(*Paper No. 3764.*)

"The New Clyde Bridge of the Caledonian Railway at Glasgow."

By DONALD ALEXANDER MATHESON, M. Inst. C.E.

THE New Clyde Bridge, which was completed in 1905, is perhaps the most outstanding structural feature of the recent extension of the Caledonian Railway Central Station in Glasgow, the scheme and general arrangement of which have already been described to The Institution.[1] The new bridge, which carries the widened railway across the River Clyde in the immediate precincts of the station (*Fig. 1*), is within a stone's throw of Telford's reconstructed "Glasgow Bridge," and immediately west of the railway-bridge which was built in connection with the old Central Station.[2]

GENERAL DESCRIPTION.

For structural reasons it was considered expedient to have the new bridge and the old bridge somewhat apart at the middle, but they are close together at the ends.

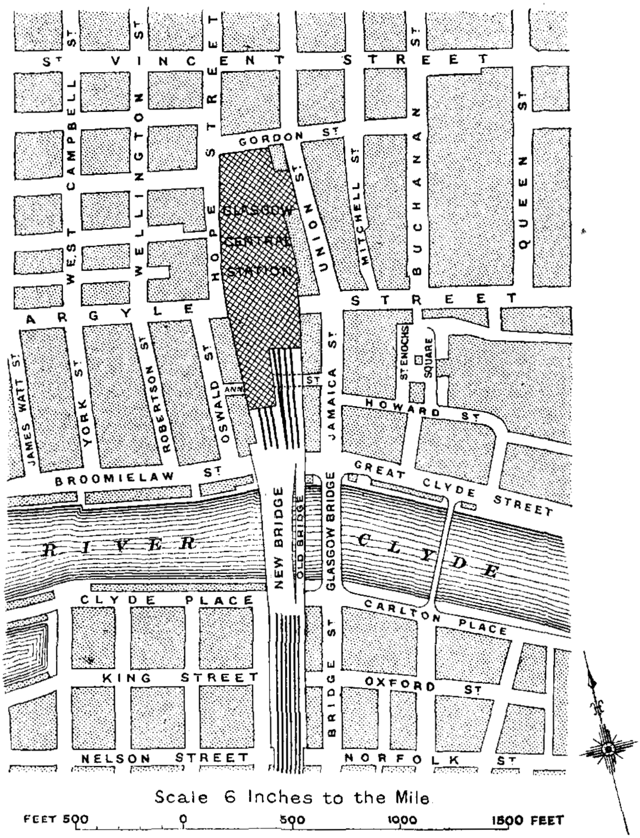
The general form and dimensions of the new bridge are shown by Figs. 2–5, Plate 1, and Figs. 21 and 22, Plate 2, from which it will be seen that the structure is in the nature of a great platform of steelwork carrying the main part of the Central Station yard, and the approach-lines thereto, across the river and the street on either side of it. The width between the parapet-girders is 114 feet at

[1] D. A. Matheson, "Glasgow Central Station Extension." Minutes of Proceedings Inst. C.E., vol. clxxv, p. 30.

[2] B. Hall Blyth, "The Caledonian Railway Viaduct over the River Clyde at Glasgow." Minutes of Proceedings Inst. C.E., vol. lxi, p. 190.

the middle of the centre span, fanning out to 205 feet at the north end, and to 118 feet at the south end; and it is believed that there are few wider railway-bridges in existence. The total length of the five spans, measured on the centre-line, between the faces of the abutments, is 702 feet 6 inches.

Fig. 1.



Plan of Site.

The bottom of the foundation of the southernmost river pier is about 110 feet below rail-level, and as the top of the pilaster is about 30 feet above rail-level, the total depth from the top of the pilaster to the bottom of the foundation is about 140 feet. The new bridge carries nine lines of rails at its north end, which converge to eight at its south end; while the old bridge carries four lines.

The range of tide in the River Clyde at the site of the bridge is about 11 feet, and high-water level is taken to be 6·20 feet above Ordnance datum.

The substructure of the bridge consists of masonry abutments and piers, the latter being composed of a series of cylindrical pillars (Figs. 3–6, Plate 1). The foundations of the abutments are only about 15 feet and 9 feet below the surface of the streets on the north and the south side of the river respectively, but the piers are carried down to considerable depths, parts of their foundations being as low as 70 feet below high-water level. The abutments and piers of the new bridge were fixed by statute to be in line with the abutments and piers of the old bridge, and the widths of the piers were similarly governed. There was, therefore, no choice in the fixing of the spans of the new bridge.

The superstructure consists of numerous steel main girders, of the parallel-flanged lattice type, laid longitudinally, with flooring laid transversely on the top flanges (Fig. 3, Plate 1). The main girders and the flooring are entirely below rail-level, or rather below formation-level. Above the flooring the surface is ballasted all over to a minimum depth of about 6 inches below the sleepers of the permanent way.

The superstructure of the old railway-bridge, which is 50 feet wide, is composed of two longitudinal main outside girders, 20 feet in depth, and between these main girders there are cross girders with longitudinal rail-bearers (Figs. 4 and 5, Plate 1).

The new bridge is of such abnormal width that the possibility of its being constructed with a high longitudinal main girder on either side, and cross girders between, was absolutely precluded. In order to allow of the permanent way of the cross connecting lines and junctions of the station-yard being of the Caledonian Railway standard pattern, and being laid in any required position on the new bridge, it was necessary to have an uninterrupted upper surface or flat top on which ballast, together with the other permanent-way materials, could be laid all over; and the design of the superstructure was governed accordingly.

The levels of the undersides of the main girders were also fixed by Act of Parliament. In determining the heights of the girders over the river and the quay on either side, regard had to be had to the requirements of the Trustees of the Clyde Navigation in respect of the navigation of the river and the uninterrupted use of the quays underneath the bridge. The level of the bottom flanges of the girders of the centre span was fixed in relation to the maximum height of the funnels of the river-craft which pass up and down the middle channel, and the levels of the bottom flanges of the girders of the side river-spans were determined by the working headroom required above the quays. The clear heights of the girders of the span over the street on each side of the river were fixed by the City Corporation to be the same as the clear height of the girders of the existing bridge, namely, 20 feet above the surface-level.

The total live load on the bridge may sometimes be very high, because the bridge carries the main part of the station-yard, and the several lines are frequently being run on simultaneously by numerous locomotives and trains. Then, by reason of the weight of the ballast and other permanent-way materials and the limited depth for construction between rail-level and the statutory levels of the bottom flanges of the main girders, with the resulting indifferent proportions of the main girders in respect of the ratio of depth to span, the flanges of the main girders are of necessity large in sectional area and the girders are consequently heavy. Massive piers are therefore required, and the gross weights transmitted to the foundations are very heavy.

FOUNDATIONS.

Geological Investigation of the Site.—It was hoped that the foundations might be constructed on rock, but a series of trial borings revealed the rock to be at such a depth as to make founding on it practically prohibitive. The borings, which were ordinary chisel-borings, were carefully made by a trustworthy boring-contractor, now deceased, and it is pleasing to put on record the accuracy of his work. The character and levels of the geological strata as indicated by the borings were identical with what were revealed in the actual excavations for the foundations (Figs. 2, Plate 1). An engineering assistant was constantly in attendance at the site while the borings were being made, and the results were immediately plotted in section as they were ascertained. Where the character of the strata appeared to change suddenly, confirmatory second borings were always made; such second borings were not infrequent, although they were always found to be corroborative of the first, the change of character being invariably ascertained to be due to a natural fault. The circumstances of the site of the Clyde Bridge rendered trial-pits prohibitive.

Borings, particularly chisel-borings, are proverbially fallacious, but their accuracy in this case was so remarkable as to suggest complete justification of the practice of chisel-boring, as distinguished from boring by the diamond drill, for all the preliminary purposes of engineering work, except the puddle-trenches of waterworks and perhaps the foundations of dock-walls. And the great importance of ensuring accurate results by boring suggests that all qualified boring-contractors should be officially accredited by a recognized authority.

There is some variation in the character of the strata at the sites of the several piers, but at the centre of the river the following may be taken as a typical section:—

	Feet below High-Water Level.
Low-water level	11
Top of mud, river-bed	23
,, muddy sand and clay	25
,, clay and sand	38
,, sand	45
,, fine sand	50
,, coarse sand	58
,, sand and gravel	64
,, sand	71
,, sand and gravel	83
,, rock	92

After careful consideration, the foundations were designed on the assumption that the rock level would not be reached.

Foundations of the Piers.—The construction of the foundations of the piers—land piers as well as river piers—was perhaps the most interesting part of the work. These foundations were constructed by sinking large steel caissons of rectangular form, by the pneumatic process, down to the level of dense sand and gravel.

As an alternative method, it was at first proposed to sink steel cylinders and carry the foundations cylindrically down to the level of the rock, which as already stated, the borings revealed to be about 92 feet below high-water level. Having regard, however, to the comparative difficulty and the inconvenience and uncertainty attaching to working under compressed air with such a head of water, the risk to human life, the possible extra cost, the greater uncertainty as to timeous completion, and the all-important fact that the geological strata at the higher level were quite suitable for founding on, it was ultimately determined to construct the foundations on the sand and gravel, and not on the rock at the lower level. The steel caissons being filled with concrete, the foundation-courses of the several piers are really large monolithic masses of concrete enclosed in skins of steel.

In order to ensure safe loads on the subsoil and have a margin of stability, it was found necessary to make the foundation-courses 4 feet 9 inches wider than the bottom diameter of the cylindrical pillars of the piers, that is 2 feet 4½ inches wider on either side. The extreme width of the caissons for the river piers and land piers had, therefore, to be 23 feet 3 inches and 20 feet 3 inches respectively, measured over the cutting edge. Execution in short lengths being the first principle in the construction of deep and otherwise difficult foundations, it was considered inexpedient to have only one caisson for each pier. A single caisson for each pier of the length which would have been required would have been unwieldy and it might have been difficult to sink it uniformly. A single caisson for the northernmost river pier, for example, would have measured about 132 feet in length by 23 feet 3 inches in width. It was therefore decided to have two caissons for each pier, but, when the work of sinking these was well on towards completion, it was determined to widen the bridge slightly at either end on the east side by "bell-mouthing" in plan, and this necessitated the sinking of two very small additional caissons, one at the east end of each of the land piers. Altogether the caissons were ten in number, and were designated and placed as shown in *Figs.* 7 (p. 16), the two additional small caissons being A 3 and D 3. The largest two caissons were 89 feet 6 inches long by 20 feet 3 inches wide and 79 feet 4 inches by 23 feet 3 inches.

In designing the foundations regard was had to the necessity of having them at such a depth as to preclude their being affected by scour of the river-bed or by deepening for navigation purposes. A homogeneous mixture of strong sand and gravel, if deep down, is for all the practical purposes of foundations almost as good as solid rock. The mixture of sand and gravel upon which the piers were founded is strong and homogeneous in character. In deciding to found at the higher level on sand and gravel by means of caissons, instead of by sinking cylinders down to the rock, there was due regard to the general economics, and it was kept in view that the sustaining-power of rock might be taken to be much greater than the sustaining-power of a mixture of sand and gravel, and that the areas of the foundations could be proportioned accordingly. The depth had also, however, to be borne in mind; and while, notwithstanding the greater depth, there might have been less volume with cylinders than with caissons, the average unit cost would have been higher; so that in respect of the gross cost it was reckoned that there was little to choose between the two forms of construction. The comparative certainty and safety of the caisson form influenced the decision in its favour, a decision which was proved by after events to be justified, for the caissons were sunk quickly and successfully without untoward incident of any serious kind.

The depths of the bottoms of the main parts of the foundations of the piers, i.e. of the several main caissons, vary from 40·30 feet to 70·47 feet below high-water level. The depths are stated in detail in Appendix I.

The variation in the depths of the caissons of the several piers is due to the different levels of the materials considered suitable for founding on, finally determined as the excavations proceeded, but subject as already stated. The foundations of the land piers were purposely kept much higher than the foundations of the river piers, for, being well protected by the quays, they cannot of course be affected by scour of the river-bed.

In calculating the stability of the foundations, the possible support to be derived from surface friction was entirely disregarded, and with the object of having a greater margin of strength, the part immersion of the piers and the resulting partial diminution of their weight was also to some extent discounted, although the substantially helpful effect of the buoyancy was of course taken into consideration. After careful investigation, it was concluded that dense deposits of sand and gravel at such depths and under the respective circumstances of the piers might be assumed to have safely sustaining-power to the load of about 5 tons per square foot in the case of the land piers and to the load of about 6 tons per square foot in the case of the river piers, and the areas of the foundations were determined on the basis of these unit loads, which however, would be the weights if weighed in air and not in water. The river piers are about 20 to 30 feet deeper than the land piers relatively to the level of low water, hence the different unit load.

The areas of the foundations and the gross and unit loads at the bottoms of the main caissons, disregarding surface friction and buoyancy, are shown by the Table on p. 11.

If allowance were made for the bearing value of frictional resistance at the sides and ends of the caissons, the unit loads in this Table might be stated at about 10 per cent. less; and they would be nearly 20 per cent. less still if the full allowance were also made for the effect of buoyancy. Surface friction is, however, very variable and altogether too indefinite and uncertain to be relied on, particularly in connection with cylinders and caissons of steel, the surfaces of which are smooth; and therefore it should not be a prime factor in the calculation of bearing-areas. Buoyancy is a more tangible thing, and it should always, of course, be given a definite and

Pier.	Bearing-area at Bottom of Caissons.	Gross Load due to dead weight and live load at Bottom of Caissons.	Unit Load due to dead weight and live load at Bottom of Caissons.
1. North land pier—	Square Feet.	Tons.	Tons per Square Foot.
Caisson A 1	1,812	7,481	4·12
Caisson A 2	1,249	5,911	4·73
2. North river pier—			
Caisson B 1	1,845	10,446	5·66
Caisson B 2	1,215	7,247	5·96
3. South river pier—			
Caisson C 1	1,718	10,388	6·04
Caisson C 2	1,129	6,921	6·12
4. South land pier—			
Caisson D 1	1,127	5,355	4·75
Caisson D 2	1,127	5,355	4·75

substantial value in determining the safe loads on submerged foundations. On the other hand, in connection with deep foundations not in water it is somewhat unusual for the initial pressure of the original superincumbent earth to receive much consideration. Neither is it very customary to make any allowance in respect of water displaced in deep foundations in strata which are water-bearing—permeable strata such as running sand, for example—although in such a case the structure may be said to be to a certain extent water-borne, there being no uncertainty as to the helpful effect of the diminution of the weight of that part of it which is below the level of the surface of the subsoil-water. With a pier or other structure of constant cross-sectional area below water-level, this helpful effect is of course identical with the intensity of the hydrostatic pressure at the base due to the head of water.

The conditions and circumstances attaching to deep foundations are so very varied and difficult as perhaps to make it almost idle to sift and tabulate recorded experience with the object of standardizing the principles and practice in respect of the calculation of safe loads. There appears, however, to be such a want of uniformity that something might be done in this direction with very great advantage.

Caissons.—The caissons were of wrought steel and, although they varied in size, the scantlings of the plates and bars were the same in them all. They are typically shown in Figs. 8 and 9, Plate 1, inclusive. The working-chamber was 8 feet high, and access to it was got by means of shafts 3 feet 6 inches in diameter. There were three access-shafts in the larger main caissons and two in the smaller, and they were so situated as to be in the centre of the cylindrical masonry pillars. There was only one access-shaft in the subsidiary caissons A3 and D3.

The shell-plates of the caissons ranged in depth from 3 feet $11\frac{1}{2}$ inches at the top of the caisson to 4 feet 11 inches at the roof of the working-chamber, but they were 8 feet 4 inches deep in the sides and ends of the working-chamber. They ranged in thickness from $\frac{3}{8}$ inch at the top to $\frac{1}{2}$ inch at the bottom, and the plating of the working-chamber was also $\frac{1}{2}$ inch thick. The shell-plates overlapped at the horizontal joints and receded towards the top, and were well stiffened by longitudinal angles 5 inches by 3 inches by $\frac{1}{2}$ inch. The vertical joints of the shell-plates and of the plating of the working-chamber were butt joints with $\frac{3}{8}$ inch covers. The caissons were also stiffened by horizontal diagonal bracings in the form of angles 4 inches by 4 inches by $\frac{1}{2}$ inch, which were subsequently built into the masonry, and further stiffening towards the bottom was afforded by horizontal girders placed transversely at the roof of the working-chamber, about 5 feet apart, between centres. The primary purpose of these girders, however, was to provide support for the ceiling-plates of the working-chamber, which were also the floor-plates of the caisson and, as such, carried the concrete filling of the caisson pending the deposition and packing of the concrete in the working-chamber. Underneath these horizontal girders there were triangular stiffening-diaphragms, which extended down to and stiffened the cutting edge.

The cutting edge was a plate, 15 inches deep and 1 inch thick, placed on the outside and riveted to the bottom shell-plate through two internal continuous stiffening-angles 4 inches by 4 inches by $\frac{5}{8}$ inch. The bottom of the plating of the working-chamber was curved round and riveted between these continuous stiffening-angles, and the angles, together with the plating and its curved and blunt form at the bottom, offered desirable retarding influence in the sinking and tended to prevent any sudden drop. The cutting edge projected its full thickness externally, and this, with the shell-plates receding from bottom to top, gave the sides of the caissons a batter of about 1 in 100, the effect of which was to somewhat lessen the surface friction and facilitate the sinking.

