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"The Metropolitan and Metropolitan District Railways."

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IT may not unreasonably appear to many that a Paper on a railway, a portion of which was opened for public traffic nearly a quarter of a century ago, must necessarily be of little present interest to members of the Institution. The Secretary has thought otherwise, however, and it is in response to his application that the present Paper has been prepared by the Author, with the cordial acquiescence of his partner, Mr. Fowler, Past-President, the originator of the present system of underground railways. If any further apology is needed for the Paper not having been written before, it must be found in the fact that the complete scheme for the "Inner Circle" of railways recommended by the Select Committee of the House of Lords in 1863, although projected long since, has only just been accomplished.

In treating on so comprehensive a subject as the general history and detailed construction of the "Underground Railway," the Author must necessarily omit many things, and touch but lightly upon other questions, such as the system of working and ventilation, which would in themselves singly afford appropriate subjects for Papers. To preserve some sort of order in the mass of material to be dealt with, he proposes to give, first a brief account of the early history of the undertaking, its gradual development, and like matters not of a strictly engineering character, and then proceed to consider, in such detail as time will permit, the engineering features of the railway, its gradients, tunnels, sewer-crossings, and other ordinary and special works of construction, confining his attention chiefly to the $11\frac{1}{4}$ miles out of the whole 13 miles of "Inner Circle" with which he was himself personally connected.

Historical and General.

Parliamentary.—The first length of Metropolitan Railway constructed was that from Paddington to the City. Various claimants have contended for the honour of originating the scheme, but the Author is of opinion that it was rather a product of the growth of London than the work of any single individual. In the year 1814 Paddington was described as, "a village situated on the Edgware Road, about a mile from London." Twenty years later the advance had been such that the public were carried by steam-power between Paddington and Moorgate Street, at the same fares as at present, but in carriages running along the surface of the Marylebone Road, instead of beneath it. Another twenty years' interval, and the year 1854 is the date of the Act of Parliament for the "North Metropolitan Railway: Paddington to the Post Office, Extensions to Paddington and the Great Western Railway, the General Post Office, the London and North-Western Railway, and the Great Northern Railway. John Fowler, Engineer; John Hargrave Stevens, Architect." Thirty years then elapsed before the entire "Inner Circle" of Metropolitan railways was completed and opened for public traffic, the dates of opening the different lengths being: Paddington to Farringdon Street, January 1863; Extension to Moorgate, December 1865; to Westminster, December 1868; to Mansion House, July 1871; to Bishopsgate, July 1875; to Aldgate, November 1876; to the Tower, September 1882; and the complete circle, October 1884.

In 1834 the steam-carriages then running were each capable of conveying about a dozen passengers from Paddington to Moorgate in thirty-five minutes, with a consumption of coke averaging from 10 lbs. to 12 lbs. per mile. In 1865 each Metropolitan train could carry between the same termini thirty to forty times the number of passengers, half as fast again, with a consumption of fuel only three times greater. Since the steam-carriages were introduced as an improvement upon the then existent omnibus service, no further evidence is required of the necessity of a Metropolitan railway of the type designed by Mr. Fowler.

About the eventful year 1845, railway companies began to realize the important commercial fact that it was necessary for their stations to be as close as possible to the sources of traffic. No less than nineteen Bills were deposited that Session for lines within the Metropolitan area, and Parliament becoming alarmed, a Royal Commission was appointed to inquire into the matter. Mr. Vignoles, Past-President, had a scheme for a Charing Cross to Cannon Street line; Messrs. Stephenson and Bidder, Past-Presidents, one for an extension of the South-Eastern Railway to Waterloo Bridge; Mr. Locke, Past-President, for an extension of the South-Western Railway to London Bridge; and Mr. Page, M. Inst. C.E., for a line from the Great Western Railway through Kensington to Westminster, and along a proposed Thames Embankment to East-cheap and Blackwall. There was also a North London Railway; a Regent's-Canal Railway; and Mr. Charles Pearson, the City Solicitor, whose name was honourably associated with the Metropolitan Railway in its early days, again set forth his pet project for a Grand Central terminus at Farringdon Street, and a connecting line from King's Cross. Quoting from the Report of the Commissioners: "Mr. Pearson would carry the line of railway between two rows of houses, which he proposes to build so as to form a spacious and handsome street, 80 feet in width and 8,506 feet in length. The railway to be on the basement level, and to be arched over so as to support the pavement of the street, which would be on the level of the ground-floor of the houses. Mr. Pearson proposes to give light and air to the railway by openings in the carriage-way and footpath." Although this system of construction presents few points of resemblance to the Metropolitan Railway as carried out, Mr. Pearson is clearly entitled to the credit of being the originator of the whole tribe of "Arcade railways," and similar devices under different names which have from time to time been brought forward at home and abroad. The Author would further point out that the City Solicitor was also the first suggestor of the "blow-holes," which have so vexed his successors. The Royal Commissioners of 1846 were not very far-seeing. They were of opinion that there were strong reasons for discouraging the carrying of a railway across the river within the Metropolis, because an increase in the number of bridges would create a new obstruction to the navigation, and to appropriate any of the existing bridges to the purposes of a railway would be an inconvenience and injury to the public. They also thought that the advantages to the public of bringing railway-stations further into the city had been exaggerated, because they found on inquiry that the average distance travelled by passengers who arrived at Euston was 64 miles, and concluded that the saving of another mile or two was of little importance. It was clear, therefore, that in 1846 the time was not ripe for the successful promotion of a Metropolitan system of railways. However, Mr. Pearson and his colleague, Mr. Stevens, architect and surveyor to the western division of the City, who had worked at the subject from the year 1837, were not to be discouraged, but kept the important question of Metropolitan communications before the public, by bringing forward a number of propositions of varying merits for a City Terminus line, and for arcades, vegetable and meat markets, Holborn Valley Viaducts, and other improvements in connection with railways. Finally in 1853, as an outcome of all this preliminary ventilation of the subject, an Act was obtained for a line $2\frac{1}{4}$ miles in length, from Edgware Road to Battle Bridge, King's Cross; Mr. Fowler being the engineer, Mr. Stevens the architect, and Mr. Burchell the solicitor.

Plans for extensions westward and eastward, to Paddington and the City respectively, were at once prepared; and whilst the 1853 line was wholly under the public road, and no buildings whatever were scheduled, the extensions were taken through private property in places, with a view to obtain more convenient stations and better ventilation. Early in 1854 the Directors were able to announce that the Great Western Railway Company considered it "so important to obtain access into the heart of the City, that they had undertaken to contribute £175,000 to the capital if Parliament should sanction the proposed line from Paddington Station to the Post Office." The contest before the Parliamentary Committee was severe, but successful. Mr. Fowler was supported by Messrs. Brunel, Hawkshaw, Scott Russell, Peacock, and Stevens, and was opposed by equally eminent witnesses. It is proverbially dangerous to prophesy before you know, and few will be surprised to learn that distinguished engineers speculating thirty years ago on the subject of the Metropolitan Railway, were occasionally somewhat wide of the mark.

What was at the time deemed an important feature of the railway of 1854 was that it accommodated the Post Office. Sir Rowland Hill, writing to the Chairman of the Company, said: "The Post-Master General thinks it necessary that such arrangements should be made as will admit of the intended railway being brought into the basement of the building, so that the bags when made up may be placed at once in the railway carriages," and it was accordingly stated in evidence by Mr. Stevens before the Parliamentary Committee that this would be done. The same witness ventured to predict that the trip from Paddington to the City would be accomplished in twelve minutes if the railway were made, but unfortunately it takes double that time. Another witness spoke very light-heartedly on the subject of tunnelling under heavy buildings without disturbing the surface or cracking the structures, because the Brunels had succeeded in carrying a tunnel under the Thames. Driving a tunnel, however, in the neighbourhood of buildings is, as the Author will show hereafter, one of the most precarious parts of the operations of a City railway contractor.

