(*Paper No. 2117.*)

"Viaduct over the River Esk at Whitby, and the Embankments and Culverts in the Ravines."

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On looking through the Proceedings of the Institution of Civil Engineers, the Author has found a marked deficiency in Papers which might serve as guides for the erection of an important brick viaduct, and it therefore occurred to him that a brief description of the work in question might prove of some service to the members of the Institution.

The viaduct forming the subject of this Paper carries the single line of the Scarborough and Whitby Railway over the valley of the Esk near Whitby, and in addition to spanning the river itself, crosses over the main line of the North Eastern Railway Company's Esk Valley Railway, and the Whitby, Redcar, and Middlesbrough Union Railway.

In designing this work it was necessary to provide for a structure, not only thoroughly substantial, but acceptable to the North Eastern Railway Company, and with this view it was decided to follow as closely as possible the general features of the graceful brick viaduct which carries the Cleveland Branch of the North Eastern Railway over the Skelton Beck near Saltburn-by-the-Sea.

The Author desires to take this opportunity of thanking Mr. Thomas Elliot Harrison, Past-President Inst. C.E., the Engineer to the North Eastern Railway Company, for his courtesy in placing at his disposal the drawings of the Saltburn Viaduct. When, however, the design of the Esk Viaduct came to be made, it was found necessary to depart from this type considerably.

The Harbour Department of the Board of Trade required considerable alterations in the plan of the river piers; the North Eastern Railway Company, for the purposes of their two railways, called for other variations; the level of the rails on the viaduct was raised some 20 feet, and these, with the peculiar nature of the foundations, all tended to change the character of the structure.

Borings were taken on the site of each pier and abutment, and in the case of all the piers rock was reached. In the case of the river piers the boring-tool failed to indicate anything except silt between the bed of the river and the rock, so that no difficulty was apprehended with the foundation.

Owing to the proximity of the viaduct to the sea, and the consequent exposure to corrosion, it was decided to avoid the use of ironwork, and to make a solid structure of brick in cement. The arches were designed to be approximately of 60-feet span, and the thickness of the piers at springing-line was kept as small as consistent with strength, their width being at that level 5 feet 6 inches. Piers Nos. 7, 8 and 9 being on the skew, and having unequal thrust, were thickened to 7 feet on the skew, or 6 feet 7 inches on square section at springing-line.

The greatest height from the bed of the river to rail-level is 120 feet. The number of arches is thirteen, and the total length of the viaduct is 915 feet (Plate 9). The land piers were sunk without difficulty by ordinary excavation, and a thoroughly satisfactory foundation upon the rock was secured in all cases, concrete made of broken slag with cement being placed under each pier to distribute the weight.

It was decided to adopt the Indian system of brick wells for the river piers, and as at low-tide there was a depth of only about 5 feet of water in the river, these were placed in position without difficulty.

A wrought-iron cutting edge was provided, the triangular space between the two sides of the shoe being filled with concrete in cement. On the top of this was built brickwork in cement of a cylindrical form on the outside, and corbelling inwards on the inside, until a brick well of 3 feet in thickness of wall was attained. By means of "grabbing" out the inside, the well was gradually sunk, and as it descended brickwork was added at the top.

It was soon found, however, that the "Priestman" grab or digger, although an excellent tool for removing material from the core, was useless for removing it from under the cutting edge, and in consequence of this Messrs. John Waddell and Sons, the Contractors for the railway, and to whose skill and energy the success of the work is greatly due, decided to make use of the grab described in the Paper on the Empress Bridge over the Sutlej.[1] By means of this excellent device the material was most efficiently

[1] Minutes of Proceedings Inst. C.E. vol. lxv. p. 248.

removed and the cylinder sunk some depth. But a much greater difficulty was to be encountered before the cylinder reached the rock, and this was due to a forest of old oak trees buried in the bed of the river. These oak trees were chiefly lying in a horizontal position and were of considerable size, many being from 2 to 3 feet in diameter. They were exceedingly tough and difficult to remove. An endeavour was made to remove these trees by the grab, but the attempt failed, nor could the water be pumped from the cylinders so as to allow them to be excavated in the dry. Dynamite was used, but the fear of injuring the cylinders prevented the employment of heavy charges, and consequently no satisfactory effect was produced.

It was feared that the pneumatic system of compressed air might have to be adopted, but as this should only be used when all other means have failed, Messrs. Waddell and Sons sent an experienced diver to remove the trees under water. The trees were chiefly cut out by saw, the resistance of the water preventing any percussive action being very effectual. When a large tree was encountered by the cutting edge of the cylinder, the diver scooped out a hole underneath, and having got into it, sawed upwards. To do this the diver had frequently to get outside of the cylinder, and when he had cut in as deep as he thought was safe, the chain from the steam crane was attached, and with a strong pull the end frequently broke off; but sometimes the operation had to be repeated.

