-caissons are shown in Fig. 12. The beams carrying the rod at the middle of the outer side were supported partly on the outer staging and partly on piles driven within the site of the caisson itself; for, had the beams been carried across to the central staging, they would have been much in the way when anything was lowered into or raised out of the caisson.

As soon as the cutting-edge had reached the highest part of the river-bed, the plates of the first section of the temporary caisson were erected; and, concurrently with this operation, divers were sent down to level the surface of the ground, to give a uniform bearing round the cutting-edge. When this had been effected, the caisson was lowered until its weight was entirely upheld by the ground. The lowering-rods next above the permanent caisson were then removed for a short time, whilst the timber frames of the temporary caisson were being fixed. After these had been put in and the lowering-rods had been re-adjusted, the sinking of the caisson was commenced. Further lengths were added to the rods as the sinking proceeded and were retained until the under-cutting beneath the caisson had been completed and the concrete filling brought up to the cutting-edge. The upper sections of the temporary caisson were added as soon as the sinking had advanced so far as to give sufficient height for their erection beneath the trussed beams. The sides of each section were delivered in two pieces, to facilitate their erection, and to render them less liable to injury in transit.

Excavating Inside the Caissons.

The material excavated was London-clay, covered in places with about a foot of ballast. It was compact and of uniform texture, and so tough that, after sinking the caissons some 4 or 5 feet into it, the water could be pumped out and reliance placed upon its tenacity to prevent the water in the river from forcing its way beneath the cutting-edge.

The middle parts of the caissons were first excavated by Priestman grabs to a depth of 5 or 6 feet beneath the bottom frames; after which divers were sent down to excavate the material round the sides and beneath the diagonal struts, and to shovel it towards the middle of the caisson into the hole made by the grabs. In the triangular-caissons the arrangement of the timbering gave three separate spaces between the cross struts for the grabs to work in. In order to prevent the grabs from displacing the timbering, upright rubbing-planks, about 2 feet apart, were spiked all round the frames and struts.

On commencing the excavation it was necessary to keep the lowering-rods set up, so as to prevent the caisson from sinking by its own weight to such a depth into the clay as would have left insufficient space for the divers to work beneath the bottom frame. The screws were not slacked until the excavation had been carried down about a foot beneath the cutting-edge and outwards to within about 6 inches of it. Thus, the caisson had to cut its own way down and a tight joint was ensured between the clay and the ironwork. The divers having once gained a sufficient depth beneath the bottom frame, the screws were slacked and the caisson was allowed to keep pace downwards with the excavation. Besides regulating the descent, the screws were of considerable service in maintaining the caisson in its correct lateral position; for, by allowing one side or corner to take the lead, the caisson was worked over bodily towards the opposite or highest side or corner. As the cutting-edge penetrated beneath the surface, to permit the free rise and fall of the tide within the caisson, in order to prevent any inequality of water-pressure from forcing a passage underneath it, a sluice 9 inches square was provided near the top of the permanent and another near the bottom of the temporary caisson (Fig. 11). After a depth of 2 or 3 feet beneath the river-bed had been attained, the height below the trussed beams became sufficient to admit of the erection of the second section of temporary caisson. By the time this had been completed and the timbering had been fixed, the depth had usually been increased to 4 or 5 feet below the river-bed. The timber frames immediately above low-water were then loaded at the corners with kentledge in the form of cast-iron blocks, each weighing about 22 cwt. In the case of the north pier the weights thus added amounted on an average to 75 tons; and their effect was to force the caisson a little lower down, making the cutting-edge from 5 to 7 feet beneath the surface, or from 4 to 6 feet into the clay. It was considered safe at this depth to pump the caissons dry and trust the clay to resist the external pressure. For reasons hereafter to be stated, the caissons of the south pier were sunk to a greater depth than the above before the pumps were fixed. These comprised a 10-inch centrifugal pump and a 12-inch direct-acting pump in each caisson, capable of discharging together about

