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Summit-Level Tunnel of the Bettws and Festiniog Railway."

By WILLIAM SMITH, M. Inst. C.E.

THE object of the Bettws y Coed and Festiniog extension of the branch which leaves the main line of the Chester and Holyhead section of the London and North Western system at Llandudno Junction near Conway, was to afford more direct railway communication between the slate-producing district of Festiniog and the home markets. The only previous connection was over the Festiniog narrow-gauge line to Mynfford Junction near Portmadoc, where there is a break of gauge; and thence, southward, by the Cambrian through Barmouth; or, northward, to Afonwen Junction, and over the London and North-Western through Carnarvon. Commencing at Bettws y Coed the new line traverses the valley of the River Conway in a southerly direction for about 1 mile; it then curves to the westward and follows the valley of the River Lledr, the gradients varying, but generally ascending to the summit-level, where, by means of a long tunnel, it passes under the mountainous ridge which divides the counties of Carnarvon and Merioneth. It afterwards crosses over and runs alongside the Dinas branch of the Festiniog narrow-gauge line with a descending gradient, and terminates at Blaenau Festiniog, betwixt Rhiwbrifdir and Duffws. The line, which except at the stations has been laid with a single way, is about 12 miles in length. The principal works consist of five short tunnels through rock, a viaduct over the turnpike road and River Lledr, 352 yards in length and 58 feet above the river bed, a road and river works at Dolwyddelen, a long tunnel, and a terminal works at Blaenau Festiniog. From Bettws y Coed to a point near the north end of the summit-level tunnel the works were carried out by contract; but the tunnel and the short length beyond at the south end were executed by the London and North-Western Railway Company.

The tunnel works (Plate 10, Fig. 1), comprise the sinking of three shafts, the driving of the advanced headings, and opening them out to the full size of the tunnel. The direction of the tunnel is nearly north and south, and, with the exception of a short length at each end, is straight. Its total length is 3,860 yards. A portion at the south end, where it passes through the rubbish from the Welsh Slate Company's quarries, is lined; the remainder is nearly all in solid rock.

FESTINIOG TUNNEL. BETTWS-Y-COED AND FESTINIOG RAILWAY.

PLATE 10.

Fig: 2.

END ELEVATION OF EXPERIMENTAL DRILL CARRIAGE.

Fig: 3.

SECTION OF EXPERIMENTAL DRILL CARRIAGE.

Fig: 1.

Fig: 4.

END ELEVATION OF DRILLING-MACHINE CARRIAGE AT SOUTH END.

Fig: 5.

SIDE ELEVATION OF DRILLING-MACHINE CARRIAGE AT SOUTH END.

Fig: 6.

PLAN OF DRILLING-MACHINE CARRIAGE AT SOUTH END.

DESIGNED BY
J. W. B. & CO. LTD.
4, ABINGDON STREET, COVENT GARDEN

The rocks perforated consist generally of bastard slate, and of other members of the metamorphic system, varying in colour from light grey to dull green, and they are more or less close in the grain. An idea of the hardness of some of the rock may be had from the fact that in boring a hole $1\frac{1}{4}$ inch in diameter and 15 inches in depth by hand-labour, near the south end of the tunnel, sixty drill-points were worn out. The tunnel has an ascending gradient from the north end of 1 in 660 for a distance of 1 mile and 58.4 chains, followed at the summit by a level measuring 0.75 chain, after which commences a descending gradient of 1 in 660 to the south end for a distance of 36 chains. The tunnel is 18 feet 6 inches in height and 16 feet 6 inches in width; but at the south end for a short length, owing to the curve, it was widened out sufficiently to command a view of the south tangent signal. A tangent heading at the north end was driven for a like purpose. The three shafts, each affording access to two headings, together with the two end workings, gave a total of eight working faces. No. 1, the northernmost shaft, is 138 yards 2 feet and 7 inches in depth; No. 2, the middle one, 143 yards 1 foot and 5 inches in depth; and No. 3, the southernmost, 63 yards 2 feet and 10 inches in depth. These shafts are rectangular 12 feet by 6 feet, the longest side being in the direction of the centre-line of the tunnel.

