January 30, 1866.

JOHN FOWLER, President,
in the Chair.

No. 1,114.—“The Craigellachie Viaduct.”¹ By WILLIAM
HEMINGWAY MILLS, M. Inst. C.E.

THE viaduct constructed for the purpose of carrying the Morayshire Railway over the River Spey, at Craigellachie, Banffshire, is about 15 miles distant from the sea, and consists of four spans, three of 57 feet each on the north bank, and one of 200 feet over the main channel of the river. The works throughout have been constructed for a single line only.

The Spey is one of the largest and most rapid rivers in Scotland; from its rise amongst the Grampian range, till it falls into the sea at the village of Garmouth on the east coast, it is about 110 miles in length, with a fall of upwards of 1,100 feet, and for the 10 miles immediately above the viaduct, the average fall is 1 in 380, or about 14 feet per mile. No portion of the river is navigable for boats, but it is much used for the conveyance of timber, in which a large trade is carried on both for home purposes and for export. The logs or planks are formed into rafts from 40 feet to 50 feet long, and from 20 feet to 30 feet broad, and are floated down to the sea-coast for shipment, or to intermediate points for loading into railway trucks. Not only is the river very rapid, but it is also subject to sudden and heavy floods, for, rising at a great altitude above the sea-level, it receives, early in its course, the drainage of more than 1,000 square miles of mountain range. Numerous rivers of considerable magnitude join it on its way down to the sea, and other tributaries and mountain streams add to its volume, so that at times it will rise as much as from 6 feet to 10 feet in as many hours; and in the summer or autumn, when swollen by heavy rains, it becomes a perfect torrent, frequently bringing down trees, logs from partially-formed rafts, and debris of all kinds; these, acquiring great force from their velocity, tear away the river bank, and destroy any works which are not of a most substantial character. A winter flood, caused by a sudden thaw, after a severe frost and heavy snow, brings large, irregular blocks of ice down with the current, in addition to

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

the increased volume of water. At ordinary seasons the channel is about 180 feet broad, and 4 feet deep in the centre.

In designing the viaduct, it was necessary to comply with two points: first, to leave the full channel free for the passage of rafts, and, secondly, to construct, in a massive and substantial manner, the parts exposed to the action of the floods, so as to resist the blows and pressure of the blocks of ice, or the floating timber. The main span is 200 feet in the clear, with a height, from the ordinary water-level to the underside of the girders, of about 20 feet. Of the three remaining spans, each of 57 feet, two are for the passage of flood waters, so that including these with the large span, there is altogether a waterway of about 300 feet. The piers and abutments are of solid ashlar masonry throughout; while the north river bank, upon the upper side of the viaduct, is protected by means of a pitched slope of 3 to 1, the bottom course being secured with short piles and walings.

For the first 9 feet below the bed of the river, the stratum consists of coarse gravel interspersed with large, irregular boulders; after which there is a compact layer of gravel and clay. These boulders vary in weight from 2 cwt. or 3 cwt. to 4 tons or 5 tons each, and are so numerous as to preclude the possibility of advantageously employing an ordinary timber pile coffer-dam. Under these circumstances it was decided to use plain cast-iron cylinder foundations for the river piers and the main abutment, and thick beds of concrete for the land pier and abutment. By this arrangement the foundations proved simple, substantial, and efficient.

The outside diameter of the cylinders in the main pier and abutment is 5 feet, and of those in the small river pier 4 feet 3 inches. The cylinders are in two lengths, each of 6 feet 9 inches, which, when bolted together, form one complete cylinder, 13 feet 6 inches long. The general thickness of the metal is $\frac{7}{8}$ ths of an inch; the lower or penetrating edge of the cylinder being made $\frac{1}{2}$ an inch thick, increased gradually to $1\frac{1}{4}$ inch thick, at 4 inches from the bottom. In the smaller of the river piers there are eleven cylinders, in the main abutment fifteen, and in the main pier eighteen; those composing each group being placed as close together as practicable, and all are carried down until the lower or penetrating edge is 13 feet 6 inches below the bed of the river. Before sinking any of the cylinders, the gravel and materials upon the surface at the site of the piers and abutments were removed as far as the water-level. A sufficient space was then enclosed and protected from the ordinary current and flood waters, by means of double rows of small piles and planking, together with bags of clay puddle, placed between and behind them, the piles being driven as close together as the boulders would permit. The enclosed space was next cleared to about 4 feet below the ordinary water-level, the water

being pumped out by means of a centrifugal pump, worked by an engine of 12 H.P. The first of the cylinders was then fixed in position. Two hand-pumps, each worked by two men, were sufficient to keep the cylinder clear of water, while a labourer inside excavated the gravel and boulders, emptying the material into boxes, which were lifted by means of a crane. The first cylinder, when thus lowered into position, as far as the ordinary water-level, was used as a well in pumping out the enclosed area. The main pipe of the centrifugal pump was lowered into this cylinder well, and was found sufficient to keep the enclosed space comparatively free from water.

