SECT. II.—OTHER SELECTED PAPERS.

---

*(Paper No. 1552.)***“The Caledonian Railway Viaduct over the River Clyde at Glasgow.”**

By BENJAMIN HALL BLYTH, M.A., M. Inst. C.E.

THIS viaduct carries the various lines of the Caledonian railway across the river Clyde at Glasgow into the large new central station on the north side.

As originally sanctioned by Parliament, in 1873, it was intended to widen the existing Broomielaw bridge, and to support the railway on columns over the widened part of the bridge. The Broomielaw is the lowest bridge over the river Clyde, and, to overcome the opposition of the Clyde Trustees to the original scheme, the Caledonian Company had to pay them the sum of £22,500. In working out the scheme it was found that it would destroy a large amount of valuable frontage property. It was therefore resolved to apply for a deviation of the line by a viaduct a little lower down the river, and an Act was obtained for this purpose in the session of 1875. The Clyde Trustees again opposed the scheme; and in order to get rid of their opposition a further sum of £48,000 was paid to them, and stringent clauses protecting their interests were inserted in the Act. A sum of £25,000 was also paid to the Glasgow Bridges Trust, as by the Act of 1873 the Company had to widen the Broomielaw bridge, and this widening was now done away with, the Bridge Trust being bound to expend the above sum in an improvement of the Broomielaw bridge.

The river, where the viaduct crosses it, is 412 feet wide, and the quays and streets on either side are together 289 feet; so that the total length of the viaduct is 701 feet.

The viaduct (Plate 6) is divided into five spans: the first, beginning on the south side of the river, is 61 feet; the next in order, 164½ feet; the centre span, 186 feet; the fourth, 151 feet; and the last span, on the north side of the river, 89 feet—measuring along the centre line. As the last pier on the north side was built on the skew, the length along the centre line of the last two spans does not represent the length of the girders, which are different on each side of the viaduct. The variation in the spans is accounted for

by a clause which was inserted in the Act at the instance of the Clyde Trustees, enacting that the position of the piers was to be fixed by their engineer; and he fixed them in the line of the piers of the Broomielaw bridge. The outer face of the girder on the down-stream side of the river is 142 feet below the Broomielaw bridge. The viaduct is constructed for four lines of rails, and its outside width is 53 feet. The rails are 37 feet 9 inches above high water of ordinary spring tides, and the viaduct has a clear headway of 32 feet above the same level, and of 20 feet above the quays and streets.

The superstructure of the viaduct is carried on piers built inside cylinders sunk through the bed of the river to the solid rock. The greatest depth of water is 13 feet below low-water mark, and the range of the tide is about 10 feet. The cylinders for the two piers in the river are 15 feet in diameter, and those for the piers on the quays 13 feet. They are of cast iron. According to the specification the contractors were allowed to cast the cylinders in six segments, but they preferred to make each length in one piece, which is 6 feet deep, with plain flange-joining surfaces projecting 3 inches inside the cylinder, and provided with rusting spaces. The joining surfaces were all turned and planed, and the different lengths were fastened together with wrought-iron bolts 1 inch in diameter, placed 6 inches apart. The iron is $1\frac{1}{4}$ inch thick, except the bottom length of each cylinder, which is $1\frac{1}{2}$ inch. Each length of the larger cylinders weighed about $6\frac{3}{4}$ tons, and of the smaller about $6\frac{1}{4}$ tons. The one hundred and twenty lengths of both sizes required for the work were all cast in one pit without a flaw, and were turned out of the works at the rate of three lengths per week. A removable core bar was used in the pit, and it and the lining were removed within thirty minutes from the time of running in the metal, thus allowing free shrinkage and equal cooling throughout.

There are four piers, each of which consists of two cylinders placed 50 feet apart from centre to centre. The strata penetrated by the cylinders were principally sand, clay, and mud, with a few small beds of gravel. The cylinders were sunk by excavating within them by means of a steel digger, an improvement on Milroy's,¹ and by weighting the cylinder inside. The digger had twelve blades, each blade being heavily weighted on the back. The blades are attached to the centre of the digger

¹ *Vide Minutes of Proceedings Inst. C.E.*, vol. xxviii., p. 339.