Working.—The original intention being to work the Metropolitan Railway by "hot-water" locomotives, no special provisions were made for ventilation. It was admitted in cross-examination that the only ventilation along a considerable portion of the line would be by the staircases, and that the stations themselves would be absolutely in the dark, or rather, dependent upon gas for illumination. Mr. Fowler foresaw and told the Committee that the traffic on the Metropolitan Railway would be essentially of an omnibus character, whilst both the through passenger traffic from the main lines and the goods traffic would be of comparative little importance. Very light trains of three carriages, running at from five to ten minutes intervals, would, he thought, best meet the requirements, and it was assumed the trains would stop at every alternate station, and perform the journey from Paddington to the City in fifteen minutes. Details of this kind are essential in order to account for some of the features of the line as constructed. Although Mr. Fowler proposed to use a locomotive burning no fuel, but having simply a reservoir of hot water capable of being heated up again at the end of each journey, and a reservoir of cold water to condense the steam, still he maintained that the line could be worked by ordinary locomotives. Mr. Brunel supported this view in most emphatic language. Quoting from his evidence before the Committee of 1854: "I believe," said he, "it would be perfectly easy to work this line with an ordinary locomotive, without any peculiar artificial means of ventilation. I thought the impression had been exploded long since that railway tunnels require much ventilation. There was a Standing Order in former days in the House that required the Committee should report on the means of ventilation; but the common answer given by engineers now is that they do not provide any. We are obliged in the Box tunnel, and one or two other tunnels, to put a screen to prevent the draught." He thought nevertheless that Mr. Fowler's proposed hot-water locomotive was "a rational and sensible way of working the line; there was nothing particularly new in it, for any one, who had driven a locomotive, knew perfectly well that if you were going only four or five miles, and had a good large boiler with plenty of steam and water, well heated up, you need not take a fire." Mr. Peacock would have even dispensed with the condenser: "I should certainly commence with using the steam in the way Mr. Fowler proposes, and exhaust it in the tunnel in the ordinary way." Mr. Scott Russell had often driven a steamboat when the fire was out, and also a locomotive. As to loss of heat by radiation, he had made an experiment, and found the loss of pressure in five hours was only 30 lbs. per square inch. To sum up briefly the evidence of the eminent experts supporting the first Metropolitan Railway Bill, perfect unanimity was exhibited in three points; firstly, that the hot-water locomotive was beyond all dispute the best way of working the line; secondly, that trains weighing 20 tons, inclusive of passengers, but without engine, were the heaviest that could be usefully employed; and thirdly, that the trip would take from twelve to fifteen minutes.

Events have proved it was just on these three points that every anticipation was mistaken:—the hot-water locomotive was not even tried; the trains necessary for accommodating the traffic weigh, exclusive of engine, about 120 tons instead of 20 tons, and the time is doubled. Bearing these facts in mind, it can hardly be a matter for surprise that some of the earlier constructed portions of the Metropolitan Railway required further ventilation, when worked with coal-burning locomotives weighing 45 tons, and dragging 120-ton trains after them.

Before adopting ordinary engines Mr. Fowler instituted experiments, and took the opinion of many experienced locomotive-engineers. The detailed design and construction of the first locomotive for the Metropolitan Railway was entrusted to Messrs. Stephenson and Co., of Newcastle, about the end of 1860. This engine had a small fire-box, and a large mass of fire-brick stowed away in a chamber in the barrel of the boiler; the idea being to work it as an ordinary locomotive with full blast in the open portions of the line, burning there an excess of fuel in order to convert the white-hot firebrick into a reservoir of heat for use in the tunnels. Close-fitting dampers were provided to prevent the discharge of gases from the incandescent coke, and an injection condenser with air-pump disposed of the steam. The engine had four coupled-wheels, 6 feet in diameter, a pair of leading wheels, and cylinders 15 inches in diameter by 24 inches length of stroke. There were 230 square feet of heating surface in the chamber for fire-brick; 259 square feet in one hundred and eighty-nine tubes, 2 inches in diameter by 2 feet 7 inches long; 83 square feet in the fire-box, and the grate area was 13¼ square feet. In working order the engine weighed 32 tons, and the tender with 1,400 gallons of water 14 tons. The cost was £4,518.

Referring to a report of the trial of this engine on the 10th of October, 1861, the Author finds the results were considered to be the reverse of satisfactory. Steam was got up to 120 lbs. in three hours, and the engine run as an ordinary locomotive 7½ miles down the Great Western line, the fire-bricks being at a clear white heat. On the return journey the dampers were closed, and the exhaust turned into the condenser. The vacuum at first was 7 lbs., but in twelve minutes the steam came out of the delivery pipe of the air-pump mixed with boiling water, and it was deemed prudent to turn the steam out of the condenser. During this time the pressure had fallen from 120 lbs. to 80 lbs., and the coke-fire and bricks had assumed almost a black appearance. Owing to a failure of the feed-pumps it was desired to drop the fire; but the mass of fire-brick still remained a source of danger.

Messrs. Stephenson, profiting by the experience with the first engine, submitted an amended design, in which the fire-brick was retained and the air-pump dispensed with, but fortunately nothing further was done in the way of fire-brick locomotives. Sir Daniel Gooch from the first took a great interest in the working of the Underground Railway, and on one occasion raised the steam in a large Great Western engine to a high pressure, dropped the fire and ran 9 miles along the line with the stored-up heat. His views were that hot water was better than fire-brick, that both the boiler and the grate-area should be large, and the dampers perfect, and above all that the engine should be as simple as possible. Sir Daniel was called upon to build an engine for Metropolitan traffic, and did so, the trial taking place in October 1862, exactly a year after that of the fire-brick engine. Referring to the report of the trial, at which Colonel Yolland and the President of the Board of Trade were present, it appears that the engine did the trip from Farringdon Street to Paddington in twenty minutes, the weight of engine being 38 tons and of train 36 tons. The condensing water got hot, the sulphurous fumes came out of the ash-pan and fire-box door and a steam-jet had to be turned on to keep up steam, so the engine was not an unqualified success. As this was the first type of engine used for working the Metropolitan Railway traffic, it may be interesting to mention that it was a six-wheel broad-gauge tank engine, having four coupled wheels 6 feet in diameter, and outside cylinders 16 inches by 24 inches. The heating surface of tubes was 615 square feet, of fire-box 125 square feet, and the grate-area was 18·5 square feet. A tank of 375 gallons capacity and a condenser of 420 gallons were provided.

For some months after the line from Paddington to Farringdon Street was opened, the Great Western Railway Company worked it on the broad gauge. Owing to a dispute as to terms the working of the line had to be carried on for a time with the assistance of the Great Northern Railway Company, and the engines used were six-wheel tender-engines having four coupled wheels 5 feet 4 inches in diameter, cylinders 15½ inches by 22 inches, and a total heating surface of from 760 to 940 square feet. Experience showed that both the Great Western and the Great Northern engines were too light for their work, and the powerful tank-engines now used on the line were designed by Mr. Fowler and Messrs. Beyer and Peacock. These engines have four coupled wheels 5 feet 9 inches in diameter, a four-wheel bogie and cylinders 17 inches in diameter by 24 inches length of stroke. The heating-surface of the fire-box is 103 square feet, of the tubes 909 square feet, and the grate-area is 19 square feet. The weight in working order is between 42 and 43 tons, with 1,000 gallons of water in the tanks.