The remainder of the cylinders in the piers and abutments were in the same manner successively lowered into position, but the main body of water being kept down by the centrifugal pump, only one hand-pump was now found necessary. When fairly sunk to the required depth, all the cylinders, and finally the cylinder well, were pumped dry, the ground at the bottom made firm by punning, and the interior filled with concrete in layers. The centrifugal pump was now transferred to an amended position, and the enclosed area pumped dry. The spaces between the tops of the cylinders were then punned and secured with strong squared pitching 18 inches deep, well grouted with lime mortar, at the level of the upper edges of the cylinder. Pumping was continued for a day or two, as a measure of precaution, and to accelerate the hardening of the concrete before the masonry was commenced. The rate of sinking varied considerably, according to the nature of the obstacles encountered, much time being occupied in breaking up with wedges some of the large boulders. The weight of the cylinder, together with that of the framework attached for hand-pumps and men, was generally found sufficient to cause it to descend as the ground below was excavated. Occasionally, however, an additional weight became requisite.

The foundations for the land pier and abutment were carried on in the same way as those of the river pier, and were filled in with a bed of concrete 4 feet thick, brought up in layers, and carefully levelled.

The masonry is of dark red freestone, with the exception of the main girder blocks, which are of granite. The lower foundation course is 2 feet in thickness, and is composed of stones having a large superficial area, many weighing 3 tons. Great attention was paid in arranging this course, so as to get the best distribution of weight over the cylinders. The second foundation course is 16 inches, and the third 14 inches thick; those in the remainder of the work ranging from 13 inches to 11 inches in height. The face of all the outer stones is left rough or rock-faced, with a marginal draft of 1 inch all round. The coping and mouldings

are of dressed ashlar. All the masonry is firmly bedded in good lime mortar, the joints on the face being pointed with Portland cement. The main pier and abutment are 12 feet thick below the coping, and the small piers and land abutment 6 feet thick, with a batter of 1 inch to 1 foot. The three piers have each a pointed cut-water upon the upper or stream side, with a batter of 1 inch to 1 foot.

The girders are of wrought iron 17 feet apart from centre to centre, and carry the railway on the lower flange. For the 57 feet spans, ordinary boiler-plate girders 5 feet deep are used. The vertical plates are $\frac{3}{8}$ ths of an inch thick at the supports, diminishing gradually to $\frac{1}{4}$ of an inch at the centre; and are the full depth of the girder, and in widths of 3 feet. T iron, $4\frac{1}{2}$ inches by $2\frac{1}{2}$ inches by $\frac{1}{2}$ inch, is securely riveted on both sides at the vertical joints. The top and bottom flanges, which are alike in section, consist of double angle irons, 4 inches by 4 inches by $\frac{5}{8}$ ths of an inch; and a horizontal plate, 18 inches by $\frac{1}{2}$ an inch, all riveted together and to the vertical plate, with $\frac{3}{4}$ -inch rivets. The joints both of the angle irons and flange plates, which are arranged so as to occur alternately, are strengthened with double angle-iron joint covers and joint plates.

The girders for the one clear span of 200 feet are on the lattice principle, the depth being 17 feet 4 inches, and the width across the top and bottom flanges is 3 feet. The portion of the girders immediately over the main pier and abutment has a vertical web of boiler plate $\frac{3}{8}$ ths of an inch thick, the tension and compression bars being riveted on each side. The plates are of the full depth, and in widths of 3 feet, the vertical joints being secured by T irons, 5 inches by 3 inches by $\frac{5}{8}$ ths of an inch, riveted on each side. The top member of the girder, which is horizontal for the 200 feet, is curved at the supports with a radius of 12 feet, the full section at that place being carried down until it unites with the bottom member. The top and bottom members, which are T shaped, and similar in section, but inverted as to position, consist of horizontal plates 3 feet wide, in lengths of 12 feet, with alternate joints; to these a vertical plate, 16 inches by $\frac{5}{8}$ ths of an inch, is connected in the centre by means of two angle irons, 4 inches by 4 inches by $\frac{5}{8}$ ths of an inch. Upon each of the outer edges of the horizontal plates is riveted an angle iron of similar dimensions. The section is thus composed of horizontal plates, a vertical plate, and four angle irons. Cover plates are used to all the angle irons and vertical plates, and a continuous cover plate, 18 inches by $\frac{5}{8}$ ths of an inch, runs from end to end of both the top and bottom members. Bat plate brackets, 9 inches wide and $\frac{5}{8}$ ths of an inch thick, are placed on both sides of the vertical plate at every 8 feet in the top and bottom members. For each girder a system of single lattice bars