The different faces of operation or headings were, for convenience of reference, numbered: No. 1 was at the north end; Nos. 2 and 3 were at the bottom of No. 1 shaft; Nos. 4 and 5 at the bottom of No. 2 shaft; Nos. 6 and 7 at the bottom of No. 3 shaft, and No. 8 was at the south end.

Four observatories were erected for setting out the tunnel, with the aid of a portable transit instrument. Cart-roads of a total length of $3\frac{3}{4}$ miles were also constructed from the turnpike road to the three shafts and the north and south ends of the tunnel.

The bulk of the rock-drilling was done by machinery driven by compressed air,¹ for which purpose five machines were employed, one at each of the different workings. The compressors at each of the shafts were of double capability to those at the north and south ends, having two faces to feed as against only one face at each end. The air-compressors were driven by steam generated in boilers supplied from the Company's works at Crewe.

At each of the three shafts a portable winding-engine was em-

¹ Minutes of Proceedings Inst. C.E., vols. xxiii., p. 258; xxxvi., p. 1; xlii., p. 228; and lvii., p. 239.

ployed. Part of the coal consumed by the air-compressors and winding-engines was carried by the London and North-Western Railway to Bettws y Coed, from which place it was conveyed to its destination by a 10-HP. traction-engine, and horses and carts; the remainder was carried over the Festiniog narrow-gauge line to a siding at the south end of the tunnel.

A mechanics' shop was built near No. 1 shaft, containing a slide-lathe, planing-machine, upright drill, and other appliances for the repair of the boring- and other tackle, the whole being driven by a small steam-engine apart from the rest of the machinery. Smithies for the sharpening of drill-points, and lesser fitting-shops were erected in connection with the different workings. Licences were taken out for the storage of mixed explosives at seven different points, two of which were for authority to store the maximum 2,000 lbs. allowed under Class D at each point, and the rest for the storage of the maximum 150 lbs. allowed under Class A at each point. Of the many explosives in the market, dynamite, lithofracteur, and cotton-powder or tonite were the only ones extensively used. Tonite answered well for the removal of rocks in comparatively exposed situations; but dynamite and lithofracteur were found the most effectual in the advanced headings and other confined places.

The winding-engines at the three shafts were, as nearly as possible, alike, and the parts were numbered and made to templates, so that they could be readily renewed or interchanged. They were semi-portable, and consisted of a boiler of the locomotive type, two small high-pressure engines mounted on the top thereof, with spur-wheel and pinion and winding-drums. The winding-drum, which was fitted with a brake actuated by the foot of the engine-man, and lagged with wood round the outer surface, was 6 feet in diameter, and the whole was arranged with the view of raising a gross load of 30 cwt. at the rate of 8 feet per second. The coal used was from the neighbourhood of Flint, and the greatest consumption upon the whole works at one time was about 25 tons per day of twenty-four hours.

The head-gearing consisted of a stout timber framing, designed to carry two pulleys, and the necessary supports for the rings in the application of Walker's detaching hook (Figs. 1) for the prevention of overwinding, and the whole was so arranged as to stand clear of the line of the tunnel over the mouth of the shaft. The head-gear pulleys were 8 feet in diameter, with V grooves to suit wire rope, and 6-inch wrought-iron shafts and pedestals to match. The grooves and bosses were of cast iron, and the spokes of

wrought iron. The detaching hook consists of two jaws, each spanning one-half of the shackle-pin at the eye of the wire rope, and held fast by a hoop or thimble sliding over them, the thimble or hoop being kept in place by two copper pins. In the event of overwinding, the detaching-hook with its thimble enters the ring

FIGS.1.