by a system of bars similar to the framework of an umbrella, and these are drawn together by means of four chains. The machine is sunk with the blades in a vertical position, suspended from a monkey hook, so that the moment the blades strike the bottom the hook is detached; the blades are then drawn together by the chains, by which the whole machine is raised. The digger sinks into the ground by its own weight; hence the side chains, and the two men required to work them under Mr. Milroy's process, are not needed. After the digger has been raised to the top of the cylinder, it is moved, by the same machinery which works it, to the side; the original hook is attached to the blades, which, on being raised, fall apart and deposit the stuff in a wagon. The digger employed was 8 feet in diameter, 15 inches deep at the sides, and 22 inches deep in the centre. It weighed 3 tons 16 cwt. When working in good stuff the average time occupied for each lift was about five minutes, the quantity of stuff raised about $1\frac{1}{2}$ cubic yard, and the depth of cylinder sunk about 3 inches. The digger frequently brought up boulders weighing between 7 and 8 cwt. each.

Each length of the cylinder, except the two lengths at the bottom, was loaded with cast-iron weights resting on the before-mentioned projecting flange. The weights were cast in segments 10 inches thick and 9 inches high, so as to fit into the concave side of the cylinders, and were between 6 and 7 feet long. Each length of cylinder of the smaller size was thus weighted with 24 tons, and of the larger size with about 30 tons.

The cylinders were in every case sunk down to the solid rock. Those on the land reached the rock at depths varying from 83 feet to 101 feet below the level of the street, and those in the river at a depth of 85 feet below high water of ordinary spring tides.

The greatest weight which can come on the base of any of the 15-foot cylinders (supposing all four lines of rails to be loaded with the heaviest locomotives) is about 2,000 tons, equal to a pressure of 11.4 tons per square foot on the foundations; the greatest weight on any of the 13-foot cylinders is about 1,550 tons, equal to 11.6 tons per square foot on the foundations, no allowance in either case being made for friction.

The first cylinders to be sunk were the two on the Broomielaw, or north quay, and these occasioned more difficulty than any of the others. A bed which had been described as sand, but which turned out to be clay of a tenacious character, had to be pierced. This lay at a depth of about 60 feet below the street. When the more easterly of the two cylinders (which was the first to be sunk) had

got some way into this bed of clay it stopped moving. The digging inside the cylinder had to be given up, as a small wall in the immediate neighbourhood had shown signs of cracking, and it was not considered safe to take out any more stuff until the cylinder itself went down. The cylinder was then weighted on the top with short rails and pig iron, but for days did not move, until, at last, when weighted with about 500 tons, the whole mass suddenly went down 19 feet 9 inches without warning, and the cylinder remained perfectly vertical. The remaining cylinder on this quay stopped in the same bed of clay, and when weighted with 425 tons sank 12 feet 6 inches in a similar manner. All the others, with one exception, went down to the rock quite easily, without causing the least trouble or anxiety. The exception was the more easterly cylinder on the south quay. This, after it had been sunk about 40 feet, got into running sand, and as the digging went on inside, the ground outside the cylinder began to fall in; after this was observed all the sand dug out from the inside was packed closely round the outside of the cylinder. A curious thing happened to this cylinder: when it got into the running sand the bottom moved about 10 inches westwards, while the top remained in correct position; it continued thus for some days, and then the top gradually followed, until the cylinder regained the perpendicular, but it still remained 10 inches out of position.

After the cylinders had been sunk, they were filled with concrete to a depth of 12 feet, that part of the bottom of the cylinder having been left without any weight. A fortnight was allowed for the concrete to set, and the water in the cylinders was then bailed out, and the cylinders were filled up with concrete, those on the land to within 5 feet of the level of the quays, and those in the river to a level of 30 feet below high water. The concrete was composed of 2 parts of stone or brick broken to pass through a 2-inch ring, 1 part of clean sand, and 1 part of the best Portland cement, mixed thoroughly. Above the concrete the columns consist of granite and freestone, in courses 2 feet in thickness. Freestone was used for economy for the inside stones, Fig. 1, which also shows the bond of both sizes of piers. The granite was obtained chiefly from the quarries of Messrs. Shearer, Smith & Co., at Dalbeattie. The abutments are of heavy freestone masonry, 7 feet thick, with granite blocks for carrying the girders.

The superstructure for each of the spans consists of two main girders, with cross girders resting on the bottom booms; the rails are carried by small longitudinal girders between the cross girders:

the girders are not continuous. Those for the three large spans are of similar construction; there are two girders for one span 199 feet long; two $177\frac{1}{2}$ feet long; and for the third span, one

FIG. 1.

girder $165\frac{1}{2}$ feet, and the other 162 feet long. These girders are 20 feet deep, measuring to the inside of the plates, the only difference in the several spans being in the number of plates.