The rivets of the caissons were $\frac{3}{4}$ inch in diameter and 3 inches pitch, excepting in the access-shafts and working-chamber, where, having regard to the effect of the high-pressure air, they were $\frac{3}{4}$ inch in diameter and 2¼ inches pitch, and in the cutting edge, where they were 1 inch in diameter and 4 inches pitch. The outside rivet-heads were hammered nearly flat, except on the outside of the cutting edge, where they were countersunk so as to lessen the friction in sinking. In order to ensure air-tightness, the joints of the working-chamber and the access-shafts were thoroughly caulked by hammering the edge of the plate into the surface against which it rested and the caissons were made watertight in a similar manner.

The over-all dimensions and weights of the steelwork of each of the main caissons of the several piers are stated in Appendix II.

The heights of the caissons, and to some extent the lengths, were determined in relation to the character of the strata suitable for founding on, but the exact lengths were governed mainly by the positions of the shafts of the working-chamber, which in their turn were fixed by the positions of the pillars of the piers.

The Masonry of the Substructure.

The abutments of the bridge are ordinary brick walls built on a concrete foundation-course, and, in accordance with statutory requirement, they are faced towards the streets with bricks of white enamelled surface. They are pierced by arched openings which give access to premises situated underneath the train-shed of the station and the station-yard, on the north and the south side of the river respectively.

There was no statutory obligation as to the number of pillars in the land piers, but there was restriction in respect of the river piers, and, in conformity with the Act of Parliament, there were five pillars in each of the river piers. There were five main pillars in the north land pier and four in the south land pier, but the "bell-mouthing" of the bridge on the east side at each end necessitated the construction of a subsidiary pillar and some additional masonry in each of the land piers. The pillars of the north and south river piers are 27 feet 1½ inch apart between centres and 25 feet 3½ inches between centres respectively, and the main pillars of the north and south land piers are 31 feet 8 inches apart between centres and 29 feet 7 inches apart between centres respectively. The lengths of the north and south river piers, measured just below the bed of the river, are about 127 feet and 120 feet respectively, while the lengths of the north and south land piers, measured just below the level of the quays, are about 158 feet and 117 feet respectively. The pillars are constructed of composite masonry in cement mortar, built and well distributed by footing-courses on the concrete monoliths. The internal masonry of the main part of the pillars is red brickwork with several through strengthening-courses of blue brickwork, and there is some concrete hearting in the form of filling of the access-shafts of the caissons. The character and form of the composite masonry of the pillars is shown by Figs. 2 to 6, Plate 1.

The pillars are faced with blue brickwork up to within 6 feet of low-water level in the case of the river piers and to within 2 feet of the surface of the quays in the case of the land piers. Above these levels the facing is of light grey granite ashlar of rock-face dressing up to high-water level and fine-axe dressing above. At the level of the top of the blue-brick facing these diameters are lessened by 1 foot 6 inches. As the pillars rise, the diameters become further reduced, for, having regard to appearance, they are built with a batter. In order to secure further architectural effect, the pillars of the river piers are connected above high-water level by granite arches of pleasing form, and there are also connecting arches between the pillars of the land piers. These latter, however, are more utilitarian in their purpose, being of brickwork and built below the level of the surface of the quays for the purpose of acting as a foundation for brick screen-walls between and in front of the pillars of the land piers. These screen-walls are also faced with bricks of white enamelled surface, under statutory obligation.

The concrete, which was machine-made, was mixed in the proportion of one part of cement to five parts of ballast, the ballast consisting of a mixture of equal volumes of broken clinker bricks and whinstone or of broken freestone and whinstone with the necessary volume of sand. The clinker bricks and the freestone and whinstone were of hard quality and were broken to an angular shape and of such size as to pass through a screen having meshes $1\frac{3}{4}$ inch square. The sand was sharp and coarse and was partly river-sand and partly pit-sand, as well as to some extent crushed freestone, the last however, as being the best, being used chiefly in the making of mortar. The main requirements were that the ballast should be thoroughly clean, that the several materials should be properly proportioned, that the aggregate and matrix should be specially well mixed, and that by means of buckets with opening bottoms the concrete should be carefully deposited in layers and be thoroughly rammed in situ with the object of ensuring density.

In the brickwork the red bricks were clay bricks as distinguished from composition bricks and were of a size to build four to the rising foot. They were built in English garden bond, and a dense mass was ensured by laying and "floating" the bricks in a deep layer of mortar which rendered grouting unnecessary and gave that best of all engineering masonry, good brickwork in cement.

Every granite stone used was dressed at the quarry and brought to the site of the bridge ready for building.

The mortar of all the kinds of masonry was cement mortar in the proportion of one part of cement to two parts of sand, and the cement grout was of similar quality, only differing from the mortar in the volume of water used in the mixing. By special requirement the mortar was mixed by hand-labour. The requirements of the specification in respect of cement were very similar to those of the British Standard specification.

In the design of the works of the bridge, as well as of the other works of the station, the unit loads which it was considered expedient to have on the several kinds of masonry were assumed to be the following:—

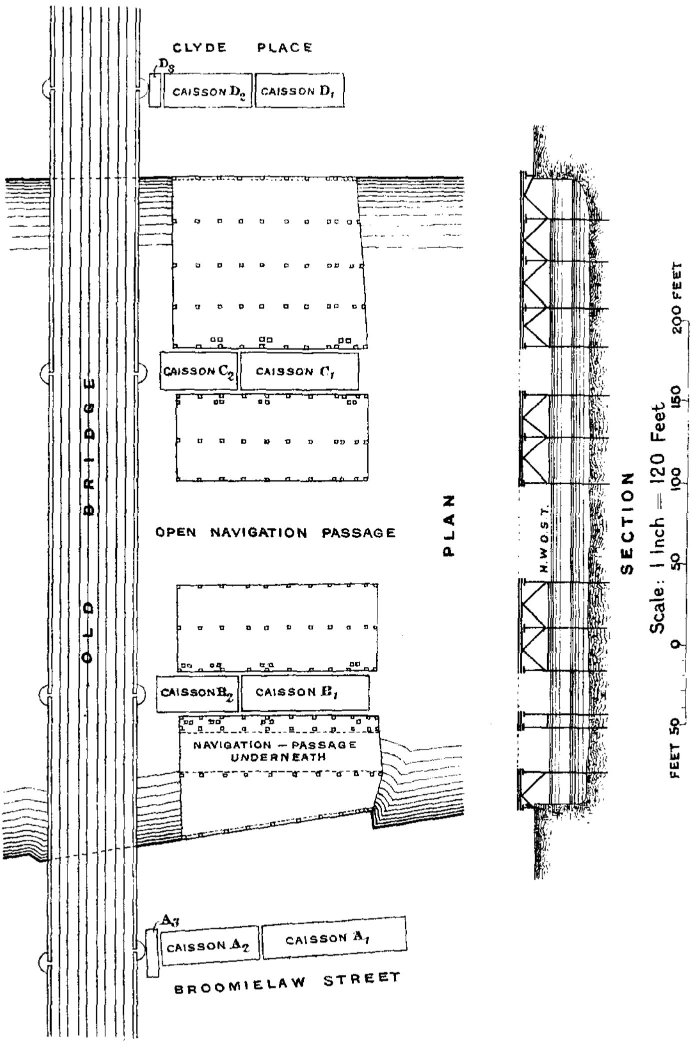
	Tons per Square Foot.
Concrete in foundations	7
,, in walls	8
Red brickwork in cement	10
Blue ,, ,, ,,	15
Freestone square rubble masonry in cement	8
,, ashlar masonry in cement	15
Granite ,, ,, ,, ,,	25
Freestone ashlar bearing-blocks	12
Granolithic bearing-blocks	12
Granite ashlar ,,	20

These are moderate loads giving considerable margin of stability, and while it cannot be said that they were strictly adopted, they served as standards. The weights of the several kinds of masonry were ascertained by careful experiment to be as stated in Appendix III.

The Temporary Staging.—The Company were authorized by the Act to erect, across the river and quays, a temporary staging of the full width of the new bridge and 21 feet wider on the west side. The only important requirement of the Clyde Navigation Trustees was that there should be two open passages underneath the staging for navigation, one on the north side adjoining Broomielaw Quay and the other in the centre of the river. The former was made 30 feet wide, while the latter was made 62 feet wide. Both passages were well lighted at night by electric lamps. The staging is shown in skeleton plan and longitudinal section by *Figs. 7* (p. 16).

The headroom of the open navigation-passages had to be the same as the headroom of the arches of Glasgow Bridge, that is, about 19 feet above high-water level.

The maximum width of the staging was about 125 feet, and its main purpose was to provide such platform accommodation over the river and quays as would facilitate erection and sinking of the caissons, erection of the main girders, and construction of the other works. The piers of the staging were placed in such positions as to allow of the caissons being sunk and the other works of the



Figs. 7.

TEMPORARY STAGING.

permanent bridge conveniently executed without modification of the staging, and the main uprights of the piers of the staging were placed on the lines of the main girders of the permanent bridge, so as to be directly under the heaviest loads which the staging was meant to carry.

The piers were in the form of a single row of pitch-pine timber piles, except those adjoining the open navigation-passages, which were formed of a double row of piles. The piles, which were 12 inches square, were driven to an average depth of 12 feet below the bed of the river, and they were thoroughly braced from about mean-tide level upwards. Except at the navigation-passages, the spans of the staging were about 27 feet, and transversely the piles were spaced about 12 feet apart between centres in the single as well as in the double rows.

The flooring of the staging, which was of 3-inch planking laid transversely, was carried on timber beams laid longitudinally from pier to pier of the staging directly on the line of the piles, while in the case of the central navigation-passage the flooring was carried on steel girders. These girders were only six in number, as with a view to economy only part of the central passage was covered at one time. At places on the staging where certain structures had to be erected for the temporary support of the caissons of the river piers during their erection and for the purpose of pitching the caissons, the main staging was strengthened by driving extra piles and laying down additional longitudinal beams as described later on. The measure of success in bridge-construction is governed by the character of the temporary staging.

The Pneumatic Installation.

Having regard to the character of the foundations of the piers of the bridge and the desirability of constructing them by working under compressed air, the importance of having an efficient pneumatic installation was early and fully recognized.

The contract obligations, in respect of the pneumatic installation, as they were stated in the Specification, are given in Appendix IV: but, on account of the moderate air-pressure, the requirements were not arbitrarily insisted on.

The principal air-compressing plant was situated at Clyde Place on the south side of the river. It consisted mainly of a boiler, an air-compressor and an air-receiver. The steam- and air-cylinders of the compressor were 16 inches and 14 inches in diameter respectively, with a stroke of 30 inches, and the air-receiver was 6 feet 6 inches in diameter and 30 feet long. There was also an auxiliary air-compressor, for use in emergency, situated on the north side of the river, but the main air-compressing plant proved very satisfactory, and the auxiliary compressor was required on only one occasion.

The air-piping between the main compressor and the receiver consisted of cast-iron flanged pipes 4 inches in diameter controlled by 4-inch valves. The outlet-piping from the air-receiver was 3 inches in diameter and also of cast iron with flanged joints. The piping was carried on the temporary staging and was led to each pier and laid longitudinally in front of each caisson. The loss of air in transmission from the receiver on the south side of the river to the caissons on the north side of the river was about 5 lbs. per square inch, presumably due to friction and leakage. In order to protect it from frost, the piping was placed in wooden casing of rectangular section and packed with stable-litter. The pipes were, however, one day frozen to such an extent that there was a stoppage of several hours.

The pneumatic plant further included an installation of air-locks, three for the passage of workmen, and three for the passage of materials, and these were attached to the access-shafts of the caissons. The locks were constructed of wrought steel. The material-locks attached to each caisson were always in use, but usually only one man-lock was used in connection with each caisson, the other being only provided for use in case of emergency. The locks were attached to the tops of the access-shafts.

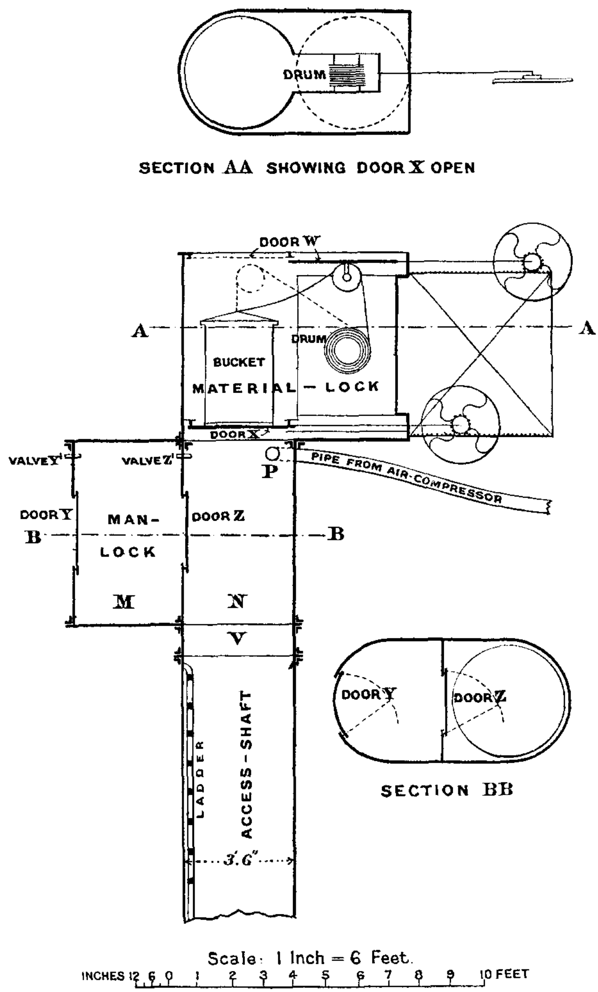
The character and relationship of the man-lock and the material-lock, with the attachment to the access-shaft of the caisson, are shown diagrammatically by *Figs. 10*.

The two locks formed one steel structure. Passage between the outer and inner chambers of the locks was by way of steel doors, all of which had beadings of indiarubber closing against the plating of the sides of the chambers, to ensure air-tightness. The man-lock was bolted tightly to the top of the access-shaft of the caisson, for which purpose the short length of shafting, V, was fixed permanently to the lock.

The inner chamber, N, of the man-lock, which was circular and 3 feet 6 inches in diameter, really formed part of the access-shaft, but for convenience in description it is designated as the "inner chamber." Compressed air was led from the air-receiver to the top of the inner chamber and access-shaft of the caisson by the pipe P, and valves (Z′ and Y′) of such small capacity as would only allow of slow passage of air were placed between the inner and outer chambers and between the outer chamber and the atmosphere. These valves regulated the air-pressure in the opening and shutting of the doors of the chambers.

In order to leave the outside door Y open after passing through the lock, the last man of an ingoing gang, before leaving the outer chamber, would open the valve Y′ and close the valve Z′ and then, getting quickly on to the ladder in the inner chamber, would

Figs. 10.



Air-Locks.

immediately close the door Z. Before one could get out of the access-shaft and inner chamber, someone from the outside had to enter the outer chamber and equalize the pressure in the outer

c 2

chamber with the pressure in the inner chamber by shutting the door Y and the valve Y′ and opening the valve Z′.

The material-lock was also in the form of an outer chamber attached to the inner chamber, but, whereas access from the man-lock to the inner chamber was by the door Z at the side, access from the material-lock was by the door X in the top.

Circular buckets were used for raising the excavations from the working-chamber (*Figs. 10* and *12*). In lowering the empty bucket, it was first deposited in the open outer material-chamber, by means of a crane, on to the top of the closed door X between the outer and inner chambers. The crane-chain was then unhooked from the bucket and the rope from a pulley which hung on the outer door W, and which was attached to a revolving drum inside the lock, was hooked to the bucket. The outer door W was now moved into position for shutting by means of a horizontal rack and pinion worked by an outside wheel, as shown by the dotted line on the diagram, and was then by means of an outside lever lifted into position with its rubbers hard against the flange. The compressed air was thereafter allowed to rush from the inner to the outer chamber by means of a large valve operated from the outside, and the air-pressure in the inner and outer chambers being thus equalized, the door X was lowered by an outside lever from its bearing on the flange and moved out by means of a horizontal rack and pinion worked by an outside wheel, as shown in *Figs. 10*. The drum in the material-lock was operated by a steam-engine attached to the outside of the lock, and communication between the outer and the inner chamber and access-shaft having been effected as described, the man in charge lowered the bucket to the working-chamber by unwinding the drum. When the bucket was filled and ready to be raised the operation was reversed.

Each of the working-chambers of all the caissons was lighted by means of three 32-candle-power electric glow-lamps. The wires were led through stuffing-glands into the outer and inner chambers of the air-lock and were taken down the access-shafts at the back of the ladder.

Signalling between the working-chamber and the outside of the locks was effected by means of an outside whistle with rope attached, the rope hanging down the full depth of the access-shaft. There was a code of signals for the several operations.

Except in connection with caisson C 1, which is founded at a depth of 70 feet below high water, the air-pressure was of moderate intensity. There was therefore little necessity for special concern in respect of the care of the workmen as, although they worked in shifts of 12 hours, divided into three separate periods by two meal-hours intervening, they enjoyed good health and liked to be employed below. The 10 hours' work was made up of two periods of 3 hours each and one period of 4 hours, the operations being carried on by relays of men working night and day.