WALKER'S DETACHING HOOK.

Scale $\frac{1}{2}$ Full Size.

fixed in the head-gear frame, the copper pins are shorn off by the thimble, the wire-rope eye with its shackle-pin is set at liberty, and the detaching-hook jaws clutch the fixed ring in the frame. There were several instances of overwinding, and in every case the detaching-hook was perfectly successful. The wire

ropes were made of steel, the breaking-strain being 20 tons. They consisted of six strands, each strand containing six wires; both strands and rope had a hempen core.

The cages were constructed of wrought-iron; they had a floor area of 5 feet by 4 feet 3 inches, and weighed 9 cwt. The top of each shaft was fitted with a catch, to relieve the wire rope of the weight of the cage and its contents on arriving at the surface, and a barricade or gate was so arranged as to be dropped into its place by the descending cage on the open side, and thus prevent persons from falling down.

The air-compressors were all of the same type, and as far as possible from the same patterns; but, as already noticed, those at the three shafts were of double capability to those at the north and south end workings, the former being fitted with an air- and steam-cylinder on each side of the receiver, the latter having but one air- and steam-cylinder, the air-cylinder being fixed on one side, and the steam-cylinder on the other side of the receiver. The receivers were constructed partly of cast iron and partly of wrought iron; the wrought-iron portion was egg-ended, the cast-iron portion was made to perform the double service of receiver-end and fixing for the fly-wheel shaft pedestals. There were two fly-wheels to each compressor, with flat bosses and crank-pins. The steam- and air-cylinders were of 16-inch bore, and 30-inch length of stroke, the piston-rod being carried through both. The fly-wheels were 7 feet 6 inches in diameter, and each weighed about 40 cwt. The cast-iron end of the receiver was bulged out to give additional strength. The wrought-iron portion was 5 feet in diameter; the length from the cast-iron end to the egg-end was 14 feet 6 inches. The air-cylinders had a water-casing to keep them cool fitted with inlet and overflow pipes. These compressors were constructed to run at about 50 revolutions per minute, and to compress, to a pressure of 50 lbs. on the square inch, sufficient air to supply six rock-boring machines at each face. The compressor steam-generators were second-hand locomotive boilers stripped and put in order for this purpose. Some of these boilers were barely equal to the duty required of them. The consumption of coal in those supplying the double-cylinder compressors was from 5 to 6 tons, and in those supplying the single-cylinder compressors from $2\frac{1}{2}$ to 3 tons, per day of twenty-four hours. The pipes for conveying the compressed air were of two sizes, namely $3\frac{1}{2}$ and $2\frac{1}{2}$ inches bore respectively. The larger size was used between the receiver and the bottom of the shafts, and the smaller size from the bottom of the shafts to the faces of the workings. These pipes

were of wrought iron with cast-iron flanges screwed on the end, and faced for the reception of a gutta-percha ring at the joint (Figs. 2). The flanges were thick, oval in form, with holes for two screw-pins only, which were found sufficient to secure a joint of this kind. Cast-iron tee pipes fitted with blow-off cocks and appliances for ventilating and other purposes were provided, and a 30-foot length of flexible tubing completed the connection of the fixed piping with the rock-drill carriage. The shafts admitted of the employment of cages of the kind already described, with room for wooden guide-bars on each side from top to bottom, and space at the end for the air-pipe, and if needed a pump-pipe. At the bottom of each shaft, in addition to an ordinary tramway, roads were laid with the view of carrying on the work uninterruptedly, whether the wagons were from the north or south workings, full or empty, ascending or descending.

FIGS. 2.

AIR-PIPE JOINT.

Scale $\frac{1}{2}$ Full Size.