3,200 gallons per minute, with a 50-foot lift. They were set to work a little before half-ebb and in about 2 or $2\frac{1}{2}$ hours the caisson was pumped dry. By that time the tide had fallen to within 2 or 3 feet of low-water, or within about 25 feet of the level of the cutting-edge. Navvies then went down and continued at work for 2 or 3 hours, filling the skips as expeditiously as possible, until the rise of the tide made it necessary to stop. The sluices were opened, so that the caisson was filled by the time the tide had risen some 25 feet above the cutting-edge—as it was considered prudent to restrict the head of water outside to that height on the first occasion of pumping out. As the caisson was lowered, however, the pumping was commenced earlier and the sluices were kept shut longer; so that, when a depth of about 13 feet below the surface was attained, the period available for excavating was extended to about 6 hours during the tide. Indeed, it might have proved safe to exclude the water altogether from the caisson some time before reaching such a depth; but, as a precaution, the sections of the temporary caisson had been so arranged that, until that depth was reached, the third section, 12 feet in height, could not be erected beneath the trussed beams; and before this was done the water could not be excluded entirely, because the top of the second section did not reach high-water level. Another reason for making the third section so high was that the fourth and last section was thereby so far reduced in height, that it could be erected beneath the beams whilst the top of the third section still remained above high-water. Thus, the latter being erected, the tide could be permanently excluded. In the case of the south pier the river-bed was some 6 inches lower than at the north pier, and in places there was a foot or two more ballast overlying the clay; so that in any case these caissons must have been sunk some 7 or 8 feet before attempting to pump out the water. It was, however, considered by the Contractor more advantageous to sink them deep enough, $12\frac{1}{2}$ feet below the river-bed, to admit of the erection of the third sections of the temporary caissons, before the pumps were fixed; for, although the divers' work was thus prolonged, considerable saving was effected in the expense of pumping.

At both the north and the south piers the water was pumped out finally from each caisson as soon as the third section had been erected; and the pumps were then removed. The subsequent small leakage at the joints was easily kept under control by baling the water into a tub, which was lifted out and emptied from time to time. In none of the caissons did the leaks exceed 1 gallon per minute, whilst some were so tight that water had to be lowered for the navvies to wet their spades with. After pumping for the last time, the excavation was continued night and day until the caisson had attained its full depth. When in this position, the level of the cutting-edge was 53 feet below Trinity high-water, or about 19 feet beneath the river-bed. This depth was considered sufficient to render the process of under-cutting beyond the edges of the caisson a comparatively safe operation.

The weights for forcing the caissons down to their full depth varied according to the degree of accuracy observed in fitting the bottom frames; for the least yielding of the frames allowed the sides of the caisson to be forced inwards—thus becoming smaller at the bottom and acting as a wedge in resisting the downward pressure. The greatest deflection of the cutting-edge at the middle of its length was 3 inches inside its original line; but the deflection usually amounted to no more than 1 or 2 inches. The weight of a square caisson, including timbering, was 166 tons, and that of a triangular caisson 207 tons. The greatest weight of the kentledge added was 274 tons in the case of a square caisson at the north pier; and the least was 86 tons for one of the triangular caissons at the south pier. For the square caissons the average weight of the kentledge was 208 tons at the north pier and 131 tons at the south pier; and for the triangular caissons 102 tons at the north pier and 92 tons at the south pier. It will be noticed that the caissons at the north pier required considerably more weight to sink them than those at the south pier; in the first place, because the former, by the water being pumped out earlier, were exposed for a longer period to the water-pressure and became consequently more deflected at the cutting-edge; and in the second, because the ground-level at the north pier being some few inches above the junction between the temporary and the permanent caissons, the projecting angle-irons at the joint opposed considerable resistance in the last few inches of the descent.