Immediately the line was opened and the regular service of trains commenced, the theories of those who had stated in 1854 that the line could be worked by ordinary locomotives, were put to the test. It was found that even with the specially designed condensing engines of the Great Western Railway, the inconvenience from the discharge of carbonic acid and carbonic oxide gases was great. Alarmist paragraphs headed "Choke-damp on the Underground Railway" appeared in the daily papers, and with a view chiefly to allay panic a small fan and engine were arranged to blow air into the Portland Road Station. The glass was removed at once from the side lights at Gower Street Station, and three years later it was removed at Baker Street Station. Owing to the increased traffic and the use of coal instead of coke, there was another outcry in 1867, and the ventilation was further improved by opening portions of the covered way at King's Cross Station, Gower Street, Baker Street, Edgware Road, and Praed Street. Finally in 1871–2 the "blow-holes" were made between Edgware Road and King's Cross. Having this experience of inadequate ventilation on the first length of Metropolitan Railway, Mr. Fowler, in laying out the subsequent extensions and the District Railway, arranged wherever possible for the stations to be in the open with a piece of cutting at each end, and an intermediate cutting somewhere between the stations.

Extensions.—For some years after the passing of the Act of 1854, the public declined to assent to the practicability or usefulness of the proposed railway. The patience and perseverance of the promoters, however, ultimately prevailed, and in 1859, with the assistance of the Corporation of London, the capital was raised, the contract made, and the works commenced in March 1860. When opened, the success of the railway exceeded every anticipation, and numerous extensions were projected. It would be useless to enumerate the different projects brought forward or even the titles of the many Acts obtained. Suffice it to say that in 1861 powers were obtained for extending the Metropolitan Railway to Moorgate Street, and for widening the line from King's Cross eastward; and in 1864 for constructing the eastern and western extensions to Tower Hill and Brompton respectively, the District Railway from Brompton to Tower Hill, and the St. John's Wood Railway. Owing to financial difficulties the Metropolitan Railway Company sought to abandon the eastern extension in 1870, but the Bill was thrown out by the Lords. An alternative mode of completing the "Inner Circle," by Fenchurch Street instead of by Tower Hill, was authorized in 1871, but the latter and original route is the one adopted. As regards the western extension, Mr. Fowler's first idea was to take it through Kensington Gardens and Hyde Park, but the authorities objected, and the present line was selected. Practically there was little choice in laying out the extensions of the Metropolitan Railway, for the Lord's Committee of 1863 decided that "it would be desirable to complete an inner circuit of railway that should abut upon, if it did not actually join, nearly all the principal railway termini in the Metropolis, commencing with the extension in an easterly and southerly direction of the Metropolitan Railway, from Finsbury Circus at the one end, and in a westerly and southerly direction from Paddington at the other, and connecting the extremities of those lines by a line on the north side of the Thames." The inner circle of railways as constructed is the direct outcome of that recommendation. The total length of the line is 13 miles 8 chains, of which about 2 miles are laid with four lines of rails, and there are twenty-seven stations.

Cost and Traffic.—A statement of the cost of the different parts of the railway would be misleading as an indication of the relative extent of the works, because the financial liabilities assumed by the contractors varied from time to time, and other complicating conditions entered into the question. Referring to the original accounts, the Author finds that the contracts for the line from

Paddington to Farringdon Street were made with Messrs. Smith and Knight and Mr. Jay in January 1860, and the amount paid to those firms in final settlement was £674,751, which is equivalent to £186,000 per mile. Mr. Kelk next contracted for extending the line to Finsbury Circus, widening the line between King's Cross and Farringdon Street, enlarging Moorgate Street, building the repairing-shops at Edgware Road, and doing sundry other works, the gross cost of which was £779,376. Excluding special items, the Author estimates this to correspond to a cost of £208,000 per mile of double-line railway. Next in succession were the contracts with Messrs. Peto, Kelk, Waring, and Lucas for the completion of the Inner Circle, the gross contract sum being £2,743,000 for works and special financial liabilities. This contract was not carried out in its entirety, as the eastern end of the Inner Circle was temporarily abandoned, and the District Railway terminated at Mansion House Station.

It need hardly be said that the cost of property varied widely at different parts of the line, as did other charges, and it is difficult to give a trustworthy estimate of the total cost per mile of the railway. In 1871, when the works had been completed and opened from Moorgate Street to Mansion House, the expenditure on capital account by the District Railway Company for works and equipment of $7\frac{1}{4}$ miles of double-line railway, was stated in the Directors' report to have been £5,147,000, and by the Metropolitan Railway Company £5,856,000 for $10\frac{1}{4}$ miles, both amounts being subject to deduction in respect of surplus lands. It must be remembered that these figures, as already intimated, are of little value to an engineer, because they include items dependent, amongst other things, upon the market value of the shares, which, in the case of the Metropolitan Railway, ranged from 50 to 140, and in that of the District from 20 to 100, during the making of the lines. Many other companies experienced almost as wide vicissitudes of fortune whilst the Inner Circle was under construction; thus the Great Western Railway and the Brighton Railway shares each ranged from about 39 to 145, and the London and North-Western Railway from 98 to 174. The Author was actively associated with the construction of the railways from the commencement of the works until their completion to Moorgate Street and Mansion House in 1871, but can give no figures respecting the subsequent expenditure.

The traffic on the $3\frac{3}{4}$ miles of line first opened was a surprise to every one. In a letter from Mr. Fowler to Mr. Gladstone, dated March 1863, that is to say, a couple of months after the opening of the railway, the Author finds a tabular statement of the number of passengers per mile per annum then travelling on different lines. The Metropolitan Railway had 2,792,200 passengers, as compared with 731,130 on the North London, 48,244 on the Brighton, 40,484 on the South-Eastern, 34,715 on the London, Chatham, and Dover, 20,183 on the London and South-Western, and 7,361 on the Great Western. Mr. Fowler found the proportion of first-class passengers to be 17 per cent., of second-class 31 per cent., and of third-class 52 per cent., and the receipts per mile per week, £629 11*s.* 5*d.* This result seemed too good to be true, and many people said it was merely "curiosity traffic." In 1867 the extension to Moorgate Street was opened, but previous to that date the receipts per mile per week fell within the following limits:—1863, from £410 to £683; 1864, from £496 to £785; 1865, from £641 to £910; and 1866, from £806 to £1,079.

The first length of the District Railway opened was the 2¼ miles from Kensington to Westminster, and the receipts averaged £300 per mile per week. When extended to Blackfriars, the earnings were about £400 per week. On both lines the subsequent increase in the main-line traffic has been enormous, but owing to the construction of branches these results are not apparent in the official traffic returns, which at the present time give, on the extended mileage, £586 per mile for the District and £633 per mile for the Metropolitan Railway. To show the growth of traffic it is only necessary to state that, whilst in 1863 the total number of passengers travelling by the "Underground Railway" was 9,455,175, and the receipts £101,707, in 1884 the number on the complete system was about 114,500,000, and the receipts about £1,012,000.

Engineering Features.

Contour of Ground.—The two leading features of a city railway, as of any other iron road, are the route followed and the level at which the rails are laid. As a rule, the route is determined by the desire to get to certain definite sources of traffic, whilst the levels are controlled by the physical configuration of the ground, the lines of drainage, and such things. The Metropolitan railways offer no exception to this rule. When a tract of country is closely covered by buildings of varying heights, and the natural water-courses are converted into covered sewers, it is difficult to form a general idea of the physical features determining more or less the character of the railway as regards level and gradients. In the case of the Metropolis, however, a sufficient record exists of the previous condition of the country, and the excavations have in many instances afforded an interesting confirmation of traditions.