In the last stages of the sinking of caisson C 1, with an air-pressure of 32 lbs. per square inch, there were some complaints of pains in the joints owing, it was thought, to too rapid passage through the air-locks. The Author's experience is that, in spite of all remonstrance and warning, workmen when passing through the air-locks, frequently equalize the pressure by means of the "muck-tap." The worst effects of the compressed air were observed when the caissons were in the clay, and this notwithstanding that the maximum pressure was not at the time higher than about 22 lbs. per square inch. With clay in the bottom, free passage of the air underneath the cutting edge was prevented, so that the atmosphere of the working-chamber became bad and exercised a fatiguing influence on the men, which, coupled with the harder excavating work, tended to exhaust them on the long shift. With the cutting edge in sand and gravel, however, the air could escape, so that in some degree there was then continual change of air. The men were also troubled somewhat during the concreting of the working-chamber, for as the concrete was deposited the place became small, the temperature high, and the air vitiated, the effect of which, and of their cramped position in working when nearing the roof, was to cause them much discomfort, though it cannot be said that there was actual suffering.

Work under compressed air was commenced in October, 1901, and was carried on until April, 1903. Some of the men worked under compressed air throughout the entire 18 months and appeared to be none the worse.

The locks, caissons, engine-room and offices were lit by electric light, the current being obtained from the Glasgow Corporation public supply, but, having regard to the inconvenience there would have been in swinging cranes in the vicinity of electric overhead wires, the outside works were lit mainly by acetylene gas.

Construction of the Piers.

In the process of sinking the caissons the external weight necessary to overcome the surface friction of the sides, the upward force of the high-pressure air in the working-chamber, and under certain circumstances perhaps some resistance of the cutting edge was not provided by means of special kentledge, but the caissons were at once loaded with the permanent masonry and sunk by the weight which it afforded. The masonry was built on the caissons as additional weight was needed, and as lowering proceeded, the work of excavating in the working-chamber being of course carried on simultaneously.

There being piers on the land and piers in the river the circumstances of the respective caissons were different, so that in the details the sinking operations varied. The main caissons for all the piers were built up and riveted complete in situ directly over their permanent sites, those for the land piers in excavated trenches, and those for the river piers on the temporary staging.

The Land Piers.—Trenches with sloping sides were excavated about 8 feet deep, measuring from the surface of the quays. These trenches were at the bottom 4 feet longer and 4 feet wider than the length and width of the caisson, to ensure convenience in the erecting and riveting of its steelwork. Resting on timbers arranged in the bottom of the trench, the cutting edge of the caisson was about 2 feet above the bottom of the trench, and this enabled the workmen readily to obtain access in the riveting and caulking of the working-chamber. The plates and bars were placed in position by means of two hand-cranes on the surface, the jibs of which were of such radii as to sweep the entire area of the caisson and trench. The caisson was thus gradually built up, riveted, and caulked, and, when completed to a height of about 16 feet above the cutting edge, it was raised from the timbers and carefully lowered into its exact position at the bottom of the trench by means of hydraulic jacks. Some lengths of access-shafting were then fixed, and the caisson was ready for sinking.

The four main caissons of the land piers (A 1, A 2, D 1, and D 2, *Figs.* 7) were erected and pitched in this way. The smaller caissons (A 3 and D 3) were similarly pitched, but in erecting them the working-chambers were not built in situ: being comparatively small, and only weighing about 20 tons, they were built up and riveted in the bridge-yard, and so brought to the site.

In the sinking of the several caissons of the land piers the operations were practically identical. Compressed air was not used in the first stages, for, although the caissons were pitched in trenches about 8 feet deep, the cutting edge was still about 9 feet above the level of the subsoil-water, so that to the extent of this latter depth the excavation in the working-chamber could be continued in the dry. It is remarkable that, although the caissons of the land piers were sunk at such short distances as 65 feet and

45 feet from the edge of the quay on the north and the south side of the river respectively, the level of the subsoil-water was never found to be higher than about 7 feet below high-water level, that is 4 feet above low-water level, and it did not appreciably vary with the level of the tide.

Immediately following the pitching of a caisson, concrete was deposited in it between the diaphragms at the sides and ends of the working-chamber and ultimately over the working-chamber and upward, as the steelwork of the upper part of the caisson was erected, and as sinking proceeded. The concrete was mixed mechanically, and was deposited by means of iron buckets of 1 cubic yard capacity, lifted and lowered by a steam-crane. The buckets had opening bottoms, and the concrete was thereby handled with a minimum drop, laid in layers, and thoroughly rammed. There was some inconvenience attaching to the deposition of the concrete in the caissons, as the buckets had to be carefully lowered between the bracing-bars.

Simultaneously with deposition of the concrete in the caisson, excavating operations were carried on in the working-chamber, the excavated materials being removed from the chamber through the open access-shafts by means of the circular buckets lowered and raised by steam-cranes. Care was taken to ensure that the caisson should be kept sinking while the concrete was being deposited, as otherwise, with the centre of gravity of the loaded caisson gradually rising, there would have been risk of the caisson canting, so that relatively it was kept deeply embedded in the ground.

The caissons were erected to their full height, and the concrete was entirely deposited from above the working-chamber upward, before sinking by the pneumatic process began, as, with the air-locks in operation, and having regard to convenient use of the cranes, it would have been impracticable to have been depositing concrete in the caisson simultaneously with excavating in the working-chamber.

The main caissons ranged in height from about 41 feet to about 52 feet, their actual height depending on the depth from a level just above subsoil-water level down to the level of the strata suitable for founding on. At the stage of the operations, therefore, when the cutting edge was just at subsoil-water level, the bottoms of the several caissons were about 18 feet below quay-level, so that the average level of the tops of the caissons, when sinking by compressed air began, was about 28 feet above quay-level.

With the cutting edge at subsoil-water level, the locks and other pneumatic appliances were installed, and the further sinking of the caissons was carried on under compressed air. In the sinking of the caissons of the land piers, the cutting edge was usually 12 inches to 18 inches deeper than the level of the excavations in the working-chamber, although at times the excavations in the working-chamber were taken out quite as low as the cutting edge, as the surface frictional resistance being considerable, there appeared to be no risk of sudden drop. If anything, the cutting edge was relatively lower when in the clay, but the clay was found more difficult to excavate than the sand and gravel, because the action of the compressed air on the clay was such as to make it quite stiff and hard on the surface, and this to such extent, indeed, that special spades had to be used in its removal instead of the ordinary excavating shovel. The frictional resistance was found to be greater in the sand and gravel than in the clay, as the clay was of a muddy and sandy character, and was naturally soft.

As already mentioned, the deposition of the concrete in the caissons was completed before sinking by the pneumatic process was commenced. In the case of caisson D 1 of the southernmost land pier, the concrete was finished to a height of about 12 feet above the top of the working-chambers of the caissons, that is, to about 20 feet above the cutting edge. This, with the caisson and the air-locks represented a total weight of over 1,000 tons, but was not found sufficient to carry the caisson farther down than to 20 feet below the bottom of the trench in which it had been pitched, out of a total depth of 48 feet below the bottom of the trench to which it had to be sunk. The necessity for greater weight was met by building the brickwork of the pillars of the piers, and by depositing the excavated material from the working-chamber as high as possible in the caisson on the concrete and around the brick pillars. In the later stages of the sinking, however, even with such additional weight, there was sometimes difficulty in forcing the caissons down. This was particularly the case when gravel was reached, and in such ground they became stubborn in the extreme, and refused to move. In these circumstances it was the practice to thoroughly clear out the working-chamber down to the cutting edge, and thereby lessen its bearing all along the sides and ends, as the inclined part of the roof of the working-chamber and the blunt edge of the bottom offered considerable but salutary resistance to sinking. This operation assisted the downward movement, but to accelerate it the high-pressure air in the working-chamber which, of course, tended to keep the caisson up, was at times temporarily reduced during meal-hours, when the men were out, by allowing it to blow off through the large valve in the material-lock after cutting off the supply, the effect of which was to assist the caisson to sink. After an operation of this kind, when access had again been got to the working-chamber of a caisson, the sinking of which had been temporarily suspended, it was found that the earth in the working-chamber was roof-high, the material having been brought in by water from beyond the sides of the working-chamber underneath the cutting edge. To this circumstance was attributed certain subsidence of parts of the surface of the quays in the vicinity of some of the caissons of the land piers.

The practice of reducing the air-pressure in the working-chamber was also adopted to right the caissons when they had got slightly off the level. Material was heaped and pounded against the lower side or end of the working-chamber, and sometimes pieces of wood were inserted below the cutting edge, which, with the reduction of the air-pressure, had the effect of lowering the higher side or end.

Immediately the sinking of the caissons became difficult, the air-locks were transferred temporarily to another caisson while the brick pillars were being built on the caisson requiring additional weight. Simultaneously with the building of the brickwork, excavations from another caisson were being heaped round the pillars to give more weight, and lengths were being added to the access-shafts in order to keep the mouths of the shafts always above the masonry. In other words, the operations were so arranged as to ensure that all the plant should be as constantly in use as possible. In the case of one of the caissons of the south land pier only one stop was made in the sinking under compressed air, and the brickwork was built during that stop to within a few feet of the height at which it was calculated the granite facing should begin after the caisson was sunk. In other caissons the brickwork of the pillars, and even of the arches between the pillars, was entirely completed before the last stage of the sinking of the caissons was commenced.

Having regard to the experience gained in connection with the caissons of the south land pier, it was determined to increase the quantity of the concrete in the caissons on the north land pier and thereby add to the weight for the purpose of facilitating the sinking. Concrete was therefore deposited 5 feet higher, that is, to 25 feet above the cutting edge. During the sinking of caisson A 1 through a thick bed of gravel, one end of the caisson got into sand, and as there was indication of the caisson tending to settle down at the sandy end, the sinking was subsequently stopped, and this caisson was founded at a level about 11 inches above the proposed foundation-level shown on the contract-drawing.

Notwithstanding the great care exercised in the sinking of the caissons of the land piers and the daily checking by levelling and otherwise, there was found to be some deviation from absolutely true line and level when the sinking was finished. The deviation was, however, very slight, never being more than 1 or 2 inches in level and 2 or 3 inches in line, and it was of little consequence, for no part of the granite work of the land piers was commenced until both the main caissons of each land pier had been sunk and the brick pillars built. There was therefore time and space for adjustment, as the brick pillars had ample projecting scarcement.

When the caissons had been sunk to the required levels, concrete was deposited in the working-chambers and access-shafts by means of the circular buckets, having opening bottoms. Experience of the difficulty of sinking the caissons in the sand and gravel having suggested that there was little risk of sudden drop and further downward movement, it became the practice in the case of the land piers to remove the excavations entirely and to clean out the working-chambers before any concrete was put in. The method of depositing the concrete in the working-chambers was in all cases the same. It was first deposited on a timber platform laid immediately below the access-shafts, and then, beginning at each end of the caissons, it was gradually spread in layers over the several areas between the access-shafts and the ends, until the working-chamber was filled to within about 12 inches of the roof. For a time it was kept as low as possible directly underneath the access-shafts, to give room for the men to work; but these places were also filled gradually, the men working themselves up into the shafts. Latterly, the men only went down to spread and ram the concrete as each third bucketful was deposited.

The packing of the concrete hard up to the roof of the working-chamber was considered to be of vital importance, and was carefully carried out in short sections and in very thin layers, each being allowed to set partially before the next was deposited. As the roof of the working-chamber was approached, grout was added, in order that the concrete should be made perfectly solid. Depressions about 6 feet in diameter and 1 foot deep were latterly formed in the concrete, directly underneath the access-shafts, into which grout was poured until it stood to a height of about 3 feet in the access-shafts. Latterly the concrete was dumped down into this liquid grout, and the filling of the access-shafts being done in a similar manner, the air-pressure was gradually reduced and ultimately withdrawn.

The River Piers.—The caissons of the two river piers were erected on the temporary staging as nearly as possible over their permanent positions. Particular care had to be taken in the setting out and sinking of the caissons, for it was intended to build the whole of the brickwork and part of the granite work of each pillar before the sinking was completed. There are two caissons in each pier, on one of which there are three pillars, and, on the other, two. With this distribution of the pillars, the necessity for accuracy in alignment will be appreciated, particularly when it is borne in mind that there were nineteen pillars in the land and river piers, several of which were being built and sunk simultaneously.

The temporary staging had been constructed so as to allow of the caissons being built on it and thereafter lowered between its piers; that is, there were openings in the staging to allow of the caissons being lowered into their permanent positions. Extra piles were driven to strengthen the staging in the vicinity of the openings, and additional beams, 12 inches square, were laid over each opening, on which 9-inch by 3-inch planks were placed transversely at the level of the staging flooring, and on these timbers the lower part of each caisson was erected.

It was essential that the erection of each of the caissons to its full height, as well as the caulking, should be entirely completed before the caisson was floated. Special appliances were therefore necessary to raise the caisson from the supporting timbers and thereafter to lower it into the river. With the caisson resting directly on the supporting timbers, it could not of course be lowered into the river without these timbers being removed, so that at some time or other it had to be supported by being hung from overhead. Having regard to the method proposed to be adopted for the suspending, lifting, and lowering of the caisson, it was thought expedient to erect only the lower part with direct bearing on the supporting timbers underneath, and after such lower part had been attached to an appliance overhead and the supporting timbers underneath had been removed, to complete the erection of the caisson as it hung in mid air. The caissons were suspended, lifted and lowered by means of special hydraulic jacks and other appliances.

The main appliances for suspending, lifting and lowering a caisson consisted of four timber trestles, four steel girders, four hydraulic jacks and four steel suspending-bars. Two of the trestles were placed on each side of the opening in the staging, and pairs of steel girders, spanning the opening, rested on the trestles. The hydraulic jacks were supported by the steel girders and were connected with the suspending-bars which hung between the girders and were attached below to certain of the cross girders of the caisson at the roof of the working-chamber (Figs. 9 and 9a, Plate 1).

The trestles were built of pitch-pine timbers 12 inches square. The uprights of each trestle, which were two in number, rested on longitudinal timber sills. The timber sills were supported on the temporary staging, which was strengthened by driving additional piles deep in the river-bed directly underneath.

Each of the two pairs of trestles was placed at about one quarter of the length of the caisson from either end of it. The caisson being 23 feet 3 inches wide, and the opening in the staging 27 feet wide, the width between the trestles was made 28 feet, and this space was spanned by the pairs of steel girders. These girders were 3 feet 6 inches apart between centres, their positions being so fixed as to allow of the suspending bars hanging freely between them.

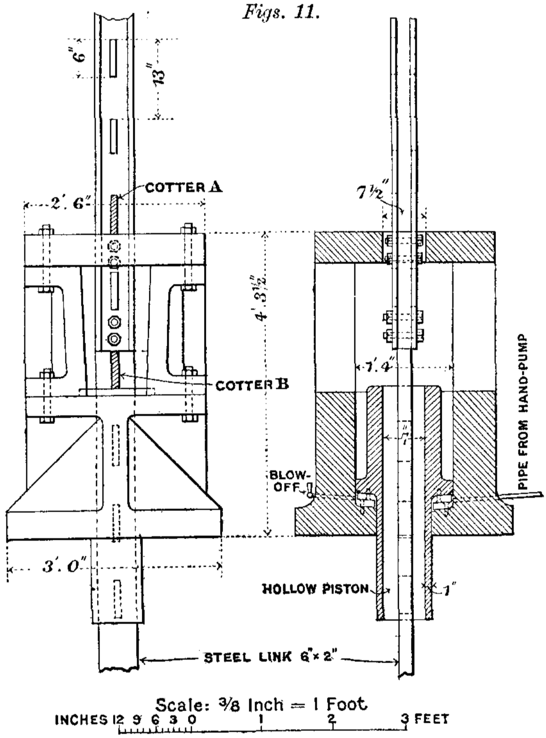
The height of the trestles was about 14 feet above the floor of the staging. The hydraulic jacks were placed over the line of either side of the caisson, resting on pairs of transverse timber beams. Four hydraulic jacks were used to each caisson, two on each of the pairs of overhead girders. The jacks had hollow pistons through which the suspending-bars for hanging the caisson were passed and attached to two of the intermediate cross girders at the top of the working-chamber (*Figs. 11*). The suspending-bars were steel-bar links, each 7 feet 4 inches long and 6 inches by 2 inches in cross section. The links were single-bar and double-bar alternately, the single-bar link being bolted between the double-bar links at either end by four bolts $1\frac{1}{2}$ inch in diameter in double shear. In the links there were slots as shown by *Figs. 11*.

The attachment of the suspending-bars to the caisson was made by means of brackets consisting of steel gusset-plates and angle-bars riveted to the top flanges of the cross girders at the top of the working-chamber, and, having regard to the transference of the heavy weight of the caisson to the suspending-bars, the rivet-area of the attaching bracket was increased by continuing the end angles of the particular cross girders upwards about a foot higher than the normal, in order to permit of horizontal riveting to the end angles as well as vertical riveting to the flange (Figs. 8 and 9, Plate 1).

The lower part of the caisson, to the top of the first plate above the working-chamber, having been erected on the staging and attached to the suspending-apparatus, it was lifted by the jacks to about 2 feet above the timber floor, to allow of the riveting and caulking of the working-chamber being completed.

At the commencement of the lifting-operations, the caisson was hanging on the cotters A (*Figs. 11*). The lifting of the caisson was performed by inserting the cotter B in the first slot of the suspending-bar above the piston of the jack, and, by means of hand-pumps attached to each jack, raising the piston of the jack against the cotter B and continuing to raise it until the slot above cotter B had cleared the upper collar of the jack, when cotter A was inserted, and the weight of the caisson was transferred again to the upper collar

Figs. 11.