A sump was sunk at the bottom of each shaft, from which superfluous water was drawn to the surface. The water was raised by a wrought-iron vessel attached to the under-side of the cage, which filled and emptied itself automatically, would carry 10 gallons of water, and weighed when full 2 cwt. This contrivance, although sufficient for the removal of the surplus water from Nos. 2 and 3 shafts, was inadequate at No. 1. Here a force-pump, actuated by compressed air, was substituted with satisfactory results. One hundred and fifty tram-wagons were used for the removal of the débris from the workings. They were built of the form and size adopted with the view of going up and down the shafts on the cages, and weighed when empty about 4 cwt. each.

It was intended to have largely employed rock-drilling machines in sinking; but from the difficulty experienced in drilling at the corners, and making secure the stretcher-bars to which the machines were attached, they were only partially employed, the bulk of the work having been performed by hand-labour. Several modifications of the common stretcher-bar were tried, but the results were not satisfactory.

A sinking frame, designed upon the same principle as the driving frames employed at the headings, might probably be attended with better success. In considering the system to be adopted in driving, an idea occurred to the Author, that if the face of the rock embraced within the cross-section of the tunnel were perforated with a sufficient number of holes of proper size and depth, each charged with a powerful explosive, and the whole fired simultaneously by electricity, the effect would be to break away a slice of rock equal in thickness to the depth of the holes. The boring of the holes by machinery mounted upon a carriage could be done rapidly; it seemed probable that from forty to sixty charges could be fired with certainty; and that a drill-carriage might be constructed, so that, after a blast and the removal of the débris, it could be run forward and recommence drilling whilst the remaining débris was being removed. With such appliances, and practice in the use of them, the Author anticipated that the full-sized tunnel might be cut at once with advantage as to cost, when compared with the usual method; and it was resolved, as an experiment, to try it at the north heading, and, if found to answer at that point, to adopt it also at the south heading.

With regard to the workings at the bottom of each shaft, it was decided to drive a top heading only in the first instance, and by this means to provide an outlet for water, and also for the débris which would come out of the lower half of the section without winding. Pending the decision to be arrived at with an experimental drill-carriage at the north end, a small drill-carriage was constructed at the south end, suitable for an advanced heading only, and put to work. The drill-carriage at the north end was equipped with six Ingersoll machines,¹ fitted with automatic feed, and each carriage at the intermediate faces with six McKean's machines of the St. Gothard pattern, with automatic feed; while the carriage at the south end was equipped with six Burleigh machines, with hand-feed. The total equipment was forty-eight machines, including those in use and those under repair. The experimental

¹ Minutes of Proceedings Inst. C.E., vol. lxi., p. 154.

drill-carriage at the north end (Plate 10, Figs. 2 and 3) consisted of a strong timber frame, fitted with a wrought-iron hood in front, transverse and radial stretcher-bars, with appliances for moving and fixing the same; and a set of four wheels carrying the whole. The sides of the frame and hood were parallel, but the top was semicircular. The transverse stretcher-bar extended from side to side, moved vertically from near the floor to the semicircular part, and was guided by clip pieces at the end, which slid along the angle-irons at the front edge of the hood. The radial stretcher-bar had the same centre as the semicircular part of the hood, to the angle-irons forming the outer edge of which it extended, being fitted with clip-piece and screws. Both transverse and radial stretcher-bars were of cast iron turned smooth, 8 inches in diameter. The transverse stretcher-bar was raised and lowered vertically by two crab-winchs and chains coupled together; and the radial-bar was actuated by an endless screw, which worked into a toothed wheel fixed on the axle. The drilling-machines were mounted upon the stretcher-bars by a wrought-iron clip, and could be moved laterally, and upon them also as a centre, and fastened in any position.

The frame was furnished with a floor on a level with the bottom of the semicircular part, upon which were the crab-winchs actuating the vertical motion of the transverse stretcher-bar, and the appliances for the movement of the radial-bar. The floor also carried the injector water-vessels, air-pipes, spare drills, &c., as well as the men employed in attending to the machines mounted on the radial-bar. At each of the four wheels carrying the frame there was an additional wheel- and pinion-appliance to aid the men in moving it backward or forward. The men attending to the machines mounted upon the transverse stretcher-bar stood upon the floor of the tunnel, except when the holes were too high for them, when they stood upon a narrow platform, which could be attached to the transverse stretcher-bar. The latter was designed to carry four, and the radial-bar two drilling-machines.