As regards the rates of progress in sinking the caissons, it should be noted that 2 or 3 days would frequently elapse without the lowering-screws being slackened at all—either to allow the divers to gain more height beneath the bottom frame, or because the lowering operations would have interfered with the erection of the upper sections of the caisson. Taking, however, the whole depth through which the caissons were sunk, to the time the pumps were erected, and dividing this by the number of days during which the divers were engaged in digging, the result gives an average daily rate of descent of about 8 inches. In a square caisson there were 4 divers, and in an angle-caisson 6 divers, at work for about 9 hours each day to effect this. A double shift was employed, so that the men were only below water during one-half of the day, being at the signal-ropes during the other half. The grabbing was usually done after the divers had finished work for the day, and occupied about 2 hours in the square, and 3 hours in the angle-caissons. The average daily descent of the caissons during tide-work, amounted to about 1 foot 4 inches; but in the square one there was only room for 20 men to be effectively employed, against 24 men in the angle-caisson. The average time available for digging at each tide was about 4 hours. After the final exclusion of the tide, a double shift of navvies was set to work, with the result that the average rate of descent was increased to about 3 feet 9 inches per day. Each shift worked for 10 hours and the numbers in each were similar to those for the tide-work.

In arriving at the foregoing average results of the sinking the rates of two of the caissons have been omitted, because in those cases considerable delays occurred. The first was due to the removal of some moorings from near the site of one of the square caissons at the north pier, which had left a hole extending, as it was thought, to a depth of 5 feet beneath the surface. The caisson was therefore sunk to a depth of 11 feet before pumping out, and after 2 days of tide-work the water was excluded. Two more days had passed and the cutting-edge had reached a depth of 16 feet beneath the river-bed, when a "blow" occurred and the water rushed in through a rent in the clay which extended to a depth of about 9 inches below the cutting-edge. The solid clay intervening between the rent and the ordinary level of the cutting-edge when sunk to its usual depth amounted only to 3 feet; so that this caisson was sunk somewhat deeper than the others, to gain a sufficient thickness of clay to withstand the water-pressure before again pumping out the water. The temporary caisson was therefore made 2 feet higher by a couple of timbers bolted all round the top, and the sinking was continued by divers to a depth of 1 foot 6 inches below the ordinary level. Towards low-water the water was pumped out from the caisson, and before the tide rose the bottom in the neighbourhood of the blow was cleaned off and the concrete was filled in to a height of 2 feet above the cutting-edge. The sluices were then opened and 3 days were allowed for the concrete to set before the water in the caisson was again pumped out. The water was now finally excluded and the remaining operations were conducted as in the case of the other caissons.

The second blow took place in one of the angle-caissons at the south pier and was due to a stage-pile in the narrow space between the two angle-caissons being driven in a slanting direction; so that, as the caisson went down, its cutting-edge came in contact with the pile and thus loosened the clay in the immediate neighbourhood. The blow occurred whilst the water was being pumped out for the first time, the cutting-edge of the caisson at the time being 13½ feet below the river-bed. This left a depth of 5½ feet to be sunk by the divers before the caisson attained its full depth. The adjoining angle-caisson had been previously sunk, and the blow being in the space between the two, all danger of another mishap was averted by driving the piles and removing the water from the narrow space between them before again pumping.

Under-Cutting.

The sides of the caissons forming the circumference of the pier were under-cut 5 feet beyond the cutting-edge and 7 feet beneath it. The excavation was sloped down from the edge of the caisson at an inclination of 1 to 1, so that an upright face 2 feet in height remained at the toe of the cutting. In addition to the above, each caisson was under-cut for a width of 2 feet 6 inches beneath the spaces intervening between it and the adjoining caissons. Before commencing the under-cutting, the kentledge was removed in order to relieve the lowering-rods and the heart of the caisson was then excavated to a depth of 4½ feet beneath the level of the cutting-edge, so that the under-cutting might be executed as rapidly as possible and afford less chance of accident from slips or swelling of the clay after exposure to the air. For a similar reason, each caisson was under-cut in sections, 3 in the square and 4 in the angle-caissons (Fig. 4). Each section was concreted before the excavation of the adjoining section was commenced; the order in which the sections were executed is indicated by numbers on the plan.