Hydraulic Jack.

of the jack by releasing the piston. By repeating these movements the caisson was gradually raised, and the slots in the suspending-bar being 13 inches apart, each operation lifted the caisson 13 inches.

After the riveting and caulking of the lower part of the suspended caisson had been completed, the timber beams and planking on which it had been erected were removed. While thus suspended, it was built up plate by plate, riveted, caulked and completed, and afterwards gradually lowered between the piers of the temporary staging.

The operation of lowering the caisson was exactly the reverse of that gone through in lifting it. It was very essential that the caisson should always be kept quite level, in order to ensure equal distribution of the load on the four points of support, i.e., the jacks, so that in the lowering as well as in the raising great care had to be taken to ensure uniformity in the simultaneous movements of the four jacks.

To provide against the possibility of flooding, the caissons of the river piers required to be about 39 feet high. Caisson C 1 was the first caisson to be built and sunk, and the experience which it provided suggested that the top tier of plates of the other caissons might be bolted in their attachment instead of being riveted. With the bolted attachment and the caisson getting into material suitable for founding on and not requiring to be sunk farther, the top tier of plates could be taken off if the caisson were not deep enough to meet the requirement of the Clyde Navigation Trustees in respect of depth of clearance. In the course of the sinking of the first river pier, caisson C 1, the clearance was fixed by the Navigation Trustees at 20 feet below low-water level. This bolted attachment was adopted for the remaining caissons, so that while caissons B 1, B 2, and C 2 were about 39 feet high in the first instance, the top tier of plates in each was only temporary and was removed when the masonry had been built to such level, that in the course of the further sinking the building-operations could not be detrimentally affected by flooding. The caissons B 1, B 2, and C 2 are therefore about or rather less than 35 feet in height, but caisson C 1 is about 39 feet in height, and it was sunk to the full depth necessary to give the required clearance below the low-water level. It was ascertained that even with the concrete fully deposited none of the caissons sank in the first instance to a level lower than that represented by the roof of the working-chamber, being about 2 feet above the bed of the river ; so that in the case of caisson C 1, there was perhaps excess of caution. The sinking of caisson C 1, it may be said, however, was to some extent experimental, and, as failure might have been disastrous, caution with the first caisson was particularly essential.

While the caissons were still hanging on the hydraulic jacks, a careful survey of the river-bed was made at the site of each pier, with the result that in the case of the north pier the bed was found to be very irregular in level. It being essential that the cutting edge of each caisson should touch the bottom on level ground, the inequalities were levelled by depositing excavated material from one of the other caissons, and uniformity of the river-bed was thus secured.

Just before the caissons were lowered into the water, five stiffening settings of timber were fixed inside each temporarily to preclude the possibility of the sides of the caisson tending to buckle by the pressure of the water. They consisted of walings 12 inches square, laid horizontally along the sides of the caisson about 4 feet 3 inches apart between centres vertically, well strutted apart by struts also 12 inches square and placed about 7 feet 6 inches apart between centres. No concrete was deposited in the caissons until they were disconnected from the suspending-bars and were floating.

For the purpose of ensuring accuracy in the sinking of the caissons, guide-piles 12 inches square were accurately but lightly driven along the sides and ends of the sites of each. A caisson having been lowered into the water until it was found to be floating, the suspending-bars were disconnected and the caisson was eased against the guide-piles into true position for sinking. Concrete was then deposited in the caisson to a total height of about 26 feet 6 inches above the bottom of the cutting edge, this level being determined partly by consideration of the weight required for sinking on the basis of the experience gained with the land piers, and partly by the fact that it was a convenient level to begin building, the bottom of the brick pillars being just at the top of one of the series of cross bracings.

With the concrete work completed, compressed air was applied, and sinking was commenced by removing the excavations in the working-chamber. The caisson being partly sunk into the bed of the river without any excavations having been removed, the working-chamber was usually found to be partly filled with soft "slurry." This material was difficult to remove, and, as the water could not be separated from the mud and blown out with compressed air, the slurry had to be bailed out in buckets before excavating proper could be commenced. For some time, therefore, after the sinking of the caissons commenced, there was room for only two or three men in the working-chamber, and it was usually a fortnight before the full complement of men could be employed.

At the commencement of the excavation in the working-chambers of the river-pier caissons, the actual air-pressure with about 27 feet head of water from the cutting edge was about $12\frac{1}{2}$ lbs. per square inch, that is, about $\frac{1}{2}$ lb. per square inch more than appeared to be theoretically needed to balance the hydrostatic pressure. The deepest foundation of the bridge was in connection with river pier C, where caisson C 1 was sunk to a depth of 70 feet below high-water level. The highest air-pressure in the sinking of caisson C 1 was about 32 lbs. per square inch, which is about 1 lb. more than the theoretical pressure due to a head of 70 feet. In tunnelling under compressed air, the Author's experience has been similar. The actual intensity of pressure appears always to exceed slightly the theoretical requirement, presumably owing to loss by leakage.

In sinking caisson C1 the number of men in the working-chamber never exceeded six, for the excavations, being mostly in sand and gravel, were comparatively easily dealt with, so that there was little trouble in "getting," and frequently the men had to wait for the return of the bucket from the top. There was no difficulty in sinking this caisson, but for a time the progress was somewhat slow, by reason of there being only one air-lock in operation, the others being in use in connection with another caisson.

The maximum number of men employed in the working-chamber in the sinking of caisson C2 was four, and here again the material of the excavations was sand and gravel. Before the concrete work of caisson C2 was quite completed—that is, the concrete outside the working-chamber—the caisson canted badly owing to one end suddenly touching hard ground. An air-lock was immediately fitted, and sinking under air-pressure was commenced, with the object of righting the caisson, and this being readily accomplished, the concrete work was finished. From time to time during the sinking of this caisson the position was carefully checked, when it was found to tend to travel towards caisson C1, already sunk, the ground being evidently loosened in that direction. This tendency was corrected by sinking the caisson in a somewhat inclined position.

The material of the excavations in the sinking of caisson B1 was for a considerable depth largely muddy clay. After the water was driven out, the action of the compressed air on the clay made it difficult to excavate, so that reasonable progress in the working-chamber could be maintained only by having nine men constantly employed: even with this larger number the men on the top had sometimes to stop, and the cranes for disloading the buckets were frequently at a standstill. The progress of the sinking of this caisson was, therefore, comparatively slow, and to make matters worse, by reason of the cutting edge of one side of the caisson suddenly getting into sand and gravel, the cutting edge of the other side seemed to slip through the clay and the caisson canted. It was, however, very quickly righted again. At another time, the compressed-air supply was suddenly cut off during the progress of the sinking of this caisson, due to freezing of the pipes, but fortunately the cutting edge happening to be well embedded, there was no noticeable movement of the caisson. Following this, the main air-compressor broke down, so that the auxiliary compressor had to be brought into operation. The auxiliary compressor was not, however, able to maintain the required pressure, and the decrease of pressure resulted in the caisson gradually dropping about 2 feet, fortunately without detriment, as no canting took place.

While the sinking of caisson B 1 thus appeared to be attended with quite a chapter of small incidents, the sinking of caisson B 2 was altogether uneventful, and it was indeed marked by excellent progress, notwithstanding that the excavations were much in the muddy clay.

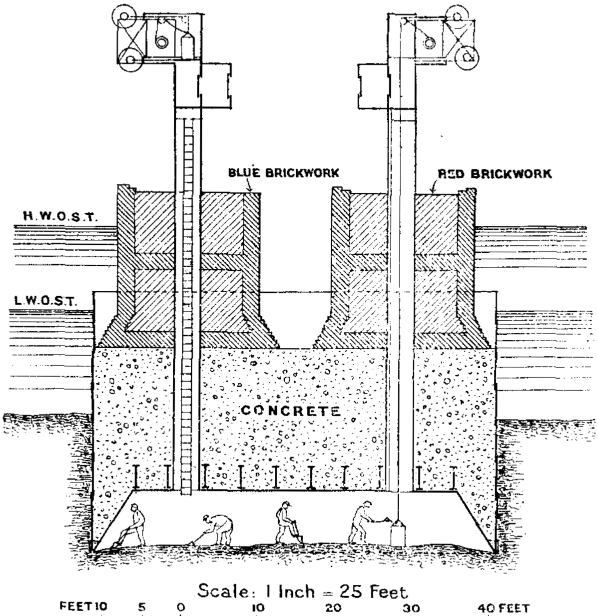
There being comparatively little surface friction in connection with the caissons of the river piers, the level of the excavations in the working-chamber was always kept about 15 inches above the level of the cutting edge. When the caissons reached their proper depths, the excavations in the working-chamber were taken down to the cutting edge in short lengths, the material being removed at the ends first, where the concrete was deposited and allowed to set in the form of a supporting block before the excavations of the centre part were removed.

The brickwork of the pillars was commenced as soon as deposition of the concrete over the working-chamber had been completed and the caisson had been levelled and firmly embedded in the bottom. It was continued during the progress of the sinking, so that, as excavating in the working-chamber proceeded and the caisson went down, the tops of the pillars were always maintained above high-water level; and as the brickwork reached the undersides of the air-locks, the locks were removed and replaced, after additional lengths of access-shaft had been added. The simultaneous excavating, building, and sinking is illustrated by *Fig. 12* (p. 34).

In some cases the top lengths of the access-shafting were temporary and were subsequently removed. Simultaneously with the building of the pillars, the excavations from the working-chamber were deposited in the caisson on the top of the concrete around the brick pillars for weighting purposes.

The granite work of the pillars was built similarly and simultaneously, so that the finishing of the sinking of the caissons of the river piers required much more care than that of the caissons of the land piers. The lowest granite course of the river piers is about 5 feet below low water, and in the building and sinking careful attention had to be paid to regularity in level as well as in line. The first caisson to be finished was caisson C 1, and owing to the fact that it showed no tendency to sink unduly quickly after the reduction of the air-pressure, the second course of granite below the moulded base-course of the several pillars was finished practically at the correct level. The line was also good, for when the sinking was completed the pillars were ascertained to be only 2 inches to the south and 3 inches to the west of their proper position. It therefore became a question of having the pillars of the other three caissons relatively correct in line and level, and the sinking and the further finishing was successfully carried out accordingly. In the case of caisson C 2 there was a difficulty in founding at the correct

Fig. 12.



SINKING A CAISSON.

level relatively to caisson C 1. When the caisson had still 4 feet to go, the working-chamber was cleaned out and the air-pressure was reduced. As the caisson sank, observations were made with the level in order that the sinking might be properly governed, and timeously stopped, but in the course of sinking, the caisson began to cant, and this to such extent that the air-pressure had to be increased, and men had to be sent down to embank material against the low side with the object of righting it. Ultimately the caisson was founded satisfactorily, and when the sinking was completed there had been three courses of granite built in each of the pillars.

The granite course immediately below the moulded base-course was in each of the pillars of the several caissons made a compensation-course, and, although its nominal thickness was 2 feet 3 inches, the actual thicknesses varied with the adjustment of the levels, but only to a slight extent.

The concrete was deposited in the working-chambers of the river-pier caissons in a manner similar to that adopted in the case of the caissons of the land piers already described. It being of vital importance, however, that the caissons of the river piers should be maintained at true level after the sinking was finished, the working-chambers were not at once wholly cleared out. They were cleared out in small sections.

Taking caisson B 1 as an example of the loads, when pitched in the river-bed with the concrete work partly executed, it weighed 866 tons, and when the concrete work was finished and sinking under compressed air was commenced, the total weight was 2,420 tons. When the sinking was finished, the aggregate weight of the steelwork, concrete, brickwork and granite was 3,854 tons, and this was further increased to a grand total of 4,597 tons by the deposition of the concrete in the working-chamber and access-shafts. The gross load (due to the dead weight and live load) at the bottom of caisson B 1 was calculated to be 10,446 tons.

Under the contract it was specified that when the masonry of the substructure of each pier was completed, the foundations should be tested by applying such weight as would temporarily load the bearing-area to an extent 25 per cent. greater than the permanent load. The character of the foundations as revealed by the actual excavations was, however, thought to be so satisfactory that it was decided that this testing need not be carried out—a decision which was subsequently ascertained to be justified. Much money was thereby saved, as about 6,000 tons of pig-iron or steel rails would, for example, have been required for caisson B 1, and, not to speak of the practical difficulty and the cost of getting such testing-materials to and from the site, the contract-prices were 5*s*. per ton for merely applying the load and 5*s*. per ton for afterwards removing it.

Rate of Progress of the Excavations in the Caissons.—The tabulated statements given in Appendix V show the character of the geological deposits through which the main caissons of the several land and river piers were sunk and the time taken to sink each caisson, etc., and they afford a means of comparison of the rate of progress of the excavations in strata of somewhat varying character. The stated volumes of excavation are based on notes taken in respect of depths near the bottom of the foundations, that is, during the period more immediately prior to completion of the sinking, when the work of excavating in each caisson was in full and active operation. For ready comparison, the final results are brought out in fractions of a cubic yard per man per hour. The variation in the results is due partly to the different character of the strata and partly to the fact that sometimes there were two locks in operation in one caisson and sometimes only one, while at other times there were three.

The average rate of excavation in the working-chambers of the caissons was at the rate of 0·47 cubic yard per man per hour in the case of the land piers, and 0·60 cubic yard per man per hour in the case of the river piers, so that the average over all may be approximately stated at rather more than ½ cubic yard per man per hour.

As already indicated, the number of men in the working-chamber varied with the size of the caisson and the special circumstances attending the sinking. In the case of the land piers six men were, as a rule, constantly employed down below, but in the working-chambers of the river-pier caissons there were sometimes as few as four and as many as nine. The men were double-shifted and each gang was 12 hours on the work at a time, but there being two meal-hours intervening, they only actually worked 10 hours per shift.

In the sinking of caisson B2, which was one of the smaller of the main caissons, with two air-locks in operation, the following men were employed, at the wages stated :—

One miner at	7*s*. per shift.
Three miners at	6*s*. ,, ,,
Two lockmen ,, ...	3*s*. 6*d*. per shift.
,, enginemen at	5*s*. per shift.
,, crane men ,, ...	6*s*. ,, ,,

In addition to these men there was a man in charge of the steam-boiler in connection with the engines at 5*s*. per shift and another in charge of the air-compressor at 5*s*. per shift, and, of course, as well as foremen there were other men employed in the general work.

Frictional Resistance of Caissons.—In the course of the sinking of the caissons tests were made with the object of ascertaining the bearing value of the frictional resistance resulting from the lateral pressure of the earth on the sides and ends of the caissons. In the case of the caissons for the river piers, owing to the softer character of the material of the excavations and the possibility of the roof of the working-chamber bearing down and crushing the men inside, it was not considered expedient to excavate entirely and clean out down to the cutting edge. And there was the further difficulty of the uncertain weight of the excavated material deposited on the caisson during the sinking; so that the results of certain tests in connection with the river piers were considered to be of comparatively little value. The circumstances of the caissons of the land piers, however, were more favourable, the material of the excavations being stiff and the surface friction on the sides and ends of the caissons so considerable that on occasions the pressure of the air had to be reduced to induce the caissons to move. It was therefore possible to make more accurate tests in connection with the caissons of the land piers, the results of which showed the value of the surface friction to range from $3\frac{1}{4}$ cwt. per square foot to $4\frac{3}{4}$ cwt. per square foot, the average of five careful observations being about $4\frac{1}{4}$ cwt. per square foot. The strata were mostly sand and gravel, and the embedded surfaces of the caissons were in contact to a depth of about 40 feet. In making the observations on the caissons of the land piers, the excavated material was entirely removed from the working-chamber as low as the cutting edge, and the edge was undercut as much as was possible. The men were then withdrawn from the working-chamber, and the air-pressure was reduced, when the caisson ultimately began to sink; as sinking commenced and continued the intensity of the air-pressure was noted on the gauge at the material-lock, and this pressure, which varied between 5 and 15 lbs. per square inch over the series of observations was discounted in arriving at the results. The gross surface friction being equal to the gross weight of the caisson and its loading minus the gross pressure of the air on the roof of the working-chamber, the unit frictional resistance was, of course, the quotient resulting from division of that difference by the area of embedded surface. In most circumstances, the certainty of there being some resistance by the cutting edge should be taken into account, so that in the safe-load calculations for foundations in such ground the bearing-value of frictional resistance might be stated at about 3 cwt. per square foot. In the determining of bearing-areas frictional resistance is, however, more of academic than practical interest, and the expediency of depending on it and giving it value in the safe-load calculations is extremely doubtful. But it is an important factor in the problem of the sinking.

Unit Prices for Substructural Work.

The items and unit prices of the substructural work of the river piers were the following:—

Clearing and levelling bed of river and pitching caissons thereon	15*s.* per square yard.
Excavations in and sinking caissons from level of bed of river downwards . . .	20*s.* ,, cubic ,,
Wrought steelwork in permanent caissons .	£15 per ton.
Concrete in caissons.	22*s.* 6*d.* per cubic yard.
,, ,, working-chambers	28*s.* 6*d.* ,, ,, ,,
Red brickwork in hearting of pillars . . .	22*s.* 6*d.* ,, ,, ,,
Blue ,, ,, through courses and facing of pillars	43*s.* ,, ,, ,,
Granite ashlar in facing of pillars below base course with chisel drafted margin and rock face	6*s.* 3*d.* ,, ,, foot.