It is believed by competent authorities[1] that long before the Roman invasion some Celtic chieftain settled in the "City," and called his place of business "Lynn-din"—the Fort of the Lake. However this may be, it is certain that in early historical times the little hill on which the City stands was fronted by a wide stretch of tidal marsh land, extending to the base of the Surrey hills, and was flanked on the east by the Wall brook, and on the west by the Fleet river. Between the City and Westminster the river overflowed its north bank to only a limited extent, but westward of that it extended inland for at least a mile, forming the swamps of St. James's Park, Pimlico, Fulham, and other low-lying districts now traversed by London railways. To the north extended the rising ground culminating in the heights of Hampstead and Highgate, and the lesser heights of Campden Hill, Notting Hill, Maida Hill, Primrose Hill, Haverstock Hill, and Pentonville Hill. Within a couple of hundred yards of the Institution building the level of the footway even now is 8 feet below the highest tides, and at Hampstead the height is 443 feet above Ordnance datum. The highest ground traversed by the "Inner Circle" railway is at Edgware Road, and the lowest at the back of Victoria Street, Westminster, the respective heights being 103 feet and 8 feet above Ordnance datum. At Swiss Cottage the rails of the St. John's Wood branch climb to a height of 167 feet, and at the Kings Scholars Pond sewer in Victoria Street the District Railway dips to a depth of 9 feet below the same datum, or 3 feet below Thames low water.

Between the different spurs of the northern range of hills are drainage depressions, formerly clear running brooks or tidal channels, but now polluted sewers with tidal flaps for storm overflow. To the west of Kensington and Chelsea, rising in the high ground, but traversing chiefly the low-lying district, was the Bridge Creek, now known as the Counters Creek sewer, which is carried under the District Railway at Warwick Road in a flat-topped channel 7 feet wide and 8 feet high. As the level of the soffit is 9 feet below highest tides, the sewer top is of iron, calculated to resist a bursting pressure, there being no weight of ground overhead. Proceeding eastwards, the next stream met with was the West Bourne, rising on the western flank of Hampstead Hill, and flowing southwards to the Serpentine, and thence into the

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[1] W. J. Loftie, F.S.A., "History of London."

Thames near Chelsea Bridge. This, now called the Ranelagh sewer, is carried under the Metropolitan Railway at Gloucester Terrace, and over the District Railway at Sloane Square station, the construction in the former case being a brick channel 9 feet wide by 8 feet high, with flat iron top, and in the latter a cast-iron tube, 9 feet in diameter, supported on wrought-iron girders of 70 feet span.

Next in order was the Ty-Bourne which flowed from Hampstead through Regents Park, thence by Marylebone Lane—whose strange windings are due to the houses having originally been built on the banks of the stream—and by the Green Park to the river between Vauxhall and Chelsea Bridges. At Baker Street the Metropolitan Railway is crossed by this stream under its present name of the Kings Scholar Pond sewer, the construction being a cast-iron oval tube resting on cast-iron girders. At Victoria Street the District Railway is similarly crossed, but the size of the tube is 14 feet by 11 feet in the latter case as compared with half those lineal dimensions at the northern crossing.

No stream of importance existed between the Ty-Bourne and the Fleet. The historical stream, known for the first portion of its course as the Hole-Bourne and for the latter portion as the Fleet, flowed from the Hampstead and Highgate ponds due south past King's Cross and along a deep tidal inlet into the Thames at Blackfriars Bridge. The sudden dip in the roadways at Holborn Valley and at Ludgate Hill remain as evidence of the former existence of this useful tidal navigable channel. Though a benefit in olden times it is hardly necessary to say that the Fleet river converted into a huge sewer constituted a serious difficulty in the construction of the Underground Railway. When building the retaining wall on the west side of Farringdon Street Station the Fleet, then carried in a slightly built brick sewer 10 feet diameter resting on the rubbish filled into the old channel, burst into the works and flooded the tunnel with sewage for a great distance. Again when constructing the District Railway at Blackfriars the Fleet had to be diverted and re-diverted, carried temporarily in syphons and otherwise carefully guarded as the large volume of water coming down it necessitated. No less than five crossings of the Fleet had to be dealt with, namely, two at King's Cross over the junction curves with the Great Northern Railway, one at Frederick Street over the Metropolitan Railway, another at the same spot over the widening lines, and finally a fifth under the District Railway at Blackfriars Bridge. The first four crossings were in cast-iron tubes of tunnel section, ranging in size from 9 feet by 8 feet to 10 feet by 10 feet, and the latter in two brick channels 11 feet 6 inches wide by 6 feet 6 inches high with flat iron tops.

Levels and Gradients.—From the preceding brief sketch of the hills, valleys and streams of the country now covered by the buildings of the Metropolis, it will be possible to gather a very fair idea of the kind of line so far as levels and gradients are concerned that the "Inner Circle" of railway must be. Thus as the southern portion of the circle traverses the old bed of the river and the swamps of Pimlico and Bridge Creek, whilst the northern portion is on the slope of ground rising to Hampstead, it is clear that the general level of the District Railway must be very much lower than that of the Metropolitan. As a matter of fact, the average rail-level of the former is 13 feet below Thames high water, and of the northern part of the latter 60 feet above the same. Again, as the ground dips from north to south at a far steeper gradient than would be admissible on a railway, it is obvious that deep cuttings or tunnels must occur at the eastern and western portions of the "Inner Circle." In construction, cuttings 42 feet deep and a tunnel 421 yards in length are found at Campden Hill on the west, and cuttings 33 feet deep and a tunnel 728 yards in length at Clerkenwell on the east, the respective gradients to get down the sloping ground being about $\frac{3}{4}$ mile of 1 in 70 on the west, and 1 mile of 1 in 100 on the east. Further, as the valleys of the West Bourne and of the Ty-Bourne are crossed by the Metropolitan Railway, dipping gradients of 1 in 75 and 1 in 100 are required at these points. On the District Railway the rise from the Fleet Valley to the hill upon which the earliest parts of the city were built has to be surmounted, and it is done by a gradient of about $\frac{1}{2}$ mile of 1 in 100.

It will thus be seen that the levels and gradients (Plate 1, Fig. 1) of the "Inner Circle" railway have been determined by the original physical configuration of the ground, and that sewers, pipes and other specialities of city lines have had little connection with the question. The curves on the other hand, which have a minimum radius of 10 chains on the "Inner Circle" and $6\frac{2}{3}$ chains on the Great Northern branch, were fixed chiefly by the situation of the sources of traffic, and by property considerations.

Nature of Soil.—As regards character of ground cut through (Plate 1, Fig. 2), a considerable depth of made ground would necessarily be looked for at the east end, as the line is carried through a city founded perhaps two thousand years ago, and ravaged and burnt by Celts, Romans, Saxons, Danes, and Normans. In places as much as 24 feet of ruins and dust were cut through.

At the mouth of the Fleet the chalk-rubble foundation of an old fort was exposed, and at the Mansion House a masonry subway was discovered intact. Similarly, at Westminster, made ground was found to a depth of 18 feet. Remembering that between the City and Westminster the line is carried along the old bed of the river, mud and silt would naturally constitute the chief part of the excavation. At Charing Cross the walls of the covered way had to be carried to a depth of 25 feet below rail-level, or 37 feet below high-water, to secure a solid foundation; at the Temple the depth was 21 feet, and at Blackfriars 13 feet below rail-level. In the swampy ground farther west, originally flooded every tide, peaty deposits would be expected. Along Tothill Street a layer of peat 700 feet in length, varying in thickness from 7 feet to 2 feet, was cut through at a depth of from 8 feet to 16 feet below the present level of roadway. At Victoria Station a layer of similar peat, 200 feet long by 3 feet thick, was met with from 9 feet to 24 feet below the surface. A few feet below this peat the London Clay was found, and between Victoria and Gloucester Road stations the foundations either rest on the clay or close to it. Over the clay were varying depths of gravel and sand, heavily charged with water.