The Ingersoll rock-drill, with which the experimental carriage was equipped, consisted of a cylinder, with piston and rod, valve-box, and slide-valve, rotating gear, and automatic feed-motion, mounted upon a frame-plate carrying the whole. The frame-plate was connected to the stretcher-bar clips by a disk joint, and secured in position by screw-pins. The drill-carriages at each of the six intermediate workings were of the type used at the St. Gothard Tunnel, and consisted of a wrought-iron frame upon four wheels, each frame fitted with adjustable

supports for four drilling-machines, air-receiver, flexible tubing, and stop-cocks for regulating the supply of compressed air. In this arrangement there were four arms, or brackets, on each side of the carriage; each arm supported one end of a drilling-machine, and was in itself supported by, and constructed to slide upon, a vertical screw when turned, the screw being held by the framework of the carriage at the top and bottom. The arms at the front of the carriage bore a stirrup, or hollow rest, for the fore end of the drilling-machine to lie upon; and, in addition to the vertical motion of adjustment of the arm, had a sliding movement worked by a screw sideways. The arms at the rear of the carriage held a rest to which the hind end of the drilling-machine was attached by a screw-bolt. This rest had, in addition to the vertical and horizontal movements, another motion whereby the drilling-machine might be made to advance or retire to the extent of several inches. Thus, each of the four supports had an appliance for adjustment in any direction at both ends, each motion of adjustment being separate from, and quite independent of, all the rest. This method of mounting gives great facility for regulating the machines when boring, with the least loss of time. The air-receiver simply acted as a vehicle for the distribution of the compressed air received from the $2\frac{1}{2}$ -inch flexible tube with stop-cock on one side. By this means the air was distributed to the four 1-inch flexible tubes fitted with stop-cocks on the other side, and carried forward by them to each drilling machine. The adjusting screw-heads were all of one size. The McKean drilling-machine, with which the foregoing carriages were equipped, consisted of a cylinder, with piston and rod, valve-box and valve-rotating gear, and automatic feed-motion, mounted upon a frame-plate carrying the whole. The frame-plate at the rear of the machine was flattened and had a hole through it, so that it might, by a screw-bolt, be fastened to the drill-carriage rest. At the front of the machine this plate was rounded so as to fit the hollow of the stirrup in which it was supported.

The drill-carriage used at the south end (Plate 10, Figs. 4, 5, and 6) consisted of a stout cast-iron base or floor-plate supported on four small cast-iron wheels, upon which were fixed two upright cast-iron round posts, 6 inches in diameter, turned smooth and parallel. Upon each of these uprights slid a clip carrying a stretcher-bar 4 inches in diameter and of sufficient length to admit one drilling-machine on each side of the upright. The clips, forming the attachment of the stretcher-bar to the uprights, were raised or lowered along with the stretcher-bars and drilling-

machines by a small crab-winch and chain to each, the chain passing over a friction-pulley at the top of the uprights, and the clips being secured by screw-pins. The machines were attached to the stretcher-bar by a clip and a disk- or plate-joint, so that they might be set in any direction, and they were secured by screw-pins. The carriage was also fitted with an air-receiver, flexible tubing, and with stop-cocks for regulating the supply of air.