Based on these unit prices, the aggregate unit cost of the substructural works—namely, the excavations and all the kinds of masonry in the caissons and pillars, including the masonry of the pillars up to low-water level—was on the average £2 15*s.* 6*d.* per cubic yard of the earth and water permanently displaced, or £2 10*s.* 6*d.* per cubic yard of such displacement if the masonry of the pillars is included only up to a level 5 feet below low-water level, that is up to the level where the brick facing ends and the granite ashlar facing begins. These costs, while inclusive of all labour at the site, do not include the cost of the steelwork of the caissons, because the caissons may be described as being of the character of service work and merely means towards an end. It would, however, be proper to include the cost of the steelwork of the caissons, and if this were done, the foregoing unit costs would need to be increased by about £1 1*s.* per cubic yard. In order to arrive at the absolutely correct cost, a portion of the general charges under the contract, such as the costs of temporary staging, setting out, watching and lighting, and several other contingent works, for which there are special prices in the contract-schedule, should also, of course, be included; but an addition of 5 per cent. would more than cover such general charges. In estimating the cost of such work for Parliamentary purposes, the Author would adopt about £3 15*s.* per cubic yard of the earth and water displaced by the permanent works, as an inclusive unit price to pay for everything submerged.

The Superstructure.

General.—As the steel superstructure of the part of the bridge over the river and quays consists of a series of main longitudinal girders carrying transverse flooring on the top flanges, there is no complexity in design and the loads are transmitted very directly.

The superstructure over the street on either side of the river is also simple, the steelwork being composed of longitudinal and transverse plate girders with buckled-plate flooring. The cross girders are attached to the webs of the longitudinal girders, a connection which, having regard to maintenance, cannot perhaps be described as ideal ; but they are also afforded support by the stiffeners of the main girders, which are made to act as stools. Experience in maintenance suggests that it is very desirable to have the cross girders of a railway-bridge resting directly on the top flange of the main girders ; but the levels of the street spans of the Clyde Bridge precluded the possibility of giving the cross girders any better support than the attachment to the webs provides. The buckled plates of the flooring of the street spans, although stamped and buckled to about the usual size, are in lengths of 14 feet; they are closely riveted to the cross girders at their ends only, and are merely attached to the intermediate cross girders by a few stitching rivets.

The main girders of the river spans are alternately supported directly over the pillars of the piers and midway between the pillars of the piers, pivoted on special cast-iron bearings which in their turn rest on steel lintel-girders spanning the spaces between the pillars.

By reason of the fan shape of the bridge at either end the longitudinal girders are not parallel in line, and in plan they form tapering bays. They are spaced at distances apart varying from 11 feet 10 inches in the south river span to 15 feet 10 inches in the north river span. There being a limit to the piling of plates in the flanges of girders, a system of wider spacing of the longitudinal main girders with cross girders between them was quite prohibitive, even if there could have been satisfactory attachment of the cross girders to the main longitudinal girders. With wider spacing of the main longitudinal girders the sectional area of their flanges would have had to be very great, as their depths are very shallow. The main longitudinal girders are indeed rather unsatisfactory in respect of the ratio of depth to span. The length from centre to centre of the bearings of the girders is 194 feet in the case of the centre span, and 151 feet 3 inches and 173 feet 3 inches respectively in the case of the north and south river spans. Measured between the centres of gravity of the flanges, the girders of the centre river span are 15 feet 9 inches deep, and of the north and south river spans each 13 feet deep. The ratio of depth to span is therefore 1 to 12·32 in the case of the centre span and 1 to 11·63 and 1 to 13·33 in the case of the north and south river spans respectively. But the best was done, and the shallow depths and indifferent proportions were unavoidable on account of the limited depth available for construction.

Each longitudinal main girder at the south end of the bridge is calculated to carry the load of a single line of rails and about the load of one and one-quarter line of rails at the north end; and these loads, combined with the heavy superincumbent dead load, necessitated considerable flange-area. The girders are therefore comparatively heavy. Except the extreme outside girders, which take less load, each main girder of the centre span weighs about 220 tons and each main girder of the north and south river spans weighs about 143 tons and about 162 tons respectively, while the weights of the outside girders of the three spans are 133 tons, 84 tons, and 111 tons respectively.

The exceptional dead load on the bridge is largely due to the superstructure being entirely covered with the ballast of the permanent way, and the live load is of course that resulting from the Company's latest and heaviest class of locomotives. These locomotives have $18\frac{3}{4}$ tons on the driving-axle, and when fully equipped, engine and tender combined weigh about 130 tons, distributed on a wheel-base of about 57 feet. The length over the buffers is 65 feet 6 inches, and having regard to the spans of the bridge and the certainty in the vicinity of a terminal station of there being exceptional loads due to several locomotives being at times coupled together, the equivalent uniformly distributed live load on all the spans of the bridge, although they are not the same, was assumed to be 2 tons per lineal foot of single line of railway, a live load which, if there is to be any regard at all for the economics of railway-maintenance, it should not in the future be allowable or necessary to exceed. From this point of view, indeed, locomotives are already more than heavy and powerful enough.

The steel was made by the Siemens-Martin open-hearth acid process, and it was specified that the tensile strength should not be less than 28 tons and not more than 32 tons per square inch of original section, with elongation of at least 20 per cent. in a length of 8 inches. By reason of the practical inconvenience which would have resulted from cutting plates and bars in the bridge-building yards and taking specimens for testing there, the specimens were taken and tested at the steelworks, a practice which, although the more common practice, perhaps leaves something to be desired. It would be better to take the specimens for testing from the material when delivered in the bridge-building yard; but practical difficulties might present themselves, and in any case such an arrangement would require united action on the part of engineers and would necessitate a standard specification.

The main girders were designed to have a working-stress of about 6 tons per square inch, thereby giving a factor of safety of about 5. In the case of the flooring, however, the working-stress was fixed at 4 tons per square inch; for although, on account of the bridge being near the station and the speed of trains being consequently low, it was not anticipated that the impact would be great, yet the girders being so directly over the river, it was thought that the tendency to corrosion might be considerable, and full allowance for deterioration was therefore made.

The practice in bridge-calculations in respect of concentrated maximum live loads and equivalent uniformly distributed loads, and the allowable stresses in the several parts of the steelwork of railway underbridges, might with much advantage be standardized; and it would be more advantageous still if a central authority, such as the Engineering Standards Committee, were to standardize the practice in respect of the dead and live loads to be assumed in calculating the strengths of the several classes of bridges carrying urban streets and country roads respectively.

For the purposes of design and payment the weights of the steel and iron of the Clyde Bridge were assumed to be as follows:—

Cast steel	492	lbs.	per	cubic foot.
Wrought steel	490	,,	,,	,,
Wrought iron	480	,,	,,	,,
Cast iron	448	,,	,,	,,

although the true weights of these are said to be fractionally less; and with no reduction for rivet-holes, 5 per cent. extra on the weights of the wrought-steel plates and bars was allowed for rivet-heads, a figure which perhaps is also somewhat high.

The Main Girders of the River Spans.—A main girder of the centre river span is shown by Figs. 13 and 14, Plate 2. It is typical of all the girders, which are of the Linville or N type of lattice girder.

While the scantlings of the main girders of the several spans of course vary with the stresses, the girders are identical in their design and construction. Although the girders differ in total length, the panels formed by the vertical members of the web-bracing are the same in each girder of the several spans, except the end panels, which vary. The vertical members of the girders of the centre span are 8 feet apart from centre to centre, while those of the north and south river spans are 7 feet and 6 feet 8 inches apart respectively.

It will be seen that the top and bottom booms of the girders are each built up with a series of horizontal plates, two vertical plates and four main angle-bars; and for the purpose of stiffening the top boom a continuous angle-bar is attached to the lower outside edge of each vertical plate. With the object of having a moderate number of piled plates the flanges were made 4 feet wide; but even with this width the thickness of the plates at the middle is in the aggregate $5\frac{5}{16}$ inches, made up of nine plates varying from $\frac{3}{8}$ inch to $\frac{5}{8}$ inch in thickness.

The vertical plates of the booms are 2 feet deep, and vary in thickness from $\frac{1}{2}$ inch at the centre of the girder to $\frac{3}{4}$ inch at the end, depending on the bearing area required by the rivets at the connections. The four main angle-bars are each 5 inches by 5 inches by $\frac{5}{8}$ inch, and the stiffening angles of the top boom are each $3\frac{1}{2}$ inches by $3\frac{1}{2}$ inches by $\frac{1}{2}$ inch. The girders were given 1 inch of camber for every 60 feet of span.

The struts of the web-bracing are of box section, built up of channel-bars varying from 10 inches by $2\frac{9}{16}$ inches by $\frac{1}{2}$ inch to 12 inches by 3 inches by $\frac{1}{2}$ inch, strengthened where required by plates of various scantlings, except near the ends of the girder where the box section is built up of plates and angles. The struts are laced with flat bars varying from 3 inches by $\frac{7}{16}$ inch at the ends of the girders to 3 inches by $\frac{3}{8}$ inch at the centre. The ties of the web-bracing are in the form of four flat bars, pairs being riveted to the vertical plates on either side. The bars vary in section as shown, and where the stresses alternate the inclined members are designed as struts, and consist of two channel-bars 9 inches by $3\frac{3}{16}$ inches by $\frac{1}{2}$ inch, stiffened at intervals with 9-inch by $\frac{1}{2}$-inch plates.

The centre-lines of the struts and ties of the separate systems of bracing intersect at the top and bottom respectively at points corresponding with the centre of gravity of the flange at each apex.

The several girders are braced together at the top and bottom booms at intervals of about 24 feet with diagonal bracing in a vertical plane, consisting of horizontal channel-bars and diagonal tee-bars, and the bottom flanges are further braced horizontally by diagonal bracing in the form of angle-bars. For the purpose of stiffening the booms at the vertical diagonal bracings, diaphragms are inserted between the vertical plates. The flooring, of course, braces the girders at the top.

The rivets through the horizontal plates of the flanges are 1 inch in diameter and at 4 inches pitch, except those near the centre-line of the flanges, which, being merely stitching rivets, are 1 inch in diameter and at 8 inches pitch. All the other rivets are $\frac{7}{8}$ inch in diameter and at about 4 inches pitch. The riveting of the girders was executed by hydraulic and pneumatic power, depending on the position of the rivets, with distinct preference for the hydraulic power where many plates were piled. There was no hand-riveting. The ties and struts of the web-bracing are not riveted together where they cross, so that they act quite independently. To prevent flapping, however, the pairs of flat bars forming the ties are held together near their middle with two bolts which pass through hollow distance-pieces fixed between the pairs of bars.

The Lintel-Girders.—The lintel-girders (Fig. 5, Plate 1, and Figs. 17, Plate 2), by which the main girders are supported, span from pillar to pillar of each pier, and are bolted to granite blocks by four $1\frac{1}{2}$-inch-diameter bolts at each bearing. They are box girders 4 feet deep, with flanges 3 feet 6 inches wide, and their effective spans vary from 19 feet to 25 feet. The details of their construction are clearly indicated in the above-mentioned Figures. The main girders rest over the centres of the lintel-girders and over the ends of adjoining lintel-girders at their bearings. It is estimated that the load at the centre of each of the lintel-girders of the river piers is about 458 tons: and, having regard to this, there is a stiff diaphragm at the centre of the lintel-girders connecting the three web-plates, and similar diaphragms at each bearing on the pillars. With a view to distribution of the load on the pillars of the piers, the lintel-girders have enlarged bearing-plates riveted to their bottom flange, and they rest on a grillage composed of 6-inch by $4\frac{1}{2}$-inch by 20-lb. rolled beams spaced about 10 inches apart and riveted to a 1-inch plate, which rests on the granite, as shown by Fig. 17, Plate 2. The bottom flanges of the lintel-girders were machined at the bearings after the girders were built, and the space between the rolled beams of the grillage is filled with granolithic concrete, finished quite smooth at the top in order to ensure true and uniform bearing of the lintel-girders.

The Bearings.—The bearings for the main girders (Figs. 18, Plate 2) rest on the top of the lintel-girders. There are two kinds of bearings, one for the expansion and the other for the fixed end of the girders. The several parts of the bearings are of cast iron, specially machined at their surfaces of contact. The rocker of the expansion-bearing is machined at the top and at the bottom to a radius of $7\frac{1}{2}$ inches, and fits into the semicircular surfaces of the top and bottom saddles, which are machined at the same radius as the rocker, for a circumferential length equal to about two-thirds of the semicircle, which is the measure of the bearing at the place of contact. The expansion-rockers under certain of the girders were set vertical when the temperature was normal, but in extremes of temperature others were set inclined from the vertical to the extent of about $\frac{5}{32}$ inch for each 10° F. variation of temperature above or below the normal, which was assumed to be about 55° F.

The fixed bearings are merely deflection-knuckles similar in form to the upper portion of the expansion-bearing. The upper part of the knuckle and the under part of the top saddle are machined to a radius of $7\frac{1}{2}$ inches, and have bearing surfaces similar to the bearing surfaces of the expansion-bearings.

The expansion and fixed bearings are similar in size and the fastenings are also identical. The main girder is bolted to the top saddle, and the bottom saddle is bolted to the lintel-girder and held longitudinally by lugs cast at the side. Pairs of expansion-bearings rest on the north river pier, and pairs of fixed bearings rest on the south river pier.

The bearings afford good points of support, and observation shows that the girders appear to adapt themselves readily enough to expansion and contraction with changes of temperature and to deflection under the loading. Similar satisfactory results might, however, have been attained with simpler bearings, recent experience in maintenance having shown that long-span girders of certain bridges and roofs had not apparently suffered, although the special bearings on which they rested had rusted and were immovable. But in these cases there was space for the girder to slide freely.

The Flooring.—With a view to lightness of dead load, the flooring of the main part of the bridge is Hobson arched-plate flooring (Figs. 13, 14 and 20, Plate 2). It is laid transversely and rests on the top flanges of the main girders, spanning spaces between these girders varying from about 8 feet to about 12 feet. It is 12 inches deep and is built up with a curved plate $\frac{1}{2}$ inch thick and a tee-bar 7 inches by $3\frac{1}{2}$ inches by $\frac{1}{2}$ inch, strengthened where the spans are wider by the substitution of two angle-bars for the tee-bars, and by the addition of an arched plate round a part of the circumference. The rivets are $\frac{7}{8}$ inch in diameter, and at 4 inches pitch, and they were put in by hydraulic pressure, a special machine having been made for the purpose.

The flooring has a bearing of 12 inches on the top flanges of the main girders, so that there is a space of about 2 feet over the main girders between the ends of the several bays of flooring. This space adapted itself to drainage purposes. The flooring is not packed up to the level throughout the length of the main girders, but follows the flange-plates and the camber of the main girders, so that the surface of the flooring near the ends of the main girders at the piers is at least 6 inches lower than the surface at the centre of the main girders. This was also taken advantage of in the drainage, as it lent itself to grading in the work of waterproofing.

As the main girders are not parallel, the flooring could not be laid normal to them all. Each arched plate of the flooring is, however, cut square at the ends, and the skew is taken up by a dished plate inserted at each end, to which the flooring is riveted, the dished plate being in its turn riveted to an angle-bar, which runs the whole length of the main girder.

At the ends of the main girders over the piers the flooring is stopped and finished with an ordinary plate cross girder, which, like the flooring, spans the space between the main girders. There is thus a space longitudinally over the piers, between the flooring cross girder of the one span and the flooring cross girder of the next span. This space, which is 16 inches wide, is covered by a plate 1 inch thick. At the fixed ends of the main girders the plate is bolted to both the cross girders and thus the flooring is made continuous over the pier. At the expansion ends, where the main girders rest on the movable bearings, the 1-inch plate is bolted to only one of the cross girders and is allowed to slide on the other cross girder, or rather on part of a plate, known as a splash-plate, bolted to the cross girder, as shown by Fig. 19, Plate 2.

The splash-plate is for the purpose of preventing water from getting on to the steelwork opposite, for here there is a drainage-outlet, and water from pipes laid longitudinally along the top of the main girders between the bays of flooring flows into a gutter, which lies, between the ends of the girders, along the tops of the piers for the whole width of the bridge.

The Parapet-Girders.—The parapet-girders, Fig. 15, Plate 2, are lattice girders, with six systems of duplicate bracing. The booms are each built up of a series of horizontal flange-plates, two vertical plates, and two angle-bars. The inside members of the web-bracing are flat bars, but the outside members are channels cut to pass each other at their intersection, where they are covered with a cast-iron rosette.

The parapet-girders are placed at a higher level than the main girders, the bottom of the former being about the same level as the top of the latter. They are 10 feet 4½ inches deep, and their top flanges are 7 feet above rail-level. They are practically self-supporting, but they are strengthened by bearing on a series of steel brackets of curved form, which are attached to the outer main girders. They are placed 6 feet 6 inches out from the centre of the main outside girders, in order that there shall be 7 feet of clearance from the rail, the effect of which is also to allow of a footpath being formed on either side of the bridge, about 5 feet wide, for the use of signalmen and other servants of the railway-company. In fixing the height of the parapet-girder at 7 feet above rail-level, and its position at 7 feet from the nearest rail, regard was had to the possibility of trains being stopped on the bridge, and passengers, thinking the train was in the station, attempting to alight.

The Erection of the Main Girders.