The Campden Hill tunnel arch is in gravel, sand, and brick-earth, but the London Clay rises at places within 6 feet of the top of the brickwork. No gravel nor sand was found at Queen's Road station, and very little between that point and Praed Street station. Thence to Gower Street station the foundations are generally on clay, overlaid with gravel, to some 4 feet above rail-level on the average. Practically no gravel was met with between Gower Street and Smithfield markets, where a layer about 10 feet in thickness was found interposed between the made ground and the clay. All the way from Smithfield to Moorgate good clean gravel was cut through, but the clay in all cases was within a few feet of rail-level.

The cuttings and longitudinal section (Fig. 2) of the railway show that, if what Sir Charles Lyell called the great ochreous gravel deposit of the Pleistocene epoch were swept away, the hills and valleys of the Metropolitan area would be practically unaltered in appearance. At what period in the remote past the sand, gravel, and brick-earth cut through by the railway in Westminster, at a level of 8 feet, and in Marylebone at 103 feet above Ordnance datum, were deposited no one can tell. It is believed, however, that England was then united to the Continent, that the present site of the North Sea was dry land, and the Thames a tributary of the Rhine. It is proved by the remains of animals swept down by floods, and buried in the gravel at Windsor, Kew, and London, that roaming about the valley of the Thames must have been the mammoth, woolly rhinoceros, hippopotamus, straight-tusked elephant, lion, elk, bison, horse, bear, wolf, reindeer, and other animals. The gravels and sands met with in the railway cuttings may have been deposited at periods separated by thousands of years, for Sir Charles Lyell points out that sandpits, even in two adjoining fields, have contained the remains of distinct species of elephant and rhinoceros belonging to different parts of the Pleistocene epoch. Was man existent at this epoch? It is very generally believed that he was. Professor Boyd Dawkins, Assoc. Inst. C.E., asserts that man is proved to have been dwelling in the neighbourhood of London whilst the gravels accumulated high above the Thames, as well as while they were being formed at and below its present level. He refers to the fact that two centuries ago flint implements were found associated with elephants' bones at Gray's Inn Road, and have since been met with in the lower part of a 9-feet bed of gravel and sand overlying the London Clay at Acton, in the bed of the Thames at Battersea and Hammersmith, and elsewhere in the London district.

In making the excavations the gravel was generally found fairly dry to about the depth of the inverts of the adjoining sewers, but below that level large volumes of water had to be dealt with. Before commencing the cuttings sumps were sunk and lined with timbering or wrought-iron cylinders, 10 feet in diameter, and chain-pumps lifted the water into the nearest sewer. In June 1868, when the District Railway was being carried on to Westminster, there were sumps and pumps at Earls Court, Gloucester Road, Prince Albert Road, Old Brompton Road, Pelham Street, Moore Street, New Road, Sloane Square, Flask Row, Victoria Street, and Broadway, Westminster. The nominal HP. of the engines ranged from 4 to 20, and was 148 HP. in all, and the size of the pumps from 8 inches by 4 inches to 24 inches by 8 inches. It was stated at the time by the contractors that the cost of pumping, including renewals and repairs, amounted to £592 per month. From Kensington to Blackfriars, a length of 4¾ miles, the permanent drainage of the line is effected by pumping-engines placed at South Kensington, Victoria, Sloane Square, and the Temple stations.

In early days the Metropolitan Railway was familiarly spoken of as the "Underground Railway," to distinguish it from the numerous other projected Metropolitan lines where it was proposed to carry the trains on a viaduct, as in the recently executed extensive system of "elevated" railways in New York. This characteristic of underground construction has been maintained on all the extensions of the Metropolitan Railway. On the "Inner Circle" the depth of rails below the surface of the ground ranges from 9 feet to 65 feet, and, as the cost of property precluded the use of ordinary open cuttings with slopes, the works necessarily consist of covered ways, tunnels, and open cuttings with retaining walls.

Covered Ways.—Under agreements with the Great Western and the Great Northern railways, the line from Paddington to Moorgate was laid with mixed gauge. The original covered way, therefore, required to be 28 feet 6 inches wide, as compared with 25 feet on the extensions where narrow gauge alone was laid. Plate 1, Fig. 3, shows the type of covered way adopted on the first portion of the Metropolitan Railway. It consists of a six-ring elliptical arch, of 28 feet 6 inches span, and 11 feet rise, with side walls three bricks thick, and 5 feet 6 inches high from the rails to the springing. No invert was constructed, nor was there any concrete under the 4 feet wide footings. Near Gower Street a short length of the side walls slid forwards, owing to the heavy engines having in the course of years worked up the clay formation, and withdrawn the support from the toe of the wall. This was stopped by putting some concrete inverts or struts between the walls. On the extensions the arch (Plate 1, Fig. 4) was five rings thick, and there was a concrete foundation 5 feet wide, and 2 feet 6 inches thick, under the side walls. Along the Thames Embankment a brick invert with concrete underneath was introduced, and on certain low-lying parts of the District Railway there was a concrete invert. Where a junction of main line and branch occurred in covered way a "bellmouth" was constructed. At Praed Street the "bellmouth" consists of the usual brick side walls, with an elliptical wrought-iron arch top, 28 feet 6 inches wide at one end, and 60 feet at the other, the ironwork much resembling the inverted hull of a large iron ship. At King's Cross the depth of ground permitted the adoption of a brick arched top. At Baker Street ordinary wrought-iron girders and jack-arches were used. Manholes or refuges were placed 50 feet apart on alternate sides of the line, and an 18-inch barrel drain was carried along the 6-feet way. Ordinary stock bricks and blue lias, or greystone lime, were used throughout.

Where there was not sufficient depth for a brick-covered way the construction shown by Plate 1, Fig. 5, was substituted. This consists generally of brick and concrete side walls, in 8-feet bays of piers and recesses, and cast-iron girders from 1 foot 6 inches to 2 feet 6 inches in depth, spaced 6 feet to 8 feet apart, with two- and three-ring jack-arches between. In places wrought-iron girders were used, but though more trustworthy than cast iron whilst new, they are exposed to greater risk from hidden oxidation. Experience has shown the trouble and cost of maintaining ironwork exposed to the atmosphere of an underground railway to be such, as would justify a considerable increase in the first cost by substituting brickwork and deep cuttings for ironwork and shallower construction. The 2 feet 6 inches cast-iron girders were tested with a load of 45 tons applied at the centre, and the 1 foot 6 inches girders with 35 tons, which loads considerably exceed those to which the girders are liable in practice. No failures or indications of failure have occurred with any of the iron-topped covered ways.

The method of executing the covered ways varied at different times and under different contractors. On Messrs. Smith and Knight's contract (1861–63) for the Paddington to Euston Square portion of the original Metropolitan Railway the excavations were got out the full width of 33 feet 6 inches, and timbered right across. At South Wharf Road (Plate 1, Fig. 6) there were heavy buildings on each side, and the road traffic had to be maintained overhead during the construction of the covered way. Balks of timber 16 inches square, and 43 feet long, spaced 5 feet apart from centre to centre, were first laid across the site of the proposed cutting, and planked for the temporary roadway, with one longitudinal and one transverse row of 12 inches by 6 inches timbers. At a depth of 2 feet below the balks was a line of 12 inches by 6 inches walings, 12 feet long, with 13 inches by 13 inches struts at each end and at the centre. Below this at a depth of 10 feet was another line of similar walings strutted in the same manner, and between the two were runners about 12 feet long, and 12 inches by 3 inches scantling. For the remainder of the depth the ground was supported by $\frac{3}{4}$-inch poling boards, and four lines of walings strutted to 10 inches by 10 inches verticals, butting on the lower row of main struts at the top end, and on the ground at the lower end. When the whole of the excavation was complete, the side walls were built to 4 feet above springing, and iron centres were then fixed 6 feet apart, and the arch turned. The cost of timbering at this point was 7*d.* per cubic yard of excavation.