The top and bottom booms consist of horizontal plates 3 feet broad, with three vertical plates 2 feet deep by $\frac{1}{2}$ inch thick; on each side of the vertical plates there is an angle-iron, 4 inches by 4 inches by $\frac{5}{8}$ inch. In the centre of the bottom boom of the longest girders there are twelve plates and one angle-iron, of an aggregate thickness of $6\frac{5}{8}$ inches; and in the centre of the top boom there are ten plates and one angle-iron, of an aggregate thickness of $5\frac{5}{8}$ inches.

The struts and ties are placed at an angle of 45° . There are four sets of lattice bars. Each strut and tie consists of three parallel sets of angle-irons and plates, fastened to the main vertical plates, to which they are attached alternately on the inside and on the outside, so that there is no difficulty at the crossing points. The

struts and ties at the ends consist of six angle-irons, 4 inches by 4 inches by $\frac{5}{8}$ inch, and three flat bars 8 inches by $\frac{1}{2}$ inch, and diminish at the centre to six angle-irons, $3\frac{1}{2}$ inches by $3\frac{1}{2}$ inches by $\frac{3}{8}$ inch; the struts and ties for the three large spans are exactly the same, working from the centre of each girder, and are stopped short to suit the respective lengths of the girders, special end-pieces being constructed for each girder.

One end of each of the girders of the three long spans rests upon a roller bed-plate, and the other upon an ordinary cast-iron bed-plate sunk into the granite.

With an aggregate thickness of plates such as has been mentioned, punching the metal for the rivets would have been out of the question; moreover, Messrs. Blyth and Cunningham have for many years insisted on all ironwork executed for them being drilled. According to the specification for this viaduct, the contractor was bound either to bolt all the plates together and to drill them through, or to drill one plate and then use it as a gauge to which the other plates were to be bolted and then drilled. The contractors adopted the former method, and to enable them to do the work efficiently they invented machinery for the purpose, which, in the Author's opinion, marks a new era in the construction of wrought-iron girders.

After all the plates had been planed, the bottom and top booms of the main girders were built up at the contractor's yard exactly as they were to be erected, with their proper camber. They were laid on strong timber beams, and the plates were kept in place by cast-iron blocks, and were all bolted together. The position of one row of rivet holes was then carefully marked on the girder. When this had been done, two drilling machines started, one at the end and the other at the centre of the girder, and they travelled along the girder on rails laid parallel to it, and drilled every hole that was necessary. In the main girders there are nine rivet holes in the section of each boom—six vertical holes through the horizontal plates and angle-irons, and three horizontal holes through the vertical plates and angle-irons; and they were all drilled simultaneously, the machine being provided with six vertical and three horizontal drills. Each machine needed three men to attend to it, and, after moving once along the boom, the whole was ready for riveting.

For the cross girders smaller machines of a lighter description were constructed, as they were not required to drill so many plates. The cross girders were built on their sides, and completed at once. All the plates, and angle-irons and web were clamped together in

a similar way to the main girders. There are five holes in the section of each boom—four through the plates and angle-irons, which were drilled horizontally, and one hole through the angle-irons and web, which was drilled vertically. Two men only were required to work each of these machines. Each cross girder (which has about seventeen hundred and fifty rivets, and five thousand four hundred holes pierced) was completely drilled in about three days. These machines secured excellent work, as they prevented variation in the size of the holes, and ensured the holes being drilled in a direct line.

In addition to this drilling machine the contractor invented a portable hydraulic riveting machine, with which the whole of the riveting was done. The cross girders were riveted up entirely at the works, and the main girders were built in position and riveted there. The machine, which is of steel, and weighs about 6 cwt., was suspended from an ordinary crane, and applied to any desired rivet. The water was conveyed from the accumulator to the cylinder through an indiarubber tube, which when tested did not burst until a pressure of 2,700 lbs. per square inch had been applied. The force applied to the rivet was equal to a pressure of 25 tons. About fifteen hundred rivets per day were put in with each machine.

The results showed, beyond a doubt, the great superiority of drilling over punching, and that with the same section a greater margin of strength can be obtained. The Author believes that, in sections involving a large number of plates, drilling is more economical than punching; and that even where only a small number of plates has to be riveted together, any additional cost of drilling will be fully covered by the reduction rendered possible in the size of iron.