The sloping face of the excavation was timbered with 1½-inch poling-boards, 12 inches wide and 3 feet 6 inches long. Their upper ends were tucked against the cutting-edge (Fig. 11) and their lower ends were temporarily held by wedges driven into the clay. When 9 or 10 boards had been inserted, a head-tree of

3-inch by 9-inch plank was laid along so as to bear against the middle of the poling-boards, and this was secured by raking struts, 5 or 6 inches square, tightened by folding wedges at their lower ends and butting against timber foot-blocks bedded in the clay. The struts were spaced 4 or 5 feet apart—one at each end and one in the centre of the head-tree. A second setting of timber was necessary for the 5-foot under-cutting, similar to the first except as regards the length of the struts. The shape of the excavation prior to the insertion of each setting of timber is shown by dotted lines in the section, Fig. 11. The upright face at the toe of the under-cutting was excavated immediately before filling in the concrete, so that no timbering was necessary; but the vertical sides adjoining the central portion of the pier were poled with 1½-inch boards, their edges being tucked behind the cutting-edge and held at the lower ends by wedges driven into the clay. No walings or struts were necessary. The timbering of the 5-foot under-cutting round the outside of the pier was permanently concreted. The poling-boards and head-trees of the 2-foot 6-inch under-cutting between the caissons, and the boards adjoining the central portion of the pier, were all removed as the excavation proceeded.

The square caissons at the up-stream or western end of each row were the first sunk, and were under-cut on the outside and each of the two sides next the adjoining caissons. When an adjoining caisson was sunk, the triangular section of clay remaining above the slope of the concrete already put in was under-cut horizontally, high enough to enable the poling-boards to be jammed between the edges of the two caissons (Fig. 13). Only 5 or 6 boards were put in at a time, so that the head-tree might be inserted to secure them before the clay had time to exert much pressure. The head-tree was propped at each end from the toe of the concrete already put in. The props were left in permanently, but the boards and head-trees were removed after the spaces between the caissons had been excavated. No accident occurred with the under-cutting at either of the piers; for, in the few cases where the clay showed any tendency to swell to a dangerous extent, it was immediately secured by additional timbering.

Concreting.

As soon as a section of the under-cutting had been completed, the concrete was filled in. It was gauged 6 parts of Thames ballast to 1 part of Portland cement and was lowered in skips into place. The cranes would not plumb the whole extent of the bottom, but men stationed below were able to swing the skips into most parts of the foundation, so that little shovelling of the concrete was necessary. No regular layers were adhered to; but as a rule the concrete was shot from the skips and slightly spread with the shovel, so as to form irregular layers about 18 inches in thickness. Wooden shutters were placed between the concrete and the untouched sections of the under-cutting and were removed on the completion of the excavation. Each section was concreted to about 6 inches above the cutting-edge, to ensure a sound support for the caisson before the removal of the lowering-rods. To facilitate the future removal of that side of the caisson adjoining the central portion of the pier, the few rivets inside the caisson, which held the sides together, were cut out before proceeding higher with the concrete. With a view to prevent the adhesion of the concrete to that side of the caisson which was to be afterwards removed, boards were laid against the ironwork, and two large wooden boxes were fixed against the boarding so as to form dove-tails in the concrete and thus effect a better junction between the concrete in the caisson and that in the central portion. The dove-tails (Figs. 3 and 5, Plate 4) extended from 6 inches above the cutting-edge up to the top of the concrete; but the boxes which formed them were in short sections, placed one above another. The first sections reached to the underside of the bottom frame of timber, and, as soon as they had been fixed in position, the concrete was carried up to the same height. An interval of one day was usually allowed for the concrete to set, when the bottom frame of timber was struck, the boarding and second sections of the dove-tail boxes were fixed and the concrete was raised to the underside of the second frame. A repetition of the process brought the concrete up to the third frame, level with the tops of the rolled joists. From this level upwards the boards were laid against the skin-plates, both on the side adjoining the central portion of the pier and also on the sides next to the adjoining caissons, in order that the latter might be removed after the spaces between the caissons had been excavated.