In the heavier ground on Mr. Jay's contract (1861–63), east of Euston Square, the excavations were also got out the full width, but the 12-inch by 7-inch walings, 13 feet in length, were spaced 7 feet apart, from centre to centre, from top to bottom of the excavation and strutted with 11-inch square balks at each end and at the centre (Plate 1, Fig. 6a). Although the greatest care was exercised in following up the excavations with the runners, and tightly wedging the same to the walings and struts, there was very frequently a draw of the ground towards the cutting, and cracks, 1 inch to 2 inches in width, would appear in walls distant 40 feet to 50 feet from the trench. Work was carried on day and night, and in a 30-feet deep cutting the advance was about 22 yards per week at each face.

A year after the works had been in progress a return was obtained of the cost of excavation in a 22 feet 3 inches deep cutting along the Marylebone Road. The work was executed in three lifts, the top one being 5 feet deep and 37 feet long, the middle 6 feet and 27 feet long, and the bottom 11 feet 3 inches in depth and 12 feet long. The materials were 18 inches road metal, 4 feet clayey gravel, 5 feet loam, and then coarse gravel and sand down to the London Clay on which the footings rested. There were twenty-one excavators in the top lift, sixteen in the middle, and twenty-one in the bottom, and the cost of labour in getting, filling and timbering, exclusive of superintendence and general charges in the respective lifts, was 1*s.* 2½*d.*, 9½*d.*, and 7½*d.* per cubic yard. Adding 3*d.* per cubic yard for use and waste of timber, the average of the whole amounted to 12½*d.* per cubic yard. Carting to spoil cost 2*s.* 3*d.* per cubic yard, but on the other hand, part of the gravel was reserved for ballast and concrete, and a large quantity was sold at 2*s.* 9*d.* per cubic yard. Taking the latter points into consideration, the Author is of opinion that a great deal of the heavily-timbered excavations on the Metropolitan Railway cost the contractors only 1*s.* per cubic yard as an average, although the clay excavations at the same point would certainly cost them as much as 3*s.* 4*d.* for labour and material alone, or say 4*s.* per cubic yard, including general charges and contingent risks.

In later days, when the District Railway was being constructed, the general practice was not to timber the entire width of covered way, but to sink a couple of 6-feet wide trenches for the side-walls, to build the latter up to 4 feet above springing, take out the excavation full width down to that level, fix the centering, turn the arch, and finally take out the "dumpling." The labour and use and waste of timbering the narrow trenches amounted to about 9*d.* per cubic yard in gravel and 13*d.* in heavy ground.

At average contract prices the cost of the different types of covered way per lineal yard would be as follows:—

1.—ARCH COVERED WAY 25 feet wide in 25 feet CUTTING.

			s.	d.	£.	s.	d.
65	cubic yards excavation to spoil	at	4	0	13	0	0
30	" " refilled	"	2	6	3	15	0
15	" brickwork	"	24	0	18	0	0
7	" concrete	"	7	6	2	12	6
11	sup. yards asphalt	"	2	9	1	10	3
1½	lin. yard 4-inch drain pipe and bends				0	4	3
1	" 18-inch barrel drain				0	15	0
					£39	17	0

2.—ARCH COVERED WAY 28 feet 6 inches wide in 25 feet CUTTING.

	£.	s.	d.
At preceding prices the cost per lineal yard	47	5	0

3.—GIRDER COVERED WAY 25 feet wide in 17 feet 6 inches CUTTING.

			s.	d.	£.	s.	d.
83	cubic yards excavation to spoil	at	4	0	16	12	0
12½	" brickwork	"	24	0	15	0	0
12	" concrete	"	7	6	4	10	0
13	sup. yards asphalt	"	2	9	1	15	9
6½	lin. yards drain pipe and blends	"	..		0	13	3
1	" barrel drain	"	..		0	15	0
32	cwt. cast-iron girders	"	8	0	12	16	0
					£52	2	0

Tunnels.—There are three tunnels on the "Inner Circle": the Clerkenwell tunnel, 728 yards long, on the original Metropolitan Railway; the "Widening" tunnel, 733 yards long, parallel to the preceding, and the Campden Hill tunnel, 421 yards in length. The two former are 28 feet 6 inches wide, with semicircular arched top, generally 6 rings thick, springing 4 feet 6 inches above the rail level. The latter is 25 feet wide with semicircular top and springing 5 feet 6 inches high. All the tunnels have four-ring inverts. A portion of the 28 feet 6 inches elliptical top covered way without invert was driven as a tunnel under the Euston Road (Plate 1, Fig. 6a), although the depth of ground over the crown bars was as little as 6 to 9 feet.

The Clerkenwell tunnel, 728 yards in length, was commenced in November 1860, and finished in May 1862. There were eleven temporary shafts, and one permanent shaft, and the depth to rail-level ranged from 29 feet to 59 feet. All of the tunnel was in London Clay, which extended from 2 feet to 11 feet over the arch, and above the clay was a bed of sand and gravel charged in places with water.

The "Widening" tunnel was begun in November 1865 and completed in May 1867. At the east end the rails dipped to pass under the original line, so the maximum depth was increased to 55 feet. Three ventilating shafts are spaced between the east tunnel mouth and the signal station, where there is open cutting for 30 feet, followed by a further length of 350 yards of tunnel-section, not driven but executed on the "cut and cover" system.

The Campden Hill tunnel, commenced in October 1865, was finished in January 1867. There was a mass of wet gravel and sand over this tunnel, extending generally down to the springing. There are no permanent ventilating shafts, but a 30-feet length of open cutting occurs at the intermediate signal station.

As a settlement in the ground, over and contiguous to the tunnel, took place in most instances, a careful investigation of the subject was made by Mr. Morton, the Resident Engineer, on the "Widening" tunnel. It was found that from the commencement of the length to the getting in of the top sill there was a settlement of $\frac{3}{4}$ inch, and from that time to the underpropping of the bottom sill, or completion of timbering, a further 2 inches. Owing to the compression of the joints in the arch after the striking of the back props when the weight first came upon the green brickwork, there was a movement of $\frac{3}{4}$ inch, which had increased to $1\frac{1}{2}$ inch twelve hours after keying. A further settlement of $1\frac{1}{4}$ inch in the arch, and $1\frac{3}{4}$ inch in the side walls and inverts, where the supporting props carried the centres, made up a total of $7\frac{1}{4}$ inches. It may be mentioned that no heading was driven in advance of the "Widening" tunnel, except a small one of 5 feet by 4 feet for getting in the first two crown bars. The tunnel was timbered in the usual way, and there were on the average eight 12 inches square crown bars and sixteen round bars at the haunches and sides of the tunnel.

The cost of labour in mining a 9-feet length was £33 for the 270 cubic yards of excavation, or 2*s.* 6*d.* per cubic yard. To this must be added the miner's profit, the cost of timber, tools, and shafts, the raising earth and carting to spoil, and the head contractor's profit, which together brought up the contract price to about 7*s.* 6*d.* per cubic yard for the excavation measured net. The actual cost of bricklaying in a 9-feet length, including loading the bricks into skips at top and delivering them to the bricklayers, was £24 for the 90 cubic yards of brickwork in the seven-ring tunnel and filling over the crown, or at the rate of 5*s.* 4*d.* per cubic yard. About 14 cubic yards of mortar and thirty-four thousand bricks were used in the 9-feet length, and adding the cost of these to that of the centering and other items, and the contractor's profit, the average contract price of 30*s.* per cubic yard for the net quantity of brickwork, exclusive of filling between bars, will be arrived at. On the preceding basis the contract price per lineal yard of tunnel 28 feet 6 inches wide would be about as follows:—

		s.	*d.*	£.	*s.*	*d.*
85 cubic yards net excavation at		7	6	31	17	6
25 ,, ,, brickwork ,,		30	0	37	10	0
				£69	7	6

On the average, sixteen miners and labourers, working nine shifts each, excavated the 9-feet length, and twelve bricklayers and labourers, working seven shifts, did the brickwork.