The main girders for the span across the Broomielaw, which are 100 feet 6 inches and 94 feet long, are of similar section to those of the larger spans; and the girders for the span across Clyde Place, which are 68 feet 6 inches long, are also similar, but without the centre vertical plate and angle-irons. These latter girders are 10 feet deep, and the diagonal bracing consists of two sets of lattice bars. In the Broomielaw span there are three stiffeners, and in the Clyde Place span one vertical stiffener. They consist of four angle-irons 4 inches by 4 inches by $\frac{5}{8}$ inch, with a web $\frac{3}{8}$ inch thick between them.

The cross girders are 10 feet apart from centre to centre, being placed at every point of junction of the diagonal bracing of the main girders. They are supported on angle-irons, 4 inches by 4 inches by $\frac{5}{8}$ inch, riveted to the outside and inside vertical plates

of the main girders. They are ordinary plate girders, having the lower boom fish-bellied, 4 feet deep at the centre and 1 foot $4\frac{3}{4}$ inches deep at the end. They are 18 inches wide, and each boom consists of two plates $\frac{5}{8}$ inch thick, with two angle-irons, 4 inches by 4 inches by $\frac{5}{8}$ inch, with a web $\frac{5}{8}$ inch thick between them. The cross girders are connected by wrought-iron cross bracing. Small longitudinal girders, or rail-bearers, are carried between the cross girders, alternately 4 feet 10 inches and 6 feet apart from centre to centre, immediately underneath the rails. Each rail-bearer is formed of two small independent girders, placed about 6 inches apart, and measuring together when so placed 1 foot 3 inches across the top. They are 1 foot 6 inches deep; and the girder consists of two angle-irons, 4 inches by 4 inches by $\frac{5}{8}$ inch, with a web $\frac{5}{16}$ inch thick connecting them. Angle-irons 4 inches by 4 inches by $\frac{5}{8}$ inch are fastened to the cross girders to which the rail-bearers are riveted.

Special cross girders, similar to those described but shorter, are placed between each pair of piers. These do not rest on the girders, but on bed plates sunk into the piers. Rail-bearers were constructed to suit the different lengths between the cross girders at the piers. They were left until the cross girders were all in position, so that their proper length could be ascertained by measurement.

The flooring of the viaduct is formed of Mallet's buckle plates $\frac{1}{4}$ inch thick, laid with the convex side downwards; and the rails are carried on timbers 1 foot 3 inches wide by 8 inches thick, placed immediately above the rail-bearers, and held in position by angle-irons on both sides, 5 inches by 3 inches by $\frac{1}{2}$ inch, riveted to each cross girder.

The tops of the girders over the river are connected by cross-bracing, 20 feet apart. These braces are light lattice girders, having the upper boom fish-bellied. They assist to stiffen the viaduct; but the object for which they were erected was to support smoke boards, which were erected, at the instance of the Clyde Trustees, to prevent sparks flying on to the shipping below. The smoke-boards consist of sheet iron, $\frac{1}{4}$ inch thick.

The iron, both in compression and in tension, was calculated for a strain of 4 tons to the square inch, except the struts, which were calculated for a strain of 3 tons to the square inch; but in those parts of the girders in compression the area of the rivet holes was included in the available section.

Cast-iron arches (Fig. 3) have been placed for ornament between each pair of piers on the river; they were dispensed with on the land piers as interfering with the headway.

Staging for sinking the cylinders was erected simultaneously on the north and south sides of the river; but before the staging for erecting the girders over the centre span was put up, that on the north side of the river was removed, so as to allow a free passage for vessels to the quays above.

The contract was let in May 1876, and on the 30th of October following the first cylinder had been sunk. The last of the cylinders was sunk on the 5th. of October 1877, and the whole work was finished by the 1st of October 1878.

The total cost of the viaduct, including a few extras, was £64,400. The cost of sinking the cylinders on land was £3 17s. 6d. per lineal foot, or about 15s. 9d. per cubic yard of stuff excavated; and of sinking the cylinders in the water £4 11s. 9d. per lineal foot below high water, or about 18s. 6d. per cubic yard of stuff excavated.

Each of the longest girders for the centre span weighs about 177 tons, and each cross girder weighs about 7 tons 13 cwt. The total weight of wrought iron in the viaduct is 2,110 tons, which cost, including all staging and erecting, £16 10s. per ton. There are 1,350 tons of cast iron, costing £8 10s. per ton.