When the tree was across both cutting edges, the diver had to saw right through at one end, which was very tedious work. One large Scotch fir, in particular, occupied from two to three weeks in being removed. When sawing failed, the chisel and hammer were used, the chisel being a large one, and the hammer having a short handle with a very heavy head. The axe was not much used. The steam crane, a powerful machine, proved very serviceable.

This was hazardous work, as the diver ran a great risk of having the air-tube cut; but so well did he complete his work, that in every case the cylinders were finally bedded on the rock, although in some of the piers the depth of oak timber to be penetrated was as much as 30 feet. Piers Nos. 6 and 10 are somewhat triangular in plan, they being the piers adjacent to the four skew arches over the river. Pier No. 6 had therefore to be differently designed to the others, and for this purpose two brick cylinders 20 feet in diameter were sunk, the interior being filled with concrete in cement.

The behaviour of the brick cylinders during sinking presented some curious features. A cylinder, say, 30 feet down would hang immovable for days, held entirely by the side friction of the silt; this, too, although everything had been carefully cleared away from under the cutting edge, and as deep a hole as possible taken out below it with the grab, and several hundred tons of rails stacked on it. Suddenly, without warning of any kind, when nothing was being done, the cylinder would silently and swiftly sink several feet. These unexpected but welcome subsidences (which were not the rule, however), generally occurred about the half-ebb following a high-tide. Generally the cylinders sank gradually and almost imperceptibly when cleared of the ancient timber. The greatest difficulty encountered was that of keeping the cylinders as they sunk for the first 15 feet vertical and in true position; this difficulty was owing to the buried tree-trunks constantly encountering the cutting edges at one point and tilting the cylinders, an action greatly assisted by the heavy "freshets" to which the river is liable in the autumn and winter months, and the rapid scouring round the cylinders caused thereby. The difficulty was met by careful watching and constant checking, and overcome by weighting the cylinders with rails on their high sides, or even grabbing the river-bed outside to draw them back. When, however, the cylinders had reached a depth of 15 or 20 feet, neither the trees nor the floods disturbed them any more.

It was considered unadvisable to employ pumps during the process of concreting, consequently the concrete was lowered into the water in "pigeon trap" boxes, and, after being by this method deposited at the bottom of the cylinder, it was carefully levelled in and trodden down by the diver. It was found that when a layer of concrete of 4 feet in thickness had been placed in position and allowed to set, the cylinders could be pumped free of water, and the remainder of the concrete put in dry.

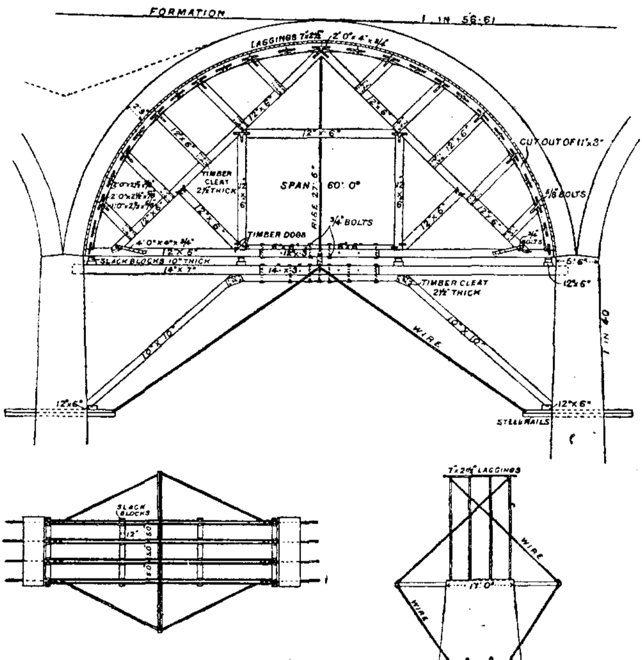
Piers Nos. 5, 7, 8, and 9, each consist of three brick wells 14 feet in external diameter, and all these were sunk and concreted in a similar manner. In the case of pier No. 9, as the cylinders when in permanent position were near the face of the rock in the ancient bed of the river, the gravel and silt in the existing river-bed were removed until the rock was exposed at the face of the pier, and a concrete apron was put in to provide against the possibility of injury from scour in the river.

When the brick cylinders were brought up to above low-water mark, and had been filled with concrete, semi-circular arches were turned between the cylinders, and upon these was constructed a continuous pier of brickwork. In order to ensure the two outside cylinders receiving their proper share of the weight, the pier was tapered upward.