In carrying out the Campden Hill tunnel a bottom heading, 9 feet square in the clear, was constructed to drain the gravel and otherwise facilitate operations. The tunnel was driven in lengths of 12 feet or 12 feet 6 inches, and was timbered in the usual way, except that the top, on account of the looseness of the ground, was supported in advance of the poling by light sheeting driven into the fine sand over the crown. When one of the 16 inches or 18 inches round bars was in position, a number of 3-feet by 6-inch by 1-inch boards, having one end sharpened, were driven over the top of the bar, and square to the same into the ground, and the rear ends of the boards were packed up to the adjoining polings, and so temporarily held in position until the next bar was fixed. Sometimes the ground was double piled in this manner; but there was the greatest difficulty in stopping the run of the sand, and as the crown bars often came down 12 inches, considerable settlement and damage to property resulted. The engineers and contractors differed as to the propriety of the mode of carrying out the works. It was contended by the engineers that in tunnelling through property, as little ground should be disturbed at a time as possible; that the lengths should be rather 6 feet than 12 feet; that the brickwork should closely follow up the excavation, and that the driving of a large heading for a long time in advance of the tunnelling necessarily unsettles the ground, and renders it less able to support the subsequent tunnelling operations. Some four or five months after the Campden Hill heading had been standing, the increasing pressure of the ground told severely on the timbering. In several instances the side trees were broken and crushed down, so as to form a knee bulging towards the interior of the heading. The head trees followed the side trees, and a settlement of 4 inches or 5 inches was common. Many of the bottom sills tilted over on one side and endangered the settings; so that, to prevent the headings falling in, a considerable length had to be double timbered, which prevented the passage of the wagons. The heading was almost wholly in clay, which was softened by water percolating through fine fissures from the gravel overhead; indeed, a large quantity of water could be observed running down the sides of the heading behind the poling boards.

Owing to a strike of the miners a 76-feet length of the Campden Hill tunnel was built in open cutting; but the results were not satisfactory. In order to keep the wagon-way free the invert was left out at first, and the side walls came in 5 inches. Again, the filling in of the broad trench over the arch with nearly 30 feet in depth of made ground caused a draw in the ground, and a general settlement in adjoining property. If executed in this manner the timbering should be left in, and other precautions taken; but in any event, owing to the nature of the ground, it would have been difficult to have avoided all damage to property at Campden Hill. On the original Metropolitan Railway the clay was hard and dry, and the difficulties were much lessened. At Clerkenwell Mr. Jay drove the Metropolitan Railway tunnel along the Bagnigge-Wells Road for a length of 160 yards within 10 feet of the heavy boundary wall of the prison, with hardly any sign of settlement, and he was equally successful in passing within 8 feet of the Clerkenwell workhouse. The "Widening" tunnel was driven under the contractors' office in Exmouth Street, without any apparent damage to the exterior of the building, and with but slight internal indications of settlement. However, with the utmost precautions, tunnelling through a town is a risky operation, and settlements may occur years after the completion of the works. Water-mains may be broken in the streets and in the houses, stone staircases fall down, and other unpleasant symptoms of small earthquakes alarm the unsuspecting occupants. At the prices already given for the 28 feet 6 inches tunnel, the cost per lineal yard of the 25-feet tunnel would be as follows:—

	s.	*d.*	£.	*s.*	*d.*
76 cubic yards net excavation at	7	6	28	10	0
23 " " brickwork "	30	0	34	10	0
			£63	0	0

It is hardly necessary to remark that heavy contingencies have to be added to tunnel estimates when, as in the case of the Metropolitan Railway, the Contractors assume the responsibility of damage to adjoining property.

Open Cuttings.—At rail-level the width of the open cutting is 28 feet 6 inches on the old line and 25 feet on the extensions. The same type of retaining-wall has been adopted throughout (Plate 1, Fig. 7), namely, a brick and concrete recessed wall in 11-feet bays, with piers 3 feet and recesses 8 feet wide on the face. The batter is 1½ inch to the foot, the depth of foundations below rail level 5 feet, and the usual thickness of the walls at the base about 40 per cent. of the height. Occasionally, when the depth is considerable, the thickness has been reduced, and one or two rows of cast-iron struts have been introduced. Plate 1, Fig. 8, shows the open cutting on the original Metropolitan Railway at Acton Street, and Plate 1, Fig. 9, a similar work on the extension.

At ordinary contract prices the cost per lineal yard of open cuttings and retaining walls would be as follows:—

Open Cutting 25 feet wide and 25 feet deep.

	s.	*d.*	£.	*s.*	*d.*
143 cubic yards excavation at	4	0	28	12	0
20 ,, brickwork ,,	24	0	24	0	0
36 ,, concrete ,,	7	6	13	10	0
6 lin. yards drain pipe and bends			0	12	6
Cost per lineal yard			£66	14	6

With one row of cast-iron struts, cost £55 2*s.* 9*d.*

Open Cutting 25 feet wide and 42 feet deep, with Two Rows of Cast-iron Struts.

	s.	*d.*	£.	*s.*	*d.*
220 cubic yards excavation at	4	0	44	0	0
30 ,, brickwork ,,	24	0	36	0	0
40 ,, concrete ,,	7	6	15	0	0
8 lineal yards drain pipes and bends			0	15	6
30 cwt. cast iron			12	0	0
Cost per lineal yard			£107	15	6

In executing open cuttings, the practice at first was to timber the whole width of excavation, and follow up with the temporary rails and wagons to convey the material to spoil-banks on the Great Western and Great Northern railways. Subsequently the more usual course was to sink trenches for the retaining walls, carting away the stuff to spoil, and afterwards removing the dumpling in railway-wagons. Comparatively light timbering served for the trenches. Walings 9 inches by 3 inches by 13 feet long, spaced 3 feet apart, and struts from 7 inches square at each end and at the centre, sufficed as a rule to uphold the polings or the 12 inches by 3 inches runners used for the upper part of the excavation and the 1-inch poling boards below, but in places heavier timbering was adopted. The Author refers to his Paper on "The Actual Lateral Pressure of Earthwork" [1] for some further particulars respecting the works in open cuttings.

Stations.—There are twenty-seven stations on the 13 miles of "Inner Circle" railway. As already explained, it was the original intention to make the stations, as well as the railway, strictly "underground," and Baker Street, Portland Road, and Gower Street stations were so constructed. Plate 2, Figs. 10 and 11, show the construction at Baker Street. A segmental arch, 45 feet 1 inch span, and 10 feet 4 inches rise, six rings thick at the crown and twelve rings at the springing, where pierced with openings for light and ventilation, extends throughout the entire 300-feet length of station. When the mixed gauge was in operation the width of the platforms was 10 feet, but they are now widened. A special feature in the structure is the extreme lightness of the abutments, which are only 5 feet 6 inches thick at the piers and 2 feet 3 inches at the back of the recesses. The excavations, 56 feet 6 inches in width, were timbered right across with three rows of main struts 10 inches square, spaced about 4 feet 6 inches apart longitudinally, and 12 inches by 6 inches walings supporting runners at the top, and poling boards at the bottom of the excavation. The contract prices were 4*s.* 6*d.* per cubic yard for earthwork to spoil, 7*s.* per cubic yard for concrete, the gravel being on the spot, and 25*s.* 6*d.* for brickwork, with white brick facing. Including booking offices, street restorations, and all contingent works, the cost of an underground station, such as Baker Street, amounts to £18,000 more than that of the same length of covered way.