The area of the viaduct is 3,709 superficial yards, so that the cost is about £17 7s. 3d. per superficial yard; or, adding the money paid by way of compensation to the Clyde Trustees and Bridge Trustees, the total cost per superficial yard is £43 2s. 3d.

In the Paper read before the Institution on "The City Terminus Extension of the Charing Cross Railway,"¹ the cost of the Charing Cross and Cannon Street viaducts, which are works of a similar description to that which has just been described, are given respectively as £18 and £24 15s. per superficial yard; so that, notwithstanding the extra expense incurred by sinking the piers of this viaduct to the rock, the cost compares favourably with that of the viaducts across the river Thames.

The works were designed by Messrs. Blyth and Cunningham, of Edinburgh, and were carried out under the immediate superintendence of the Author—Messrs. Wm. Arrol and Co., of Glasgow, being the contractors.

The communication is illustrated by drawings and photographs, from which certain figures have been selected for reproduction, and Plate 6 has been engraved.

¹ *Vide* Minutes of Proceedings Inst. C.E., vol. xxvii., p. 410.

APPENDIX.—TABLE SHOWING THE TESTS APPLIED ON THE 17th of JUNE, 1873, by Major-General HUTCHINSON, R.E., Assoc. Inst. C.E., ON BEHALF OF THE BOARD OF TRADE, TO EACH OF THE THREE LARGER GIRDERS, WITH THEIR RESULTS.

	Number of Engines on Span.	Total Length of Engines.		Total Weight of Engines.		Weight on Span.	Lines Loaded.	Lines Unloaded.	Deflection.		Deflection.
		Feet.	Ins.	Tons.	Cwt.				West Girder.	East Girder.	
North Span. — Clear span of West Girder, 149 feet. Clear span of East Girder, 152 feet 6 inches . . .	4	157	4	207	0	201	I.	II, III, IV.	Feet.	Feet.	0·020
	8	314	8	414	0	402	I, II.	III, IV.	0·025	0·025	0·025
	12	472	0	621	0	603	I, II, III.	IV.	0·050	0·050	0·050
	16	629	4	828	0	804	I, II, III, IV.	..	0·075	0·075	0·100
	12	472	0	621	0	603	II, III, IV.	I.	0·045	0·045	0·090
	8	314	8	414	0	402	III, IV.	I, II, III.	0·025	0·025	0·070
	4	157	4	207	0	201	..	I, II, III, IV.	0·005	0·005	0·050
	..	..	..	..	..	..	..	..	..	..	..
Centre Span. — Clear span of each girder, 186 feet	5	204	9	270	16	248	IV.	II, III.	0·030	0·030	0·060
	10	409	6	541	12	496	III, IV.	I, II.	0·050	0·050	0·100
	15	614	3	812	8	744	II, III, IV.	I.	0·090	0·090	0·120
	20	819	0	1,083	4	992	I, II, III, IV.	..	0·150	0·150	0·150
	15	614	3	812	8	744	I, II, III.	IV.	0·150	0·150	0·100
	10	409	6	541	12	496	II, III.	III, IV.	0·050	0·050	0·100
	5	204	9	270	16	248	I.	II, III, IV.	0·090	0·090	0·030
	..	..	..	..	..	..	..	I, II, III, IV.	0·050	0·050	0·020
South Span. — Clear span of each girder, 164 feet 6 inches . .	5	204	9	270	16	219	I.	II, III, IV.	0·040	0·040	0·020
	10	409	6	541	12	438	I, II.	III, IV.	0·070	0·070	0·050
	14	566	10	748	12	571	I, II, III.	IV.	0·090	0·090	0·100
	19	771	7	1,019	8	790	I, II, III, IV.	..	0·090	0·090	0·140
	14	566	10	748	12	571	II, III, IV.	I.	0·065	0·065	0·120
	9	362	1	477	16	352	I, II, III, IV.	I, II, III.	0·040	0·040	0·070
	5	204	9	270	16	219	..	I, II, III, IV.	0·010	0·010	0·050
	..	..	..	..	..	..	..	..	..	..	..

NOTE.—The viaduct has four lines of rails which are numbered in the foregoing Table from west to east, I., II., III., IV. respectively.

THE CLYDE VIADUCT. ON THE CALEDONIAN RAILWAY.

PLATE 6.

Fig. 1.

Fig. 3.

ELEVATION

CROSS SECTION

Fig. 2.

PLAN.