The main girders were constructed on the temporary staging across the river and on extensions of it over parts of the quays. The struts of the main bracing, together with the connecting plates, were built up in the bridge-yard, and so conveyed to the site, but all the other parts of the girders were taken to the site in the form of prepared plates and bars, and were built up and riveted there. In erection, the girders were supported on camber-blocks or wedges, and on a series of timbers laid transversely 7 feet apart and built up to a height sufficient to allow of the workmen conveniently passing underneath the girders for riveting and other purposes. At first the work of building the girders had to be carried on entirely at the level of the staging, but as girders were completed, use was made of some of them for erection of the others of the same span, by placing cranes and having bogie-roads on them and otherwise. When the riveting was completed, the camber-blocks were removed and the several girders were eased into position and lowered to their permanent bearings by means of hydraulic jacks.

The Steelwork of the Signal-Cabin.

The signal-cabin, which is 106 feet long and 16 feet wide, is situated between the new and the old bridges, the floor being 15 feet above rail-level. It is carried on an overhanging steel frame attached to the parapet of the new bridge, and is otherwise supported by a series of brackets attached to the main outside girder

Access to the signal-cabin is got by means of a gangway, 5 feet wide in the clear, erected across the bridge on the line of the north river pier, as shown on Figs. 2 and 4, Plate 1. The main girders of this gangway are of the Vierendeel type, being so designed in order to afford a clearer view than could be got through the bracing of an ordinary lattice girder, it being the intention to use the gangway as a platform from which men will direct the movements of trains. The span of the gangway is 120 feet and the girders are 10 feet deep at the centre and 5 feet deep at the ends. The scantlings are as shown in Figs. 16, Plate 2. Access to this gangway is got by means of a spiral stair constructed inside the granite pilaster of the bridge at the north river pier.

The Painting.

Except the caissons and the upper surface of the plate flooring, the steelwork of the bridge was first coated with boiled linseed-oil and afterwards painted with four coats of paint. The plates and bars were coated with oil before being put together, and, after being riveted up, they received a priming coat of red and white lead mixed with pure linseed-oil. The priming coat was put on in the bridge-yard before there was any corrosion, and after all loose scale and dirt had been carefully removed and the steel was made thoroughly clean; and the remaining three coats, also composed of leads and linseed-oil, were put on after erection of the structure. In order to ensure the painting being properly executed, the several coats were tinted to different shades, the finishing coat being of a light stone colour.

Experience has shown that lead paint is the best preservative of steel and iron; but the expediency of first coating the metal with oil is somewhat doubtful, although the possibility of corrosion setting in before the paint has been applied should be absolutely precluded.

With a view to provide permanent facilities for inspection and future painting and other maintenance work, light gangways have been erected along one side of each of the main girders at the level of the bottom flanges: these gangways are connected with each other by means of a transverse gangway at the middle of each span. They are in the form of steel brackets attached to the main girders and have a timber floor and a light iron handrail. Access to the gangways is obtained from the footpath at rail-level on either side of the bridge by means of man-ways and iron ladders.

The Waterproofing.

Apart from a statutory obligation on the Company to have the superstructure of the bridge thoroughly watertight and thereby preclude the possibility of water dripping through on to the streets and quays below, the importance of proper waterproofing was recognized from the point of view of the preservation of the structure.

In the design of the waterproofing it was made an imperative condition that the surface to be protected should be properly prepared to receive the waterproofing by being carefully graded and steeply sloped in all the necessary directions. As a means towards this end it was necessary to lay a "levelling up" layer to form a bed for the waterproofing, and this layer also acted as a preservative covering.

There was much consideration of the character of the waterproofing, and experience having shown the futility of waterproofing with artificial asphalt even if "reinforced" with layers of tarred brown paper or bagging or other textile material, and regard being had to elasticity and rigidity and the influence of temperature and vibration, it was decided to waterproof the steel structures with natural rock asphalt, and those of masonry with cement rendering, the graded bed or preservative covering underneath being either cement concrete or bituminous concrete. The waterproofing was therefore made to consist of two layers, a lower or preservative layer and an upper or protective layer.

In the execution of the waterproofing work the upper surface of the Hobson flooring of the bridge was first of all brushed and cleaned and coated all over with boiling bitumen. The hollows at the joints between the arch-plates of the flooring were then carefully plugged in the bottom with Seyssel rock asphalt to a depth of about 3 inches. Above this plugging, the arched plating was haunched with bituminous concrete (a conglomerate mixture of broken stone and boiling pitch) to the level of its upper surface, and to some extent above it at the centre of each of the bays of flooring between adjoining longitudinal girders, where a summit was formed and the surface was so graded as to ensure there being a good cross fall on either side towards the channel on the top of each longitudinal girder which formed itself between the ends of each of the bays of flooring. These channels were shaped in the bottom by filling with fine concrete in cement to such a semicircular form as would properly receive drainage-pipes, Fig. 20, Plate 2, and they were so graded in level longitudinally as to give a sufficient fall towards either end.

With the surfaces of the flooring and the channels thus prepared with the preservative covering, they were protected by being waterproofed and made impervious with an all-over layer of Seyssel rock asphalt $\frac{3}{4}$ inch thick, the finished surface of which is somewhat similar to that of the paving of some of the streets of London.

In each of the semicircular channels on the tops of the main girders between the ends of the bays of flooring, there are 6-inch-diameter cast-iron pipes perforated on their upper surface, and having inspection-chambers about 50 feet apart. The pipes, which have open joints, are haunched with concrete at their undersides and covered over with broken stone, so that the water from the graded surfaces of the respective bays of flooring flows freely into them; and being connected with gutters laid longitudinally along the piers between the ends of the main girders, they ultimately have their outfall in the river.

The waterproofing of the buckled-plate portions of the flooring of the parts of the bridge over the streets was somewhat similarly executed, but, instead of bituminous concrete, fine cement concrete was used as a preservative and making-up covering, and, being laid to the level of the top of the tee-bars and carefully graded, was also covered all over and made impervious with a layer of Seyssel rock asphalt $\frac{3}{4}$ inch thick. The water is led to down pipes which discharge into drains having connection with the public sewer.

In order to preclude the possibility of injury by the angular ballast of the permanent way and the picks and shovels of the surface-men, the waterproofing throughout its entire area is covered with a layer of very finely crushed whinstone, about 2 inches deep, on which the ordinary under-ballast is laid directly.

The bottom booms of the main girders were waterproofed with a filling of bituminous concrete shaped to circular form and laid to proper fall, the outfall being through certain vacant rivet-holes.

From the point of view of the economics of maintenance, waterproofing work does not appear to have always received that consideration and care which its importance imperatively demands. A preserving layer of concrete covered with a protecting layer of natural rock asphalt is the best waterproofing that can be executed; but the primary requirement in all waterproofing work is to provide plenty of "fall."

The Elevation.

The Company were under statutory obligation to the City Corporation in respect of the appearance of the bridge, so that in the design special regard was given to the perspective, which was carefully studied by means of a model. Endeavour was made to secure effect by the introduction of pleasing lines and by contrast in light and shade, rather than by added ornament; and without sacrificing economic principle, the several parts of the structure were treated accordingly. The result is indicated in Fig. 21, Plate 2.

The pillars of the piers taper 1 in 72 upwards from a moulded base-course, which is situated about high-water level. The outer pillars are built up to the level of the top of the main girders and finish there with a heavily projecting capital, on which the parapet girders are borne. Above the capitals the outer piers are continued upwards in the form of pilasters of semi-octagonal shape and of otherwise varied outline, and they are finished at the top with massive moulded copings. The masonry of the pillars is light grey granite ashlar of rock-face dressing below the level of the base-course and of fine-axe dressing above.

The parapet-girder was designed to give the appearance of mass, as well as continuity, and, with this in view, it is constructed in the form of a box girder having numerous horizontal lines at the top and bottom flanges. These lines are provided by the members of a cast-iron moulded base-course and a cast-iron moulded coping, simple in their detail, but with heavy projections and resulting light and shade. It was thought that the appearance of the bridge might also be improved by having the main girders deeply in shadow, and this was secured by placing the parapet and main girders in different vertical planes. The contrast between the main and the parapet girders is further accentuated by the web-bracing of the parapet-girder being made different from the web-bracing of the main girder. The latter with its heavy loads, even in appearance, calls for substantial vertical struts, but as the former is more in the nature of a fence, it was thought that from an æsthetic point of view, its requirements might better be met by having multiple systems of comparatively light inclined latticing with the bars covered at their intersections by rosettes of cast iron.

In the case of the river piers, the pilasters are carried up to a considerable height above the parapet-girders. This was done with a view to lead the eye upward, and in the perspective to emphasize the masonry and tend to dispel, or rather render less noticeable, the difference in level of the bearings of the main girders on either side of the several piers. It was thought at first that the broken line and want of continuity of the underside of the superstructure, due to the difference in level of the main girders of the several spans, might be detrimental æsthetically, but this possible defect in the appearance can be said to have been successfully corrected in the perspective by the adoption of the idea described. With the object of further enhancing the appearance of the bridge and relieving the angularity, its lines have been softened by the introduction of a series of curved brackets attached to the outside main girders. The parapet-girders rest on these brackets, and in the perspective the brackets have the appearance of continuously connecting the parapet and main girders by a line of pleasing curvature.

Unit Prices for Superstructural Work.

The unit prices of certain of the superstructural works were the following:—

Masonry.

Brickwork in hearting of pillars of piers of red bricks	22*s*. 6*d*. per cubic yard.
Granite ashlar in bearing blocks of main girders, fine axed	7*s*. 9*d*. per cubic foot.
Granite ashlar in facing of pillars of piers below base-course with chisel-drafted margin and rock face	6*s*. 3*d*. ,, ,, ,,
Granite ashlar in moulded base-course of pillars of piers, fine axed	11*s*. 8*d*. ,, ,, ,,
Granite ashlar in shafts of pillars of piers, fine axed	7*s*. 10*d*. ,, ,, ,,
Granite ashlar in capitals of pillars of piers and bases, dadoes and capitals of pilasters heavily cut and moulded and fine axed	16*s*. 1*d*. ,, ,, ,,

Steel and Iron Work.

Wrought steelwork in open web main, plate main, box lintel, lattice parapet and other girders	£13 17*s*. 6*d*. per ton.
Wrought steelwork in curved brackets under lattice parapet girders	£13 17*s*. 6*d*. ,, ,,
Wrought steelwork in Hobson flooring	£13 17*s*. 6*d*. ,, ,,
Wrought steelwork in buckled plate flooring	£13 17*s*. 6*d*. ,, ,,
Cast ironwork in fixed and expansion bearings	£19 per ton.
Cast ironwork in moulded plinth cornice and coping of parapets	£18 ,, ,,

Waterproofing.

Bituminous concrete in haunches of and over the Hobson flooring	39*s*. 9*d*. per cubic yard.
Fine cement concrete (5 to 1) over the buckled plate flooring	24*s*. 9*d*. ,, ,, ,,
Seyssel asphalt ¾-inch thick covering the bituminous concrete over the Hobson flooring and the fine cement concrete over the buckled plate flooring	4*s*. 5*d*. per square yard.

These are the prices of the several items of work as stated in the contract-schedule, but, as in the case of the cost of the substructural works, if they are used for estimating total costs, a percentage should be added to cover the general charges which are common to contracts of this character.

The Testing.

For testing purposes, the bridge was loaded with locomotives in such a manner, and to such an extent, as to bring the greatest possible weight on to individual main girders. Nineteen engines were used, which were of the Company's heaviest class, their aggregate weight being about 1,167 tons. They were so placed on the lines of rails directly over the girders, and immediately adjoining the girders, as to load the main girders of the north river span, the centre river span, and the south river span, with a uniformly distributed weight to the extent of about 330 tons, 400 tons, and 300 tons respectively. The maximum deflections under these loads were about $\frac{5}{8}$ inch, $\frac{7}{8}$ inch, and $\frac{3}{4}$ inch for the north, centre, and south river spans of 151 feet, 194 feet, and 173 feet respectively; and these results were considered satisfactory. The lintel-girders were also tested, and, while there was indication of deflection, it did not in any case exceed $\frac{1}{16}$ inch. But with all the loading there was no indication of settlement of the foundations.

Raising the Old Bridge.

Having regard to the levels of the extended station and of the approach-lines on the new bridge, it was necessary to raise the approach-lines on the old bridge. The old bridge has five spans which over the river vary from 151 feet to 194 feet, and it carries four lines of rails on rail-bearers, and cross girders resting on two outside main longitudinal girders 20 feet deep, which have their bearing on cylindrical granite pillars. Calculation having shown that it would be inexpedient to put any additional load on the old bridge in the raising of the rail-level, it was determined to raise the superstructure bodily. It had to be raised 1 foot 4 inches at its south end, and 3 feet at its north end, but with the bridge temporarily closed for traffic, the work was readily accomplished by means of hydraulic jacks applied to temporary steel brackets bolted to the end plates of the two outside main longitudinal girders of the several spans, purchase being got from the cylindrical pillars of the piers.

THE STRENGTH OF THE IRON OF THE OLD BRIDGE.

It was thought desirable to ascertain if the wrought iron of the girders of the old bridge had suffered from the effects of the strains and exposure to which it had been subjected in its life of 27 years. Tests were therefore made on pieces of an angle-bar member of one of the struts of the web-bracing. There was very little variation in the results of the tests, and the breaking-weights were ascertained to average 23½ tons per square inch, the limit of elasticity 13½ tons per square inch, and the elongation on a length of 8 inches about 10 per cent. Two bending-tests were also made, with the result that pieces bent round a diameter of about 1 inch merely showed the slightest indication of fracture. The wrought iron had been kept well painted, and, there being little if any diminution of section and, as the tests showed, no deterioration in quality, the metal was considered to be still in a remarkably satisfactory condition.

The locomotives of the day are already found burdensome enough, and were it not that sooner or later those of the future may prove to be too fatiguing, the wrought iron of the old bridge, having regard to the likelihood of less corrosion, might last as long as the steel of the new, notwithstanding that the wrought iron has already been 27 years longer in existence. From the point of view of true economy, therefore, it is suggested in this connection that, taking everything into account, there may have been some inexpediency in so drastically discarding wrought iron for mild steel in bridges and other structural work.

THE EXECUTIVE.

The new bridge was designed and constructed under the direction of the Author, with Sir John Wolfe Barry, K.C.B., as Consulting Engineer. Mr. D. McLellan, M. Inst. C.E., acted as Resident Engineer during the earlier part of the work, and was succeeded by Mr. H. Cunningham, Assoc. M. Inst. C.E. Mr. Alexander Grant was the Superintending Inspector of Works.

The contractors were Messrs. Sir William Arrol and Company and Messrs. Morrison and Mason, Glasgow, and their engineering representatives on the works were respectively Mr. William Burnside and Mr. James Waddell, M. Inst. C.E.

The Paper is accompanied by twenty-two drawings and tracings, from which Plates 1 and 2 and the Figures in the text have been prepared; there are also the following Appendixes.

[APPENDIXES.

APPENDIXES.

APPENDIX I.

Depths of the Main Caissons.

Pier.	Depth below High-water Level.	Depth below Surface of Quays.	Depth below Bed of River.
1. North land pier—	Feet.	Feet.	Feet.
Caisson A 1	40·30	50·10	
Caisson A 2	51·24	61·04	
2. North river pier—			
Caisson B 1	66·55	..	44·10
Caisson B 2	66·55	..	44·10
3. South river pier—			
Caisson C 1	70·47	..	48·02
Caisson C 2	66·43	..	43·98
4. South land pier—			
Caisson D 1	45·50	57·30	
Caisson D 2	45·40	57·20	

APPENDIX II.

Dimensions and Weights of the Main Caissons.

Pier.	Length.		Width.		Height from Cutting Edge to Top of Uppermost Skin-plate.		Weight of Steel.
1. North land pier—	Ft.	Ins.	Ft.	Ins.	Ft.	Ins.	Tons.
Caisson A 1	89	6	20	3	41	1	195
Caisson A 2	61	8	20	3	52	1	167
2. North river pier—							
Caisson B 1	79	4	23	3	34	3½	203
Caisson B 2	52	3	23	3	34	3½	142
3. South river pier—							
Caisson C 1	73	10½	23	3	38	11½	195
Caisson C 2	48	7	23	3	35	0	133
4. South land pier—							
Caisson D 1	55	8	20	3	45	3	137
Caisson D 2	55	8	20	3	45	3	137

APPENDIX III.

Weights of Masonry as ascertained by Experiment.

	Lbs. per Cubic Foot.
Cement concrete (5-to-1)	130
Granolithic concrete (2-to-1)	138
Red brickwork in cement	122
Blue brickwork in cement	147
Freestone rubble masonry in cement	138
Freestone ashlar	145
Granite ashlar	164½

APPENDIX IV.

The Pneumatic Installation—Excerpt from Contract Specification.

"For the purpose of sinking the cylinders and caissons by the pneumatic process, such number of compressed-air installations shall be provided as will ensure safe and timeous completion of the works. The contractor shall, without extra charge beyond the contract prices, provide for each installation, in duplicate or in greater number as may be required, all engines, boilers, machinery, pumps, compressors, receivers, locks, high-pressure grouting appliances, hoisting gear and other apparatus, instruments, appliances and plant, together with all furnishings and fittings necessary to ensure the providing of an abundant and constant supply of compressed air of sufficient pressure. All the engines, boilers, machinery, appliances, plant and things for each installation shall be of such power as to maintain the necessary pressure, but the duplicate or other sets shall at all times be ready for immediate work, and be so connected that the stoppage of one set or of one boiler or engine or pump or appliance will have no prejudicial effect. The air-locks and working-chambers of the cylinders and caissons, as well as all other parts of the works, shall be properly lighted with electric light.