The removal of the adjoining sides of the permanent caissons was not originally contemplated; and no special joints to facilitate the separation of the sides had been provided. Only their upper portions, therefore, above the level of the rolled joists, were removed—the cutting to effect this being much less than would have been necessary for the lower portions. Moreover, there was less reason for the removal of the latter, because the concrete of the under-cutting formed a good junction below. Besides the large dove-tails next to the central portion, small dove-tails were fixed against the boarding between the third and fourth frames on the sides next to the adjoining caissons (Figs. 3 and 5). This construction considerably weakened the concrete between the third and fourth frames; and it was found expedient, before striking the fourth frame, to allow about two days for the concrete to set sufficiently to withstand the pressure consequent upon the withdrawal of the timber.

The finished level of the concrete was reached at a few inches below the fifth or top frame of the permanent caisson. The work remained at this level until a more extensive area for commencing the masonry than that afforded by a single caisson could be obtained by the removal of the sides and the bonding between adjacent caissons.

Bonding between the Caissons.

Before excluding the water from the narrow spaces between the caissons, cross-struts, shown in Fig. 7, Plate 4, had to be inserted at each timber frame; these took the place of the diagonals which ceased to do their work as soon as the water-pressure was removed from one end, whilst still remaining upon the other. At the junctions between the square caissons and the triangular caissons, additional struts were required to replace those bearing against the space between them. These are shown upon the plan (Fig. 7), where will be seen also the arrangement of timbering inserted between the two triangular caissons prior to the piles being driven between them; so that the pressures from the struts of one caisson might be conveyed across the intermediate space to balance those of the other. The joints between the caissons were each made with two piles, the first of which had a tapered filling-piece, wider below than above, bolted against it. The second, or closing pile, was tapered the reverse way, and by this means a very tight joint was obtained. The first pile was fitted with a sheeting-shoe, so that, in driving, it was kept hard against the pile-groove. The closing pile was diamond-pointed. An accurate fit, between the angle-irons forming the pile-grooves and the sides of the piles, was ensured by bevelling the latter so that the outer edges of the angle-irons cut into the fibres of the wood. All the pressure being thus thrown upon the sides of the piles, their backs were kept clear of the ironwork; and after the piles had been driven, the intervening spaces were filled in from the top with cement-grout.

To counteract the tendency of the pile-driving to force the caissons apart, they were held together by tie-bolts, about 2 feet apart, through the bolt-holes next the pile-grooves. These could only be put in above low-water level; but the greater part of the temporary caissons being so secured, and the concrete filling preventing any displacement of the permanent caissons, there was small chance of the intermediate portions being disturbed. As soon, however, as the water was removed from between the caissons, the tie-bolts were inserted down to the bottom of the temporary caissons; and this was most necessary, inasmuch as, upon the removal of the adjoining sides, they formed the only connection in a longitudinal direction between the remaining plates of the temporary caissons. When the pile-joints had been made, some bolts were knocked out and the water was allowed to drain from the narrow space through the bolt-holes into one of the neighbouring caissons. Thence it was pumped by a 2-inch pulsometer pump placed in one of the large dove-tail-holes in the concrete, which formed a convenient sump.

The adjoining sides of the temporary caissons were next removed, after the bolts at the horizontal joints and the remainder of those at the vertical joints next to the pile-grooves had been withdrawn. A connection between the outer and the inner sides of the caissons was still maintained by the bolts joining the cross timbers with the ironwork; and some additional transverse strength was gained by bolting half-timber diagonals from top to bottom of the cross timbers. The work of excavation in the narrow space between the caissons was somewhat tedious, as only 2 men at a time could be employed in digging and all the excavated material had to be raised in buckets to the top of the permanent caisson, where it was deposited on the concrete and afterwards removed in the skips.