The Burleigh drilling-machines, used at the south end of the tunnel, consisted of a cylinder with piston and rod, valve and valve-box, rotating gear and hand-feed, mounted upon a frame-plate fastened to the stretcher-bar by a clip and disk-joint. These were the only drilling-machines in use on the works fitted solely with hand-feed; experience tends to show that from the difficulty of avoiding too much feed and its consequences on the one hand, and too little feed on the other, the automatic is the more satisfactory. The drills were forged out of 1-inch octagon bars of the best cast-steel, one end being made to fit the socket of the drilling-machine reciprocating-bar, and the other being forged to a form suited to the work to be performed, and carefully tempered. They were of various lengths, so that, as soon as the limit of travel of the reciprocating bar had been reached, the bar was drawn back, the short drill removed, and a longer one substituted, this process being repeated until the holes were deep enough.

Of the many forms of drill-points two only were extensively used on the works. These were the chisel-point and the cross-point. The single cutting edge was used when the rock was solid, but when the rock was much intersected with joints or changed a good deal in character, the cross-point was adopted.

Driving the advanced heading comprised three distinct operations, namely, boring holes at the face, charging these with explosive and firing them, and the removal of the débris. The advanced heading was about 8 feet square, and usually required from fifteen to thirty holes to bring away a complete slice off the face. The average depth of the holes was $3\frac{1}{2}$ feet, and they were from 1 inch to 2 inches in diameter. They varied in direction, those near the middle of the face being generally made to converge with the view of removing the central portion, and preparing the remainder for removal with the least expenditure of explosive power. The boring was thus performed: The carriage with the machines, having been run forward to

the face of the heading, was secured by scotches behind the wheels and coupled to the fixed compressed-air pipes by the flexible high-pressure tubing. Each drill was adjusted and fixed, compressed air was turned on, and the drills at once commenced their reciprocating motion at a speed of from 300 to 500 strokes per minute. This was continued until such a depth had been attained as was considered would render the explosive charge most effectual. After the holes had been bored, the drilling-machines were uncoupled from the fixed air-pipes, and the carriage was unscotched and run back to a place of safety. The miners then charged the holes with either dynamite, lithofracteur, or tonite, inserted the fuse with detonator attached, tamped the same with clay, and prepared the fuses for firing by hand. The process here was somewhat different to that ordinarily pursued. The time-fuse reaching down to the explosive charge was cut to such a length as to admit of the piece outside the blast-hole being formed into a small loop by a lump of moist clay stuck on the face of the rock to be removed. A short bit of candle also was fixed directly under each of these loops in the same way, and when the ends of all the fuses, from half-a-dozen upwards, had been so dealt with, the candles were lit as speedily as possible and left to burn through the casing of the fuse, the men in the meantime removing out of danger. The charges, although they did not explode simultaneously, seldom missed fire. After the explosion the labourers proceeded with the removal of the debris, which had to be loaded into wagons, and either run out at the ends of the tunnel or wound up one of the shafts. The driving was carried on in two shifts, and three rounds of operations usually occupied two shifts of twelve hours each. With the view of preventing accidents from misfires or other causes special regulations were adopted. These provided "That no explosive whatever was allowed underground except such as was required for immediate use, and which had to be conveyed to the face where wanted in the copper cans supplied by the Company for the purpose. That if, when charging any hole, the cartridge should by any means stick fast before it reached the bottom, no attempt whatever was to be made to force it, but the hole was to be tamped and fired in the usual way with the cartridge in the position in which it had stuck fast. That the use of any other kind of tamping-rod than a wooden one was strictly forbidden, and in tamping no hammering or violence of any kind was to be employed. That the deepening of blast-holes after having once been charged and fired was strictly forbidden, and a new hole was invariably to be bored rather than deepen an old one. That if a

hole, after having been charged, tamped, and fired, failed to explode, the hole and its misfired contents was invariably to be forsaken and left, and a new hole bored in lieu thereof after a sufficient time had elapsed to justify the men in returning to the spot; and any attempt to extract or meddle with a misfired charge was strictly forbidden; and, that any breach of the regulations would be severely dealt with, and the offender or offenders held responsible for the consequences arising therefrom."