is used. These are placed at an angle of 45° , and are, in horizontal measurement, 4 feet apart from centre to centre. The angle irons, of which the lattice bars consist, vary in section according to their position and relative strain. The lightest, in the centre, is 5 inches by $3\frac{1}{2}$ inches by $\frac{1}{2}$ an inch; the end tension bars are 5 inches by $3\frac{1}{2}$ inches by $\frac{3}{4}$ of an inch, and the end compression bars are double angle irons, one 5 inches by $3\frac{1}{2}$ inches by $\frac{3}{4}$ of an inch, and the other 4 inches by 3 inches by $\frac{1}{2}$ an inch. The lattice bars are riveted to the vertical plates of the top and bottom members, with a number of rivets equivalent to the necessary section. At the intersection of the bars nearest the abutment and pier, large malleable iron washers, 8 inches by 8 inches by $\frac{5}{8}$ ths of an inch, are placed, and securely fastened with five rivets; the remainder of the lattice bars have a washer 3 inches square and $\frac{5}{8}$ ths of an inch thick, with one rivet in the centre.

The cross girders, which are of wrought iron, and placed 4 feet apart from centre to centre, from end to end of the entire viaduct, are 12 inches in depth, the ends taking their bearing on the angle irons at the vertical plate. The top and bottom flanges consist of double angle irons, 3 inches by 3 inches by $\frac{1}{2}$ an inch, securely riveted to a vertical web of boiler plate, $\frac{1}{4}$ of an inch thick. The angle irons are carried down at the ends, and form an upright bracket, by which the cross girders are riveted to the vertical plate; a packing plate, of the same thickness as the angle iron, being placed between the end of the cross girders and the vertical plate.

The lattice girders are held together laterally by means of five wrought-iron diaphragms, one being placed at each point of support, one in the centre, and the two others at intermediate distances. These diaphragms are strong frames, of the full depth of the girder, 17 feet 4 inches. The lower member of each diaphragm is similar to a cross girder, but is only 10 inches deep; being thus constructed in order that no portion of the weight of the structure or passing load can be brought upon it, so as in any way to interfere with its duty as a stiffening frame. It is riveted to the vertical plate of the main girder in a similar manner to the cross girders. The vertical members are each divided into two pieces 18 inches broad, placed upon both sides of the series of lattice bars, and are securely riveted together from the top to the bottom. The top member of the diaphragm is 1 foot 4 inches deep in the centre; it is riveted to the vertical plate of the top web of the main girder, and by means of a large plate, 4 feet by 3 feet by $\frac{1}{2}$ an inch, to the main horizontal plates of the top web also. The upper and lower members of the diaphragms are elliptical on the inner outline, gradually joining the perpendicular lines of the vertical members. All the boiler-plate and angle-iron joints are strengthened with suitable cover plates.

The lattice girders and the plate girders for the three small spans are riveted together at the main pier, and thus form one continuous system of girder from end to end of the viaduct. At the main pier the girders are bolted down to the masonry, while at the other piers and abutments the girders rest upon turned cast-iron rollers.

The rails are carried upon two longitudinal timbers, 14 inches by 7 inches, bolted to the cross girders with $\frac{3}{4}$ -inch bolts. The centre and side planking is 2 inches thick, and is nailed on to cross pieces, 6 inches by 3 inches, which are bolted to the cross girders. Longitudinal spaces of $\frac{3}{4}$ of an inch are left between the side planking. The centre planking is laid close, and covered, almost to the rail level, with strong gravel and broken stones.

The holes for the rivets were in general punched from carefully prepared iron-pattern plates, but in the more important parts, such as the intersections of lattice bars, bolt holes, &c., the holes were drilled.

In the erection of the 57-foot girders no scaffolding was used. These were simply riveted on the ground, and lifted by cranes into position on the small piers and abutment. For the lattice girders a strong temporary wooden bridge, or scaffolding, was constructed for the full length of the span from the main pier to the abutment. The space of 200 feet was divided into six openings of 25 feet each, and one opening of 42 feet for the passage of rafts.