When the excavation reached the level of the cutting-edge, the boards and head-trees of the under-cutting were taken away and the concrete was filled in for a height of about 7 feet—this being a convenient level for the workmen to stand at whilst cutting away the upper portions of the permanent caissons. To effect this, the row of rivets at the horizontal joint next above the rolled joists was cut out and vertical chisel-cuts were made in the skin-plates close to the pile-grooves. The internal angle-irons at the horizontal joints had been previously cut through from the inside of the caisson, before depositing the concrete. On removing the plates of the permanent caissons, the timbering of the small dove-tails was taken out and the concrete was filled in to the top.

It should be noted that, even after the junctions between all the caissons had been constructed, so as to form a continuous caisson enclosing the whole circuit of the pier, communication between the water on the outside and that in the central portion of the pier was still maintained by means of a 12-inch pipe passing through the piles and in the space between two of the caissons. By this means the pressures against the outer and the inner sides of the caissons nearly balanced one another; for, even with a rapidly rising or falling tide, the water-level on the outside never differed more than about 20 inches from that on the inside, and the transverse strength of the caissons was ample to withstand this slight difference of pressure. The 12-inch pipe was fitted with a sluice, so that the water might be shut off altogether from the central portion.

Building in the Temporary Caissons.

The piers from the river-bed upwards are faced with rough-picked Cornish granite, in courses between 2 feet and 2 feet 6 inches in height. The interior is built with wire-cut gault bricks, except the part that supports the opening span and the inside facework, which are of Staffordshire brindle bricks. All the work is set in Portland cement-mortar, $2\frac{1}{2}$ to 1 for the gault brickwork, and $1\frac{1}{2}$ to 1 for the brindle brickwork and granite. The masonry was commenced in the 4 square caissons on either side of the pier as soon as the bonding between them was completed. The first course of granite was set on a bed of brickwork 2 feet thick over the whole surface of the concrete and extending level with the tops of the permanent caissons. Each alternate course of brickwork was butted tight against the caisson-plates; the other courses being set back so as to form a bond for the work to be afterwards built at the ends and in the central portion of the pier. Additional bond was afforded by the recesses left in the brickwork above the large dove-tails, which extended to the top of the concrete.

Before a second course of granite was set, the struts across the caisson next above the first course had to be removed. To render this feasible, short timbers to take their places were inserted between the longitudinal timbers supporting the outer skin of the caissons and the face of the masonry already set (Fig. 8). These struts were inclined on account of the masonry being below the longitudinal timbers; but, as the struts were about 9 feet long, the inclination was not so great as to impair their efficiency. In the triangular caissons, however, where the struts were 3 or 4 feet shorter than in the square caissons, the inclination would have been too steep if the above system had been adopted. In these caissons, therefore, some of the stones of the second course were set and backed up in the spaces between the cross struts, which latter were placed horizontally against these detached portions of the second course. When the work had set sufficiently to withstand the water-pressure, the cross-struts were removed and the stones to complete the course were set. In some cases, where the height was considerable between the top of a course and the frame next above it, instead of setting the detached portions of the succeeding course between the cross-struts, it was found more convenient to insert an additional longitudinal below the original frame, so that the short struts between this and the masonry might be placed horizontally, or nearly so. The upper courses were set in a similar manner to those already described.

The masonry was racked back at each end of the 4 square caissons until the bonding between the adjoining triangular caissons had been completed. The work in these was then brought up level with that in the square caissons, and the whole proceeded together. Similarly, the masonry was racked back at the cut-waters where the bonding between the two triangular caissons was built at a later date than that between the triangular and the square caissons. Upon the completion of the wall surrounding the pier, the remaining sides of the temporary caissons were removed. The piles at the outside joints between the caissons, which had previously been partially bored through from inside the caissons, were broken off level with the tops of the permanent caissons. The piles at the inside joints were removed after the central portion of the pier had been excavated.

The Central Portion of the Piers.

Before finally excluding the tide, 5 double-timber struts were placed across the central portion from one wall to the other at about high-water level (Fig. 8). The walls were strong enough to stand alone, but the struts were required to prevent the external water-pressure from unduly compressing the clay beneath the inner edges of the concrete foundations. On draining away the water, the central portion of the north pier was found to have silted up 14 feet above the original level of the river-bed. This had occurred during an interval of 13 months, dating from the lowering of the first triangular caisson, which may be considered as the time when the silt first began to accumulate. At the south pier, where a somewhat shorter period elapsed, the depth of the silt was 12 feet 9 inches. The silt was dug out with Priestman grabs.