Following in the wake of the advanced heading was the removal of the two sides. This changed the section of the opening from a square to a semicircle, and was done principally by hand-labour. The rectangular or lower portion of the tunnel was then attacked by driving a gullet along one side of about half the width of the tunnel, and to the full depth, leaving the remaining half for a roadway upon which to carry the débris from the sides of the top heading, and from which junctions were made with the lowest level by inclines. This was done by the machine-drills and carriages previously engaged in the top headings. The remaining portion was then attacked partly by hand, partly by machine-drills at numerous points, and sidings were opened from the main gullet into each working.

The experimental drill-carriage at the north-end, so far as could be tried, appeared likely to answer the purpose intended; but the lack of success in simultaneous firing by electricity, prevented its being brought fully into use. The upper or radial stretcher-bar was, therefore, removed, and the carriage afterwards employed in boring for the excavation of the lower half of the tunnel in the rear of the advanced heading, which had been hitherto driven by hand. Eventually, however, the St. Gothard drill-carriage and machine were substituted for it.

With regard to simultaneous firing by electricity, several experiments were conducted with various results, but the success was not sufficient to justify the abandonment of hand-firing. In one instance, fifty detonators in circuit above ground were tried, when all went off except two or three. In another case, twenty-one holes underground were charged, and the detonators placed in the circuit of the electric wire; but not more than six of the charges could be exploded at once, and it took no less than four attempts to explode all. After the last experiments, the electricians intimated that they were prepared to guarantee the firing of not less than sixteen charges, and a communication was subsequently received offering to do more; but, the works being so advanced, the men so accustomed to the system of hand-firing,

and the delay caused by experimenting having been considerable, the offer was declined. Although, in sinking the shafts, the bulk of the work was done by hand-labour; in driving, the opposite course was pursued, and hand-boring was employed as sparingly as possible. The sinking and driving were carried on continuously day and night, except from twelve o'clock on Saturday night to twelve o'clock on Sunday night.

No. 1 shaft was commenced on the 6th of December, 1873; the full depth of 416 feet 7 inches was reached on the 25th of August, 1876, the average progress being 2·94 feet per week, including Sundays and lost time. This shaft was cased with timber to a depth of 45 feet from the surface; water, sparingly met with at first, gradually increased with the depth, until a constant flow of about 500 gallons per hour was reached in July 1876.

No. 2 shaft was commenced on the 25th of May, 1874; the full depth of 430 feet 5 inches was reached on the 18th of February, 1876; the average progress being 4·75 feet per week, including Sundays and lost time. This shaft was cased with timber to a depth of 195 feet from the surface. No more water was met with than could be raised to the surface by the automatic vessel attached to the underside of the cage.

No. 3 shaft was commenced on the 25th of May, 1874; the full depth of 191 feet 10 inches was reached on the 7th of July, 1875; the average rate of progress being 3·29 feet per week, including Sundays and lost time. This shaft was cased with timber to a depth of 105 feet from the surface, the water was easily kept under by the automatic water-vessel.

No. 1 heading, worked from the north end, the length of which was 1,864·50 feet, was commenced on the 26th of March, 1875, and was joined to No. 2 on the 26th of February, 1878; the average rate of progress was 12·26 feet per week, inclusive.

No. 2 heading, leading from No. 1 shaft, the length of which was 1,395·90 feet, was commenced on the 25th of August, 1876; the average progress was 17·78 feet per week, inclusive.

No. 3 heading, worked from No. 1 shaft, and 971 feet long, was commenced on the 25th of August, 1876, and was joined to No. 4 on the 4th of April, 1878; the average progress was 11·58 feet per week, inclusive.

No. 4 heading, worked from No. 2 shaft, 2,619 feet long, was commenced on the 18th of February, 1876; the average progress was 23·62 feet per week, including Sundays, time lost by flooding, and other causes.

No. 5 heading, worked from No. 2 shaft, 1,139·50 feet long, was

commenced on the 18th of February, 1876, and was joined to No. 6 on the 7th of July, 1877; the average rate of progress was 15·79 feet per week, inclusive.