The excavations were commenced May 17th, 1862, and the first cylinder was put into position on July 30th following. The sinking of the cylinders was carried on day and night, every effort being used to get this part of the work finished as soon as possible, both for avoiding risk of damage to the foundations, by flood waters, and also to save cost of pumping. The last cylinder was filled with concrete November 3rd, 1862. The masonry was commenced June 30th, 1862, and completed November 15th of the same year. The first pile of the service bridge was driven February 7th, 1863, and a line of temporary rails was laid on the top, ready for the conveyance of materials on March 21st. Some heavy floods occurred during the construction of the viaduct, and upon several occasions all progress was suspended for nearly three weeks. When the waters subsided, much time was lost in clearing the site of the foundations, and in restoring the plant, cranes, &c. The first plate of the lattice girders was laid April 6th, and a trial train of engines and wagons was taken over on May 30th, 1863. Much of this expedition was due to the systematic manner in which the girders were first put together at the maker's works. All the parts were there carefully fitted and legibly numbered, so that the pieces, on arriving at the ground, were carried at once to their approximate positions.

In the specification, it was stipulated that the wrought iron should be capable of withstanding a tensile strain of 20 tons per square inch of section. As soon as the angle irons, bars, plates, &c., arrived at the maker's works, specimens were selected, and were subjected to test. The results of several experiments showed, that the average breaking weight of the plates was 22·39 tons per square inch, and of the angle irons 24·16 tons per square inch. The cross girders were tested with a load of 12 tons in the centre, and gave an average deflection of $\frac{3}{8}$ ths of an inch. The lattice girders were built with a camber of $2\frac{1}{2}$ inches on the tressels, rising gradually from the supports. After the girders were completed, with the cross girders, and when the plank-ing and permanent way were laid, the wedges were struck, and the girders left to swing clear. It was then found that the girders had only settled $1\frac{3}{8}$ inch in the centre from their own weight.

At the Government inspection, the viaduct was tested at different speeds, with an arranged train consisting of two engines and heavily loaded wagons, so as to make a moving load equal to 1 ton per lineal foot for the total length of the span. With this load the deflections were found to be as follows:—

First, or land opening of 57 feet,	$\frac{3}{16}$ ths of an inch.
Second ditto	" $\frac{1}{8}$ "
Third ditto	" $\frac{3}{16}$ "
Lattice girders of 200 feet span	" $\frac{7}{8}$ "

There was no permanent set in any of the girders. When testing the lattice girders, the two engines were placed in the middle of the train of wagons, and the deflection was taken when at the centre of the span. The effective sectional area of the bottom member, deducting for cover-plates, rivets, &c., and as approved by the Government Inspector, is 70 square inches, which, worked out for a moving load of 1 ton per lineal foot for the entire span, gives a tensile strain of 4·10 tons per square inch. In a similar manner, the effective section of the top member, without deducting for cover-plate, is 75·74 square inches, which gives a compressive strain of 3·78 tons per square inch.

The weight of iron in the different portions of the work is as follows:—

	Tons.	cwt.	qrs.
Wrought iron in the plates, angle irons, rivets, &c., of the three 57 feet spans	45	13	0
Ditto ditto in the cross girders	22	6	1
Ditto ditto in the roller frames, bolts, &c..	0	14	0
	68	13	1

	Tons. cwt. qrs.		
Wrought iron in the plates, angle irons, rivets, &c., of the lattice girders and plated ends	172	9	3
Ditto ditto in the five diaphragms	15	4	0
Ditto ditto in the cross girders	25	1	0
Ditto ditto in the roller frames, bolts, &c..	0	12	2
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	213	7	1
Cast iron in the bed plates, and in the rollers for the small girders	5	18	0
Ditto ditto for the lattice girders	6	0	0
Cast iron in the cylinders	157	0	0

Of the wrought iron, the weight of the rivets alone amounted to 16 tons 7 cwt., the number used being about 73,500. There were 504 cubic yards of concrete in the foundations, 27,838 cubic feet of masonry in the whole structure, and 1,672 cubic feet of timber in the bearers and planking.

The cost of the whole structure was as follows:—

	£.	s.	d.
Foundations, including excavations, cylinders and sinking, concrete, pitching, and pumping	2,774	1	6
Masonry in abutments and piers	3,642	5	0
Ironwork, &c., in the superstructure of the three small openings of 57 feet each, including girders, cross girders, longitudinal bearers, planking, rollers, bed plates, and painting	1,501	12	0
Ironwork, &c., in the superstructure of the 200-foot span, including lattice girders, cross girders, diaphragms, longitudinal bearers, planking, rollers, bed plates, temporary bridge, and painting	4,281	2	10
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	£12,199	1	4

As the total length of the viaduct is 413 feet, the cost per lineal foot was £29 10s. 9d.

The Engineers were Mr. James Samuel, M. Inst. C.E., and the Author. The contractors for the foundations and masonry were Messrs. Mitchell and Ireland, Montrose; and for the ironwork, &c., including the temporary bridge, Messrs. M'Kenzie, Clunes, and Holland, Worcester.

The communication is accompanied by several drawings.