"The air-locks for the men, as well as those for the materials, shall be constructed of steel plates with strong doors. If necessary, the doors shall be interlocked, and the contractor shall in all cases, by means of the most improved arrangements and appliances, specially provide for the ready passage of the workmen through the locks and for their safety, and for the convenient introduction of plant and materials to the working-chambers, as well as for the removal and discharge of the excavations from the working-chambers. There shall also be provided numerous valves, gauges, taps, alarm whistles, electric or other signalling apparatus and speaking instruments for communication with the working-chambers, as well as means whereby passage of the workmen through the air-locks shall be gradual in respect of pressure and temperature. To ensure gradual change of pressure, the air taps in the man-locks shall be of such small bore as will prevent sudden change from the higher to the lower pressure or vice versa, and there shall be provided safety-locks and warm dressing-rooms for the workmen as well as a special compartment or hospital fully equipped for the treatment of any who may be injuriously affected by working under compressed air. The safety, comfort and convenience of the workmen shall be specially kept in view, and to regulate and ensure their continued good health, they shall be supplied with special clothing for the working-chambers and with warm jackets for wear after leaving work, and there shall be provided in the dressing-room hot water for washing and all conveniences for dressing and waiting as shall be directed. The men engaged in the working-chambers shall be on specially short shifts proportioned suitable to the working pressure, and it is recommended that, after leaving the working-chambers but before passing through the air-locks, they be supplied with suitable stimulant, and that arrangements also be made whereby they may, if necessary, have without delay the benefit of the advice of a special medical practitioner. Quick passage of the men through the air-lock shall be absolutely prohibited, and they shall be allowed such sufficient time there and in the dressing-room as will prevent subsequent injurious results.

"The compressed air shall be kept perfectly cool by cold water jacketing and otherwise, and special precautions shall be taken to ensure its purity in the working-chambers, the carbonic acid gas being kept low, and, as a test of the purity of the air, it shall be frequently analysed by a qualified chemist.

"The air-locks and other appliances shall be altered in position as the requirements necessitate, and sufficient air-pressure shall always be maintained night and day in the working-chambers, whether excavating and sinking is proceeding or not; and, in building the concrete hearting of the cylinders and caissons, as hereinafter specified, the air-pressure shall be constantly maintained until the work is entirely completed."

APPENDIX V—Progress of the Excavations in the Caissons.

(1) Land Piers.

Caisson.	Depth from Surface of Quays.	Character of Strata.	Depth of Excavations at Bottom on which Calculations are based.	Volume of Excavations.	Men-Hours.	Volume of Excavations per Man per Hour.	Time in Months from Commencement to Completion of Excavations in Working-Chamber.	Remarks.
	Ft. Ins.		Ft. Ins.	Cubic Yards.		Cubic Yards.		
A 1	18 0 37 0 50 0	Made ground . . . Muddy sand and gravel Sharp sand and coarse gravel	23 0	1,544	3,540	0·43	5·33	Depth of digging in working-chamber 43 feet; sand and gravel, but with some large stones; very coarse shingle.
A 2	22 0 56 0 61 0	Made ground . . . Muddy and stiff clay (average) . . . Sand and gravel (average) . . .	18 0	833	3,000	0·28	5·33	Depth of digging in working-chamber 51 feet; stiff clay, requiring special tools to cut.
D 1	11 0 22 0 40 0 48 0 51 6 57 0	Made ground . . . Muddy sand . . . Sharp sand . . . Gravel . . . . . Sharp sand . . . Sharp sand and gravel	24 4½	1,017	1,620	0·63	4·20	Depth of digging in working-chamber 50 feet; sand and gravel, easily handled.
D 2	11 6 24 0 44 0 57 0	Made ground . . . Muddy sand . . . Sharp sand . . . Sharp sand and gravel	24 9½	1,034	1,800	0·57	5·17	Depth of digging in working-chamber 50 feet; sand and gravel, easily handled.

APPENDIX V—*continued.*

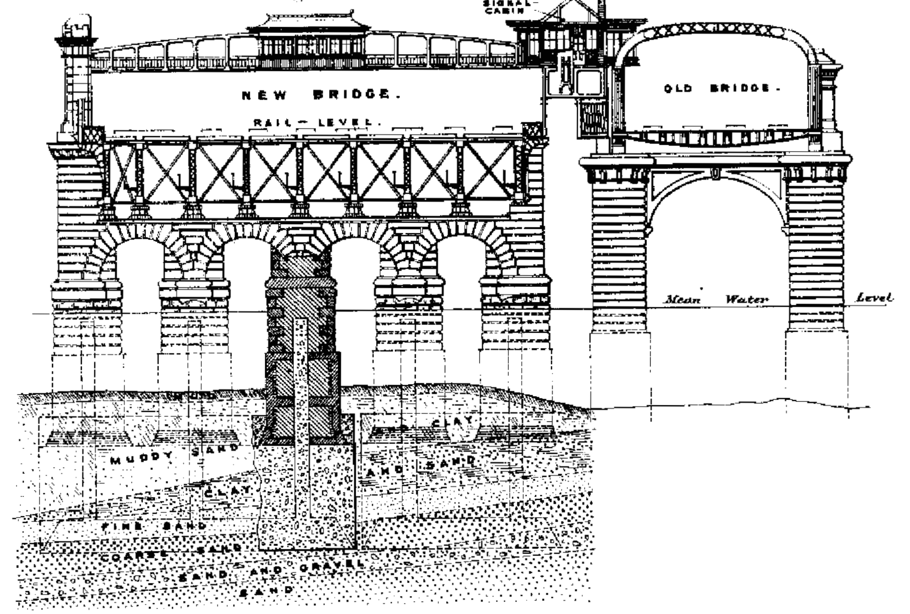
(2) River Piers.

Caisson.	Depth from Bed of River. Ft. Ins.	Character of Strata.	Depth of Excavations at Bottom on which Calculations are based. Ft. Ins.	Volume of Excavations. Cubic Yards.	Men-Hours.	Volume of Excavations per Man per Hour. Cubic Yards.	Time in Months from Commencement to Completion of Excavations in Working-Chamber.	Remarks.
B 1	1 6	Mud	..	1,037	4,140	0·25	2·67	Depth of digging in working-chamber 38 feet; largely through clay, which was found difficult to cut.
	24 6	Muddy clay	..					
	31 0	Clay with sand	3 4					
	43 0	Sand	12 0					
B 2	1 6	Mud	..	831	1,200	0·70	1·67	Depth of digging in working-chamber 38 feet; sand and gravel in bottom, and everything favourable.
	16 0	Muddy clay	..					
	28 0	Sand with clay	3 2					
	43 6	Sand and gravel	15 6					
C 1	1 0	Mud	..	1,216	2,280	0·55	3·75	Depth of digging in working-chamber 42 feet; sand and gravel, easily handled.
	11 0	Muddy sand	..					
	34 9	Coarse sand	6 1					
	40 0	Gravel	5 3					
	43 0	Sand	3 0					
	48 0	Sand and gravel	5 0					
C 2	1 0	Mud	..	819	800	1·02	2·75	Depth of digging in working-chamber 40 feet; sand and gravel; easily handled; men on bonus system.
	12 0	Muddy sand	..					
	34 9	Sand	10 10					
	39 6	Coarse sand	4 9					
	43 9	Sand and gravel	4 3					

THE NEW CLYDE BRIDGE

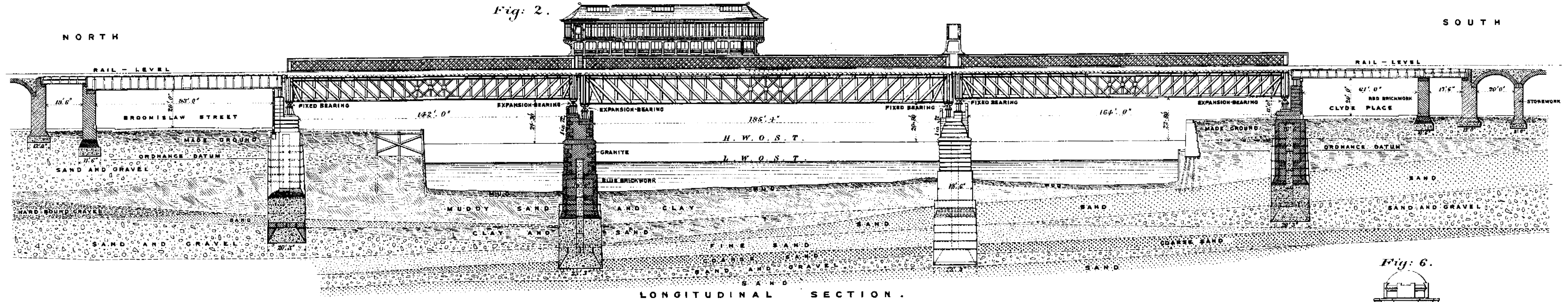
GLASGOW CENTRAL STATION EXTENSION.

Figs 4.



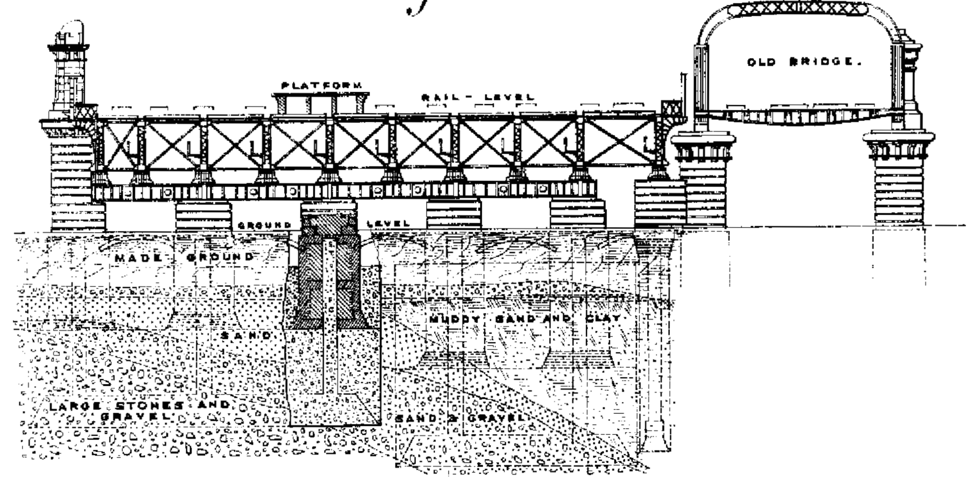
SECTION B.B.

Fig: 2.



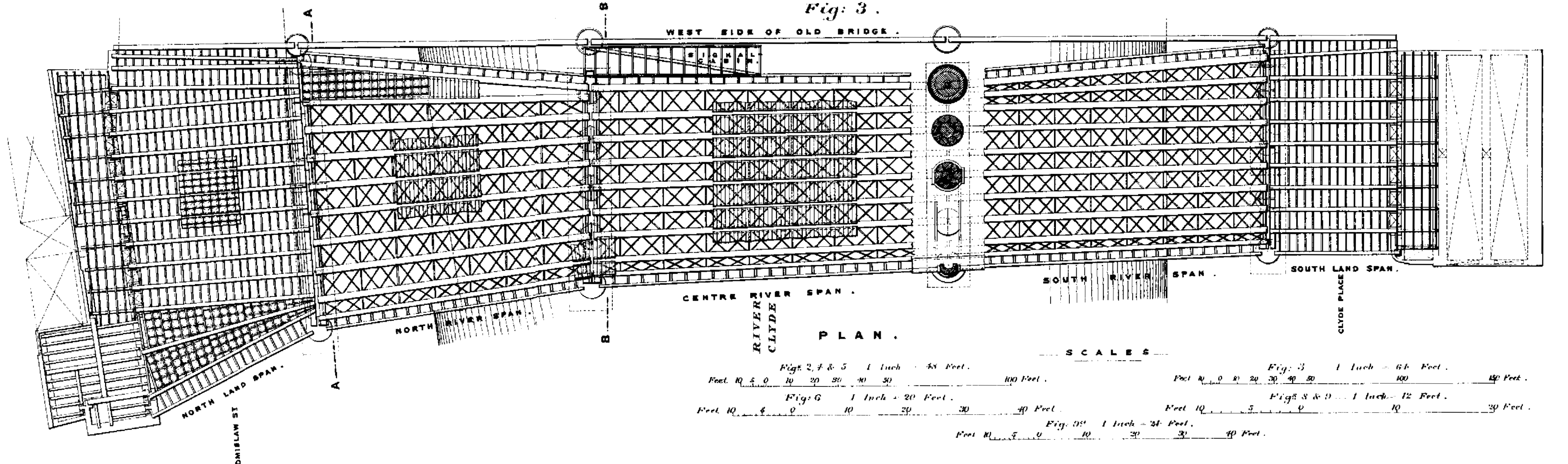
LONGITUDINAL SECTION.

Fig: 5.



SECTION A.A.

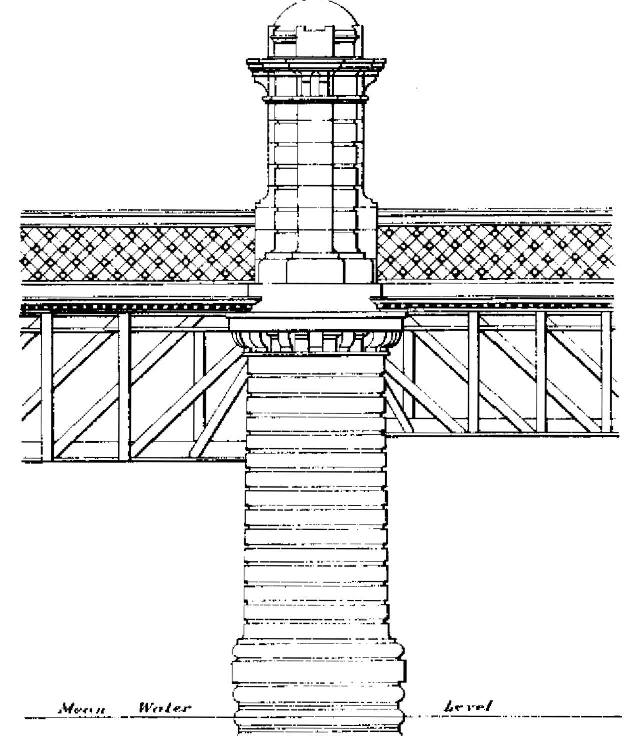
Fig: 3.



PLAN.

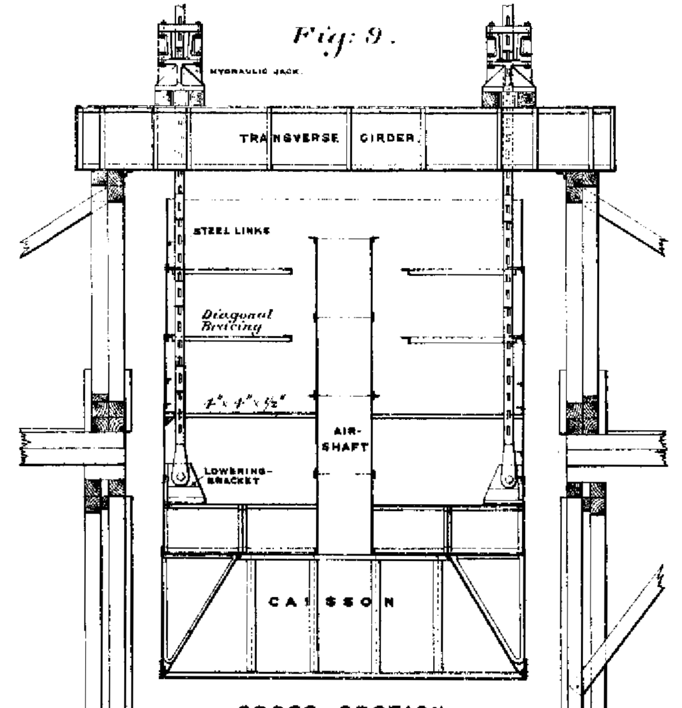
SCALES.

Fig: 6.



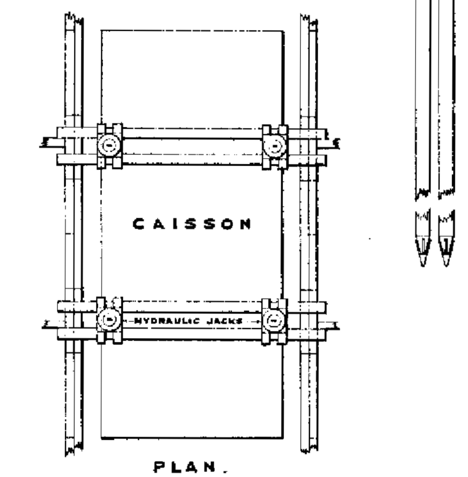
ELEVATION OF SOUTH RIVER PIER.

Fig: 9.



CROSS SECTION.