As soon as the progress of the excavation permitted, the inner plates of the temporary caissons were removed and a second set of cross-struts, about 20 feet below the first, was placed across from one wall to the other. The excavation was carried down over the whole surface to a depth of 5 feet below the tops of the permanent caissons; but below this level it was taken out in 4 sections, their divisions corresponding with the joints between the caissons. No two adjoining sections were excavated simultaneously, so that the walls were never left unsupported for a greater length than about 30 feet at one time. No pumping was necessary during the excavation, as the walls proved water-tight, except for a slight weeping through the concrete, amounting over the whole extent of the pier to a maximum of 40 gallons per hour. This small quantity was baled out from time to time. As the excavation proceeded, the iron-workers followed, cutting out the rivets which connected the inner sides of the permanent caissons to the cross sides; thus, upon the completion of the excavation, the plates were quickly removed. The dove-tails were then cleaned out and the concrete was filled in to within about 4 feet of the finished level. The latter part was left until the 4 sections had been brought to the same height, after which the whole surface was finished off. Additional bond was thus secured, as well as a fair surface for the commencement of the brickwork. This latter was all straightforward—the only point that required attention being the careful raking out and accurate fitting of the bricks into the toothings left during the building of the work in the caissons.

Conclusion.

The erection of the first caisson was commenced in September, 1886; but it was not until January, 1890, that both the piers were completed to the limits of the contract. The following were the chief hindrances to the rapid execution of the works: It was rendered compulsory, by a clause in the Tower Bridge Act, to maintain continually a clear water-way of 160 feet between the piers whilst the operations were in progress. This could only be done by deferring the excavation of one side of one of the piers until the staging should be cleared away from the neighbouring side of the other pier. Had both piers proceeded simultaneously, a saving of 13 or 14 months might have been effected. As a slight set-off against this unavoidable loss of time, the cost of half the temporary caissons for the south pier was saved by using those from the north pier over again. Another delay arose from all vessels and barges arriving at the works being compelled to moor on the shore sides of the piers, in order that the navigation of the central water-way should not be impeded. Hence the labour in handling materials required for the sides of the piers next the central water-way, and the removal of the excavated material therefrom, was doubled in comparison with the labour that would have sufficed had vessels been allowed to moor on both sides of the piers. Again, it was found that the area of the temporary staging —although considerable, and as large perhaps as was consistent with the interests of the river traffic—was far too restricted for the rapid execution of the work. The plant alone occupied a large part of the staging [1] and, deducting the space for the crane roads, little room remained for the storage of materials. These were consequently ordered piecemeal and frequent delays resulted from the failure of their delivery at the required moment.

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[1] The following is a list of the principal items of plant in use at one time upon a single pier:—

3 Priestman 5-ton travelling-cranes and grabs.
3 Booth 4-ton travelling-cranes.
1 4-ton Scotch crane.
1 10-inch Gwynne centrifugal pump.
1 12-inch Owen direct-acting force-pump.
2 2-inch pulsometer pumps.
2 2,000-gallon water-tanks.
5 Lucigen lights, each of 2,500 candle-power.
1 Air-compressing engine for ditto.
3 Vertical boilers for pumps and lights.
6 Sets of diving-gear and shed for divers.
Coal- and cement-stores.

The total cost of the 2 piers to a height of 4 feet above Trinity high-water, including all temporary works, amounted to £111,122. The principal items comprised in the above sum are:—

140.000	cubic feet of timbering in staging, caissons, &c.
997	tons of wrought-iron and steel in 24 permanent caissons.
915	tons of wrought-iron in 18 temporary caissons.
27,710	cubic yards of excavation, exclusive of 4,200 cubic yards of silt.
25,220	cubic yards of Portland cement concrete, 6 to 1.
20,600	,, ,, Gault brickwork in cement.
1,800	,, ,, Staffordshire brindle brickwork in cement.
3,340	,, ,, Cornish granite.
Total 50,960	,, ,, concrete, brickwork and granite.