Where the local conditions admitted it, the stations were placed in open cuttings with vertical retaining-walls, elliptical arched iron roofs (Plate 2, Fig. 12), and short lengths of open cutting at each end for ventilation. The platforms are 300 feet long by 15 feet wide, and the roofs 50 feet 6 inches span. On the average the cost of such a station, beyond that of the corresponding length of ordinary railway, ranged from about £14,000 in the instance of Queen's Road, Bayswater, to £22,000 in that of Victoria. At

[1] Minutes of Proceedings Inst. C.E., vol. lxv., p. 140.

St. James's Park station the cost price of the roof, 330 feet in length by 50 feet 6 inches span, was £4,040, or £24 5*s.* per square measured on the flat. There are 79 tons 18 cwt. of wrought iron, 52 tons 13 cwt. of cast iron, one hundred and sixteen squares of zinc, and ninety-five squares of rough plate glass in the roof referred to. The general price of the booking offices, including gas and all other fittings, was 10½*d.* per cubic foot. Separate entrance and exit staircases and galleries are provided at the stations, but not always used, as they involve a double staff of ticket-men. Ordinarily the width of stairs is 6 feet, and the treads are 11 inches by 6 inches.

At the Temple (Plate 2, Fig. 13) a special kind of station had to be devised, as the agreement with the Duke of Norfolk precluded the use of a raised roof. At the Mansion House (Plate 2, Fig. 14) also the works are of an unusual character, as they lie partly under the subways and vaults of Queen Victoria Street. The wrought-iron columns carrying the girders are connected by continuous walls of brickwork in cement and timber copings, with a view to deflect the blow of any de-railed train.

Permanent Way.—From Paddington to Farringdon Street the permanent way originally consisted of a 60-lbs. wrought-iron flange rail, with case-hardened top, secured to 13 inches by 6½ inches longitudinals by ⅝-inch fang-bolts. A steel rail of the same section was next adopted, and carried the heavy traffic safely, though the wear was great and the trouble of renewals considerable. On extending the line to Moorgate Street in 1863, an 83-lbs. steel flange-rail, laid on 10 inches by 5 inches cross-sleepers, was substituted for the original light longitudinal sleeper-road. The price paid for the first lot of 83-lbs. rails was £18 15*s.* per ton, and for the double-line road complete, including ballasting, £5 per lineal yard, or nearly £9,000 per mile. The flange-rail was used until 1873, when it was gradually replaced by a chair road.

Special Works.

With present experience the construction of underground city railways need cause the engineer or contractor but little anxiety compared with that encountered by the pioneers of such works twenty-five years ago. It is known now what precautions are necessary to ensure the safety of valuable buildings near to the excavations; how to timber the cuttings securely, and keep them clear of water without drawing the sand from under the foundations of adjoining houses; how to underpin walls, and, if necessary, carry the railway under houses and within a few inches of the kitchen floors without pulling anything down; how to drive tunnels; divert sewers over or under the railway, keep up the numerous gas and water mains, and maintain the road traffic when the railway is being carried underneath; and finally, how to construct the covered way, so that buildings of any height and weight may be erected over the railway without risk of subsequent injury from settlement or vibration. The Author from personal experience can testify that many of the expedients, which now appear obviously safe and proper, received much anxious discussion and criticism before they were decided upon twenty-five years ago. Such questions as the admissible stress on brick arches loaded on one haunch only; the extent to which expansion and contraction of iron girders would affect buildings carried by them, the ability of made ground to resist the lateral thrust of arches, and a multitude of similar problems had to be dealt with tentatively at first, and with increasing boldness as experience was gained. Novel problems and special works occur in abundance on the "Inner Circle Railway," but only a few can be touched upon in the present Paper.

Sewers.—Siphons were rarely resorted to for carrying sewers across the railway. An early constructed one occurs at Stafford Street, where a 5 feet by 3 feet sewer is carried in a 3 feet diameter cast-iron siphon 81 feet long, with a dip of 14 feet under the railway, flushing sluices and mud-doors being provided to minimise the evils of deposit. At Blackfriars the Fleet sewer was temporarily siphoned under the line, and the same course was followed with some other sewers. As a rule, however, sewers if not wholly diverted were either carried over the line in a cast-iron tube, or under it in a brick channel with iron top. Plate 2, Figs. 15 and 16, show the Fleet crossing of the Metropolitan Railway and the "widening" lines at Frederick Street. The sewer, 10 feet 2 inches wide by 9 feet 7 inches high, is carried in a cast-iron built-up tube, supported on cast-iron girders. At each end the ironwork is built into the brickwork, and though the effects of expansion were somewhat feared, no trouble has arisen from that cause. At Farringdon Street the Middle Level Sewer crosses the station yard in a wrought-iron tube 8 feet 9 inches in diameter, 130 feet long, supported on wrought-iron girders. Provision for expansion was made by connecting the wrought-iron tube and brick sewer with an assumedly flexible sheet-lead joint, but whether this still exists or has long since disappeared from galvanic action, the Author cannot say. At Sloane Square he substituted a cast-iron tube 9 feet in diameter and 86 feet long, and a flexible wrought-iron expansion joint (Plate 2, Fig. 17), as offering a greater chance of durability. Many of the smaller sewers were carried in pipes of oval section, cast in about 9-feet lengths, and bolted together. One at Gloucester Road, 85 feet long, was made up of ten lengths of 5 feet 6 inches by 3 feet tube, $1\frac{1}{8}$ inch thick, securely bolted together; but in all cases, however strong the sewer castings might be in themselves, girders were introduced to carry the sewer. Occasionally cast-iron troughs with skew ends were let into the brickwork, and sometimes a pair of girders with flat plates resting on the bottom flanges were introduced for carrying sewers and pipes across the arch. The sewage was conveyed temporarily in well calked wooden troughs, round which in some cases the permanent cast-iron sewers were built. To avoid siphons the side walls were often underpinned and the inverts lowered for a considerable length; thus at Gloucester Terrace the Ranelagh sewer (Plate 2, Fig. 18) was underpinned to a depth of 8 feet, and for a length of 1,000 feet to carry it under the railway and into the Middle Level Sewer. A noticeable piece of special construction in connection with sewers occurs at Blackfriars (Plate 2, Fig. 19), where the Low Level sewer 8 feet 6 inches in diameter, crosses diagonally under the railway. As this sewer is subject to hydrostatic pressure, wrought-iron hoops are built into the brickwork to resist the bursting stress.

Gas and Water Mains.—These were generally carried across the line in cast-iron troughs or similar construction. Occasionally very expensive diversions were necessary; thus, in passing Broad Sanctuary no less than 2,000 feet of gas-mains, ranging from 14 to 30 inches in diameter, had to be diverted, and in the simple crossing of High Street, Kensington, 600 feet of gas and water-pipes, from 3 to 30 inches in diameter, blocked the way. Where the covered way was deep enough to clear the existing mains, the latter merely required to be slung temporarily from heavy balks, whilst the works were executed beneath.

Temporary Roadways.—In the case of interference with busy thoroughfares, the authorities sometimes required the whole width of roadway to be kept open for vehicular traffic. Whether the whole or only a part of the roadway were dealt with, the principle was the same, namely, to throw heavy timbers across the railway, occasionally extending them up to the front walls of the houses on either side, to serve as struts, and to plank these timbers for the roadway, and support them with props as the excavation proceeded underneath. No difficulty was found even in the earliest days in maintaining the street traffic during the progress of the works, but the cost was necessarily considerable, amounting sometimes to 5*s.* per superficial foot of temporary roadway, or more than the brickwork of the covered way itself.

Supporting Buildings.—In passing a sound building on a good foundation, the only precaution found necessary was to execute the work in short lengths, with carefully timbered trenches quickly followed up by the concrete and brickwork of the retaining-walls or covered way. Plate 2, Figs. 19 to 21 are examples of work so executed without any resultant cracks in the buildings. Old buildings were always substantially shored, and in many cases underpinning was resorted to previous to the commencement of the railway works. The first piece of work of the kind on the Metropolitan Railway was