No. 6 heading, worked from No. 3 shaft, 1,486 feet long, was commenced on the 7th of July, 1875; the average progress was 14·28 feet per week, inclusive.

No. 7 heading, worked from No. 3 shaft, 1,145 feet long, was commenced on the 7th of July, 1875, and was joined to No. 8 on the 11th of October, 1877; the average progress having been 9·71 feet per week, inclusive.

No. 8 heading, 961 feet in length, worked from the south end, was commenced on the 24th of May, 1875, and completed on the 11th of October, 1877; the average progress was 7·73 feet per week, including Sundays and lost time, as well as thirty-four and a half weeks occupied in the driving and timbering through the slate débris at the south end of the tunnel.

The general average progress upon the whole of the eight heading faces, amounted to 14·09 feet per week. On the 27th of August, 1877, when No. 4 heading had been driven a distance of 1,294 feet from No. 2 shaft, water was struck at the face. This flowed at the rate of about 60 gallons per minute, flooded the heading, and stopped the works at that point until the 14th of September. The interval of eighteen days was employed in providing pumps for draining the heading. This inlet of water has continued to flow at about the same rate; and the total quantity of water finding its way into the tunnel from every source, has amounted to about 100,000 gallons per day.

The lining through the slate débris at the south end of the tunnel consists of two parallel side walls, surmounted by a semi-circular roof. The side walls are built of slate débris, and the arch above of brickwork, backed with slate débris. The soffit of the arch is composed of Staffordshire brown or brindled, and the rest of ordinary red, bricks, set in hydraulic-lime mortar. As soon as the lining was built, as many as possible of the timbers were removed, and the space built up solid. This work was carried on in lengths of about 12 feet each. The greatest care was required in the mining operations, owing to the peculiar nature of the materials to be removed, and the lining had to be unusually strong, to resist any movement in the mass of débris. The casing of the other parts of the tunnel consisted similarly of side walls of slate débris, with the arch above built of brown or brindled bricks, backed with common red bricks and slate débris, and the whole set in hydraulic-lime mortar.

The timber casing at the three shafts, on the completion of the tunnel, was removed, and a permanent casing of brickwork set in hydraulic-lime mortar, oval in form, substituted. The top was finished with the view of securing the advantage of being open, and at the same time affording protection to the tunnel below from stones falling from above. This was accomplished by arching over the top of the shaft below the surface of the ground, and connecting it by a horizontal gallery or arched heading, with a tower which stands about 6 feet distance from, and forms above ground a continuation of, the shaft.

The total cost of the tunnel and three shafts complete, including labour, plant, materials, and sundries of all kinds, amounted to £302,850, which, divided by 3,860, the length in yards, gives £78 9s. as the cost per lineal yard. The cost of labour alone was £203,000, or £52 12s. per lineal yard; the cost of plant amounted to £25,630, or £6 12s. 9d. per lineal yard; and the cost of the materials and sundries used was £74,220, or £19 4s. 6d. per lineal yard. The cost of materials and sundries per lineal yard of tunnel was—of steel, 12s. 3d.; of explosives, £7 3s.; of fuse and detonators, 6s.; of fuel, £2; of candles, £1 5s., and of the remaining items, £7 18s. Assuming that the plant used will eventually realise one-half of the original cost, and that this amount be placed to credit, the reduced cost would be £75 per lineal yard. Taking the total cubical amount of rock and of other substances actually removed, the cost is £2 8s. 10d. per cubic yard.

The work was completed, with the exception of the permanent casing and finishing of the shafts, and a train passed through the tunnel, on the 20th of June, 1879. The tunnel was opened for public traffic on the 22nd of the following month.

The Paper is illustrated by numerous diagrams and small-scale drawings, from which Plate 10 and the woodcuts in the text have been prepared.