Stone springer-beds were provided for the skew arches, and in these "checks" were cut to receive the various rings of brickwork. The entire structure, with the exception of the haunching of the arches, is built in cement.

The arches are seven rings, 2 feet 9 inches in thickness. The spans vary from 55 to 65 feet, with a uniform rise of 27 feet

Figs. 1.



6 inches. The arches are backed up with brickwork in mortar, which with the arches were coated with asphalt about $\frac{3}{4}$ inch in thickness, laid on in two coats; the intervening space between the brickwork and the permanent-way is filled with clean ashes. Independent centres being necessary, eleven of the arches were thus centred at the same time, the remaining two being provided with the centres of arches Nos. 1 and 2.

Figs. 1 represent the description of centre employed. This was of pitch pine, and consisted of four ribs; each rib was carried on

x 2

a foot-beam built into the piers at the end, and these foot-beams were further strengthened by diagonal struts from the piers, in which lengths of steel rails were built for the purpose. Lateral stability (until the weight of the arches came on) was obtained by steel-wire ropes, secured by tightening screws to anchor piles driven into the ground.

In consequence of the exposed position of the viaduct, it was necessary that all the arches should, when once commenced, be keyed in as quickly as possible. The brickwork of the arches was commenced on the 13th of May, 1884, and the last arch was keyed in September of same year.

The width of the viaduct between the parapets is 14 feet 6 inches on the straight, and 15 feet on the curve.

The parapets are 4 feet 6 inches in height above the rail, and are 18 inches in thickness.

Refuges for the plate-layers are provided over each pier.

The quantities of work in the structure are as follow :—

	Cubic yards.
Excavation in foundations of abutments and land piers .	3,446
,, cylinders and apron	3,726
Concrete in cement in foundations	1,733
,, ,, cylinder and apron	1,444
Brickwork in cement ($1\frac{1}{2}$ to 1) in cylinders and jack arches	2,887
,, ,, (4 to 1) in interior of cylinders . .	206
,, ,, 6 to 1	7,170
,, ,, in arches.	2,698
,, lime in haunching	976
Ashlar in springers of skew arches and coping	2,627 cub.ft.
Timber.	1,473 ,,
Ironwork in drain-pipes, &c.	17 cwt.
Ashes, filling-in of spandrels	1,248 c. yds.
Total number of bricks in structure about	5,000,000
	Tons.
,, weight of entire structure	25,700
Pressure per square foot on cylinders at level of river bed .	$3\frac{1}{2}$
,, ,, ,, bottom	$5\frac{1}{3}$
,, ,, brickwork at springing of arches	7·9
,, ,, ,, crown ,,	3

For the purposes of calculating the stability of the structure under wind-pressure, an isolated pier, No. 4, with its two adjacent half-arches, was taken, and over the whole surface of the structure, including a passing train, a pressure of 56 lbs. per square foot was assumed. The results are as follow :—

	Foot-tons.
The moment of stability	= 21,600
And the moment of overturning	= 5,037
Giving a factor of safety of	4·28

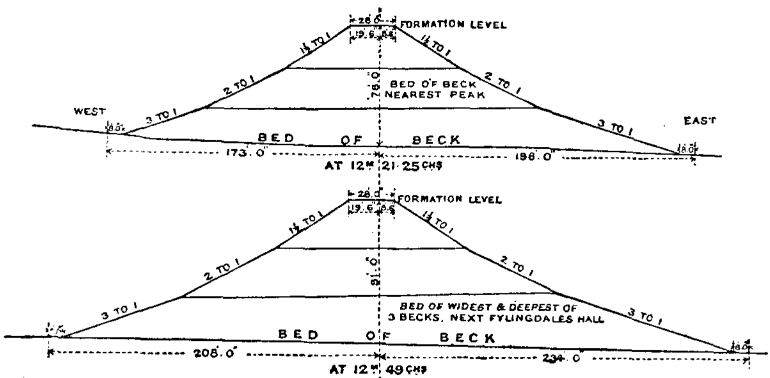
In the above no credit has been taken for the horizontal continuity of the structure, which in fact acts as a girder, held at each end by the abutments, thus offering great resistance to any horizontal force.

The first spadeful of earth was turned in the foundations early in October, 1882, and the first engine ran on the bridge on the 24th of October, 1884, a period of a little over two years.

The whole structure was completed without the loss of a single life. Only two serious accidents occurred to the men employed; both were falls from the piers, and both men recovered.

On the same railway several deep ravines had to be crossed; and, as the formation is glacial drift, it was decided to fill these with solid embankments rather than run the risk of the bad

FIGS. 2.