The first 4 items may be regarded as subsidiary to the execution of the concrete, brickwork and granite which form the permanent portions of the work. Dividing the total cost by the cubic contents of the last-named items, the average cost is £2 3*s.* 7*d.* per cubic yard.

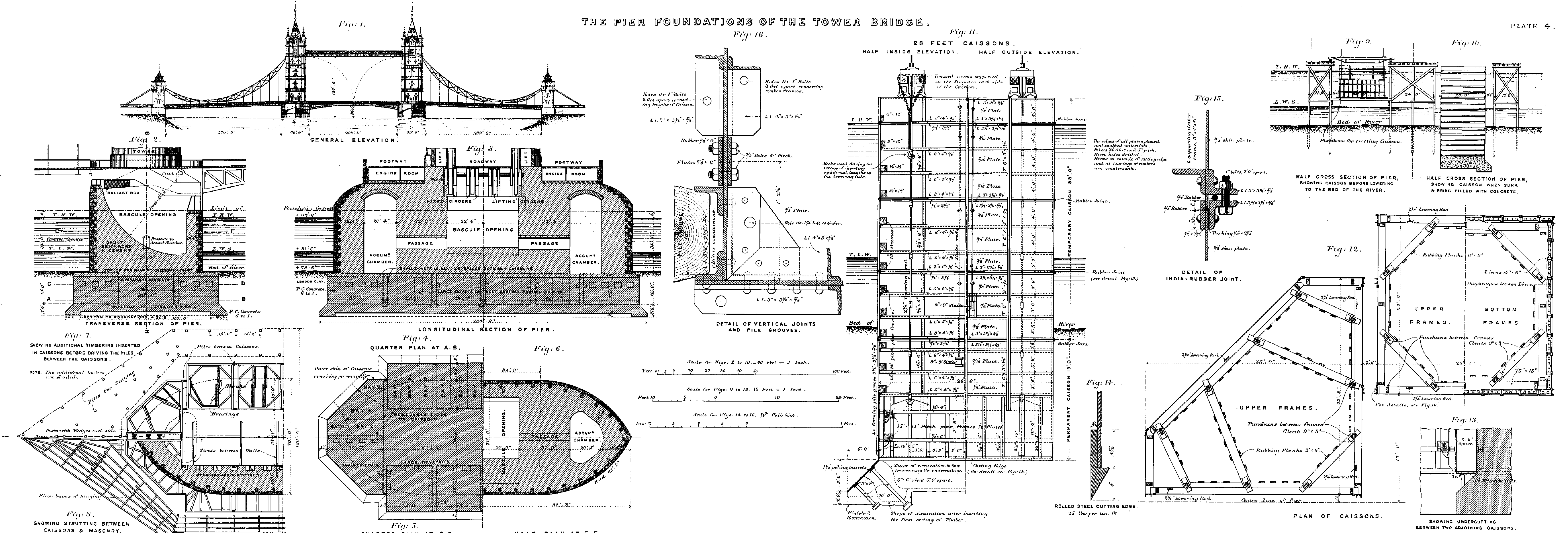
The bridge is being constructed by the Corporation of the City of London. The Contractor for the part of the work described was Mr. John Jackson, who was represented on the works by Messrs. W. Wilkinson and G. H. Scott. The original proposal for a bascule opening bridge came from the City Architect, the late Sir Horace Jones, with whom was associated Mr. J. Wolfe Barry, as Engineer, and the Author is the Resident Engineer.

The Paper is accompanied by a sheet of tracings, from which Plate 4 has been prepared.

[DISCUSSION.

THE PIER FOUNDATIONS OF THE TOWER BRIDGE.

PLATE 4.



G. E. W. CRUTTWELL.

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THOS KELL & SON, LITH. 40 KING ST COVENT GARDEN.