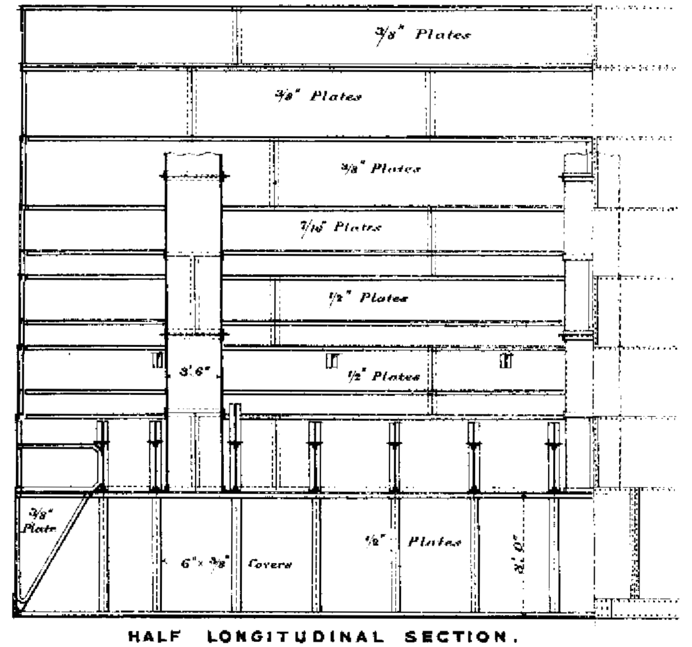
Fig: 9a.



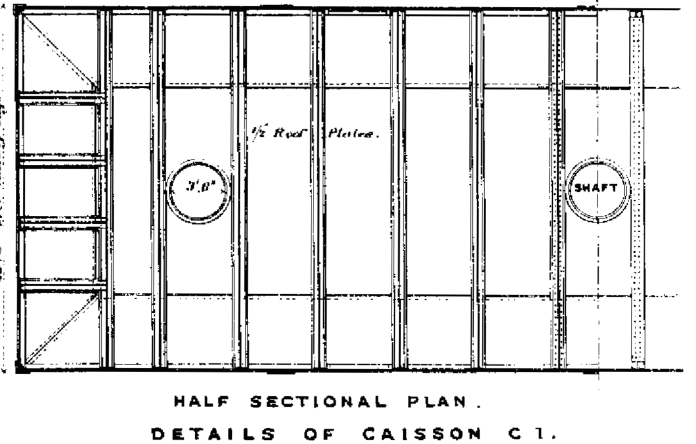
PLAN.

METHOD OF LOWERING CAISSON.

Figs 8.



HALF LONGITUDINAL SECTION.



HALF SECTIONAL PLAN.

DETAILS OF CAISSON C 1.

Fig: 8a.

PLAN SHOWING BRACING.

D. A. MATHESON.

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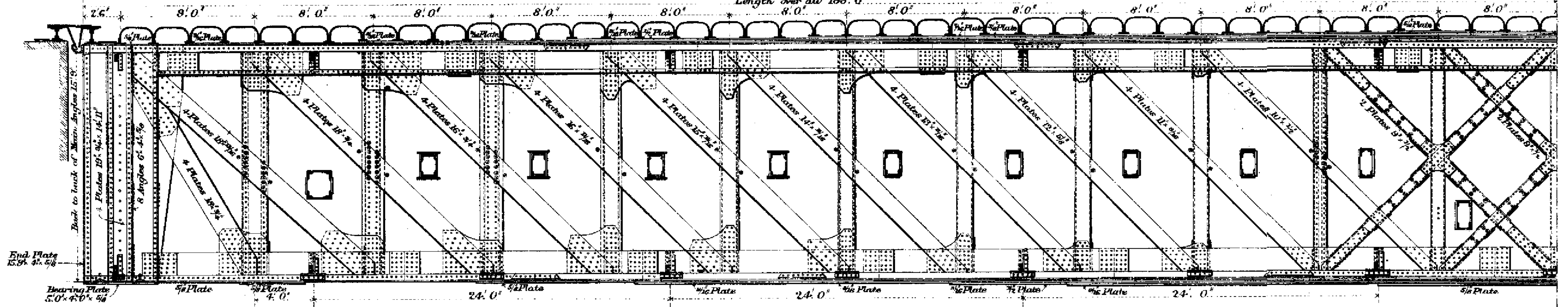
THE NEW CLYDE BRIDGE

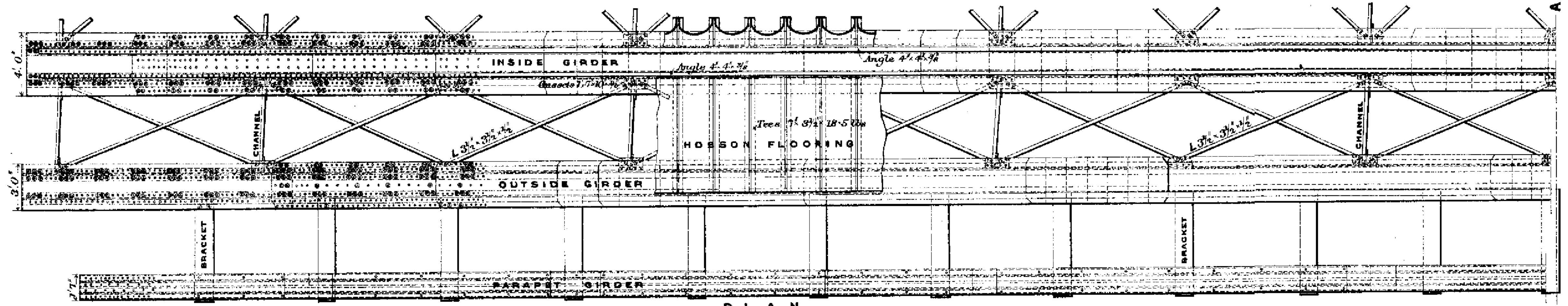
GLASGOW CENTRAL STATION EXTENSION.

PLATE 2.

Figs: 13.



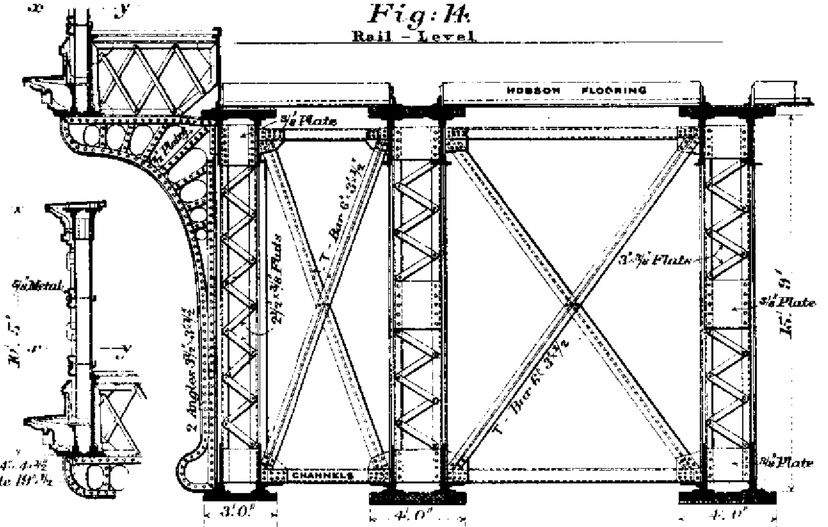
ELEVATION OF INNER GIRDER



PLAN

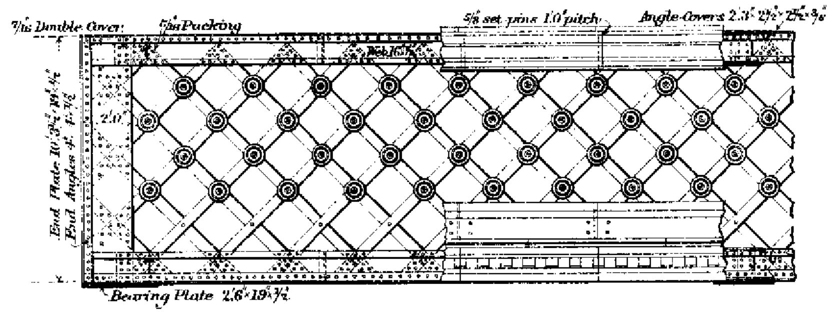
MAIN GIRDERS OVER CENTRE SPAN

Fig: 14.



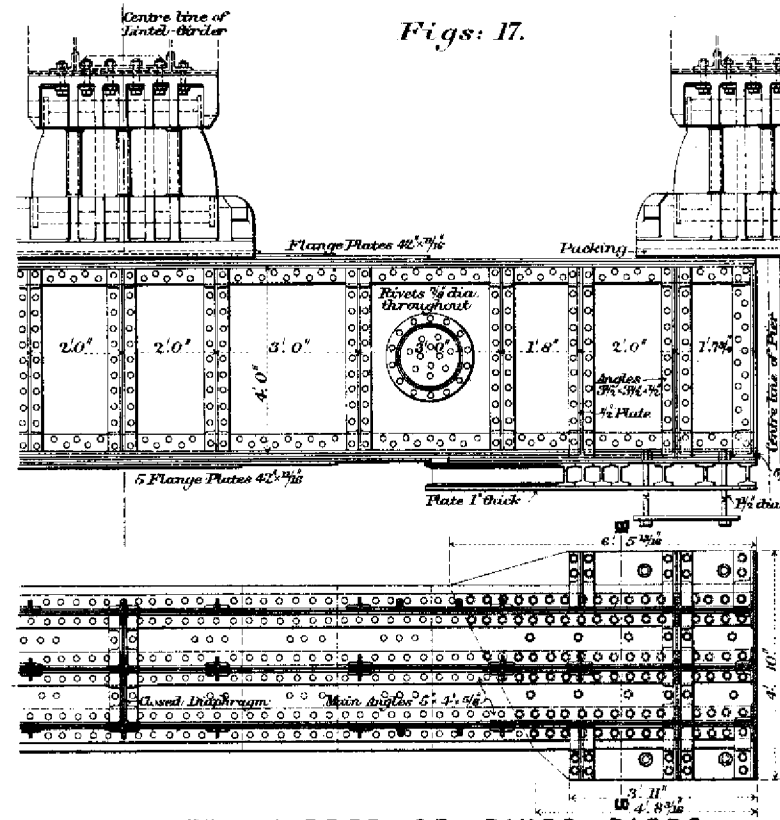
CROSS SECTION AA

Fig: 15.



PART ELEVATION OF PARAPET-GIRDER

Figs: 17.



LINTEL-GIRDER OF RIVER PIERS

SCALES

Figs 13 to 16 ...... 1 Inch = 8 Feet

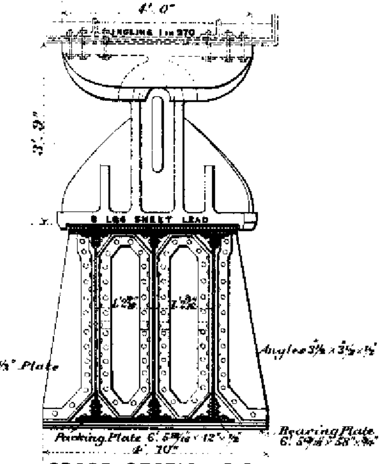
Figs 17 and 18 ...... 1 Inch = 4 Feet

Fig: 19 ...... 3/4 Inch = 1 Foot

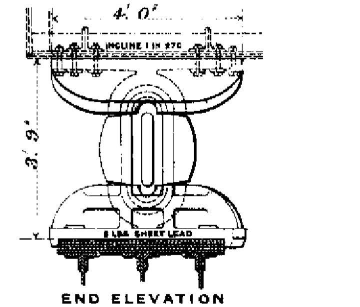
Figs 20 ...... 1 Inch = 2 Feet

Fig: 22 ...... 1 Inch = 64 Feet

Figs: 18.

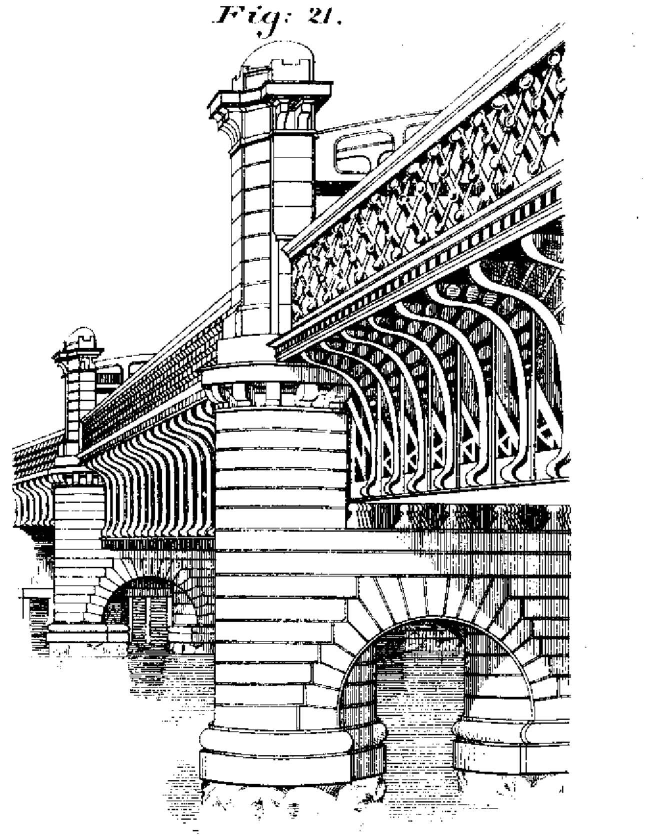


CROSS SECTION BB.
FIXED BEARING.



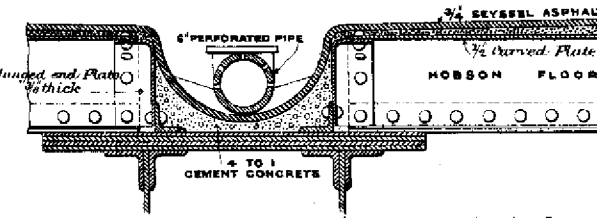
END ELEVATION
EXPANSION-BEARING

Fig: 21.

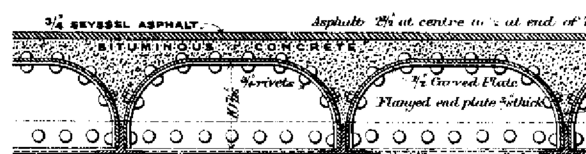


VIEW OF BRIDGE.

Figs: 20.

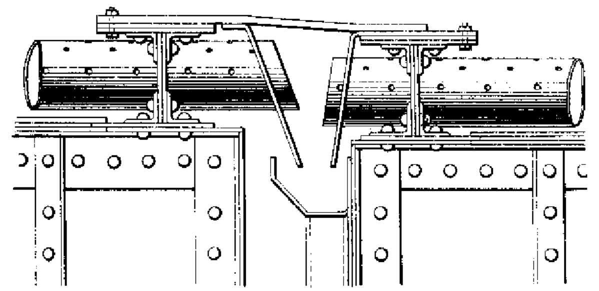


SECTION SHOWING DRAINAGE AT MAIN GIRDERS.



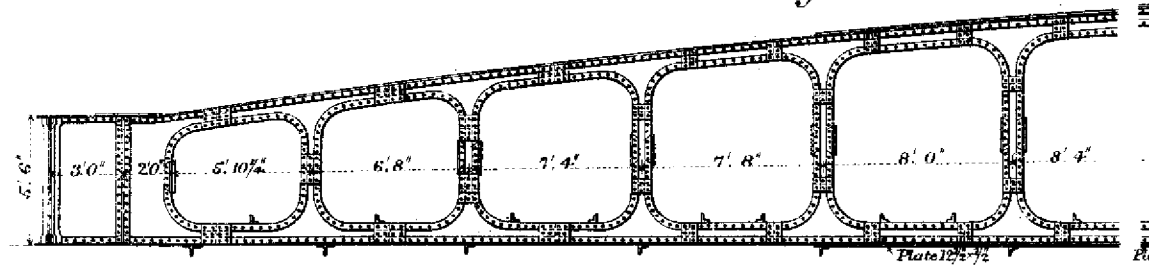
CROSS SECTION OF FLOORING

Fig: 19.

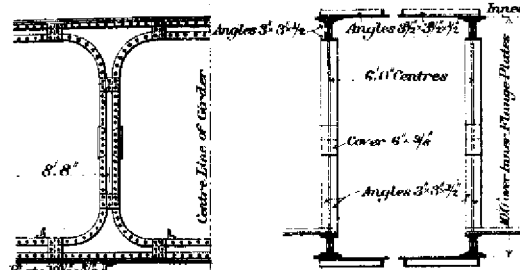


DETAIL AT EXPANSION-JOINT

Figs: 16.

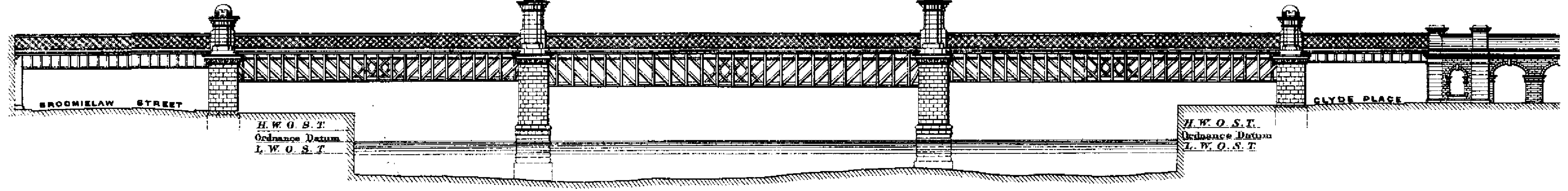


GIRDER OF OVERHEAD GANGWAY TO SIGNAL-CABIN



CROSS SECTION

Fig: 22.



WEST ELEVATION