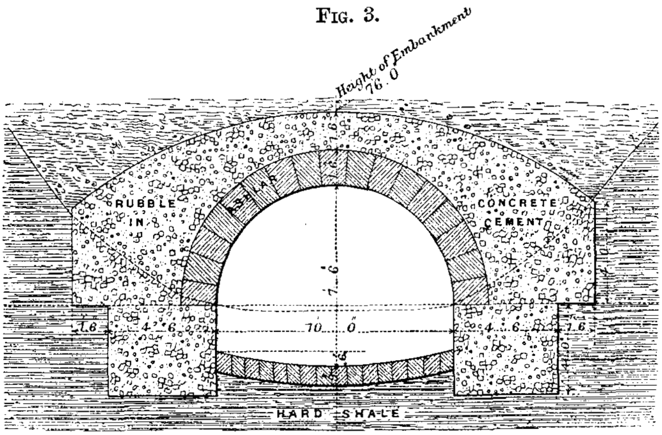
foundations which would have been encountered had viaducts been adopted. The height of one of these embankments was 85 feet on the centre line (or 100 feet at the lower foot of the slope), and others were 76 feet and 74 feet.

To avoid risk of slips, these embankments were tipped with varying slopes. Thus for the bottom third of the height the slopes are 3 to 1, for the middle third 2 to 1, and for the remaining or upper third $1\frac{1}{2}$ to 1. This precaution was fully justified by the treacherous character of the clay, and the result has been most satisfactory.

Cross-sections of two of the ravines or becks are shown by Figs. 2.

The culverts for these high embankments gave rise to much careful investigation. The largest is that carrying Mill Beck, Fig. 3; it is 10 feet in width, with a height of 7 feet 6 inches, the height of rails above the invert of the culvert being 86 feet. The barrel of the arch consists of ashlar masonry 18 inches in

Fig. 3.

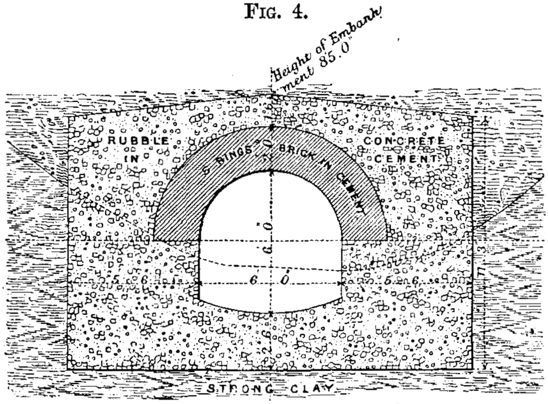


13 M. 38 CHS MILL BECK.
A deep & narrow gorge, with perpendicular Shale sides, fall 1 in 55, Length of Culvert 330.0

Scale 8 Feet = 1 Inch.
Inches 12 6 0 5 10 20 *Feet*

thickness, strengthened by a covering of rubble concrete in cement. Owing to the liability of heavy floods, an invert 9 inches in thickness was provided. The length is 330 feet.

Fig. 4.



12 M. 47 CHS ALLISON HEAD BECK.
A wide & deep ravine, with treacherous slipping sides of a slope of 2½ to 1 fall of beck 1 in 34, Length of Culvert 375.0

In the case of the Allison Head Beck (Fig. 4), the height of the rails above the invert of the culvert is 95 feet. The arch is 6 feet span, with five rings of brick in cement, protected by a covering of rubble concrete in cement. The length is 375 feet.

Screens of iron rails are provided above the upper entrance to these culverts, for the purpose of intercepting trees and débris.

In carrying forward the high embankments from each side of the ravines, the precaution was always taken of previously covering the culverts from end to end with a depth of from 20 to 30 (or even more) feet of earth, tipped down a spout and wheeled forward over the culvert. This was to protect the culvert from the side-long thrust and irresistible "ploughshare" action of the advancing toe of the embankment in the soft and treacherous ground. The becks crossed were generally of a steep gradient, and had very steep slopes, heavily wooded; hence it was necessary not only to provide for permanently, but to contend with several times whilst the culverts were in progress, floods which would convert in an hour a trickling rivulet into a raging torrent 3 or 4 feet deep, carrying along with it a mass of débris, gravel, and boulders. The foundations of the culverts were everywhere taken down to rock or strong clay, and the faces protected by pitched aprons and wing-walls.

Mr. Charles Arthur Rowlandson, to whom much of the credit of the work was due, was the Resident Engineer. The Contractors, Messrs. John Waddell and Sons, were well represented by Mr. Percy N. Meares.

The Paper is illustrated by several drawings, from which Plate 9 and the Figs. in the text have been prepared.

ELEVATION FROM THE EAST, LOOKING SQUARE TO CENTRE LINE.

(Section of Ground being taken at Centre Line.)

Scale: 40 Feet = 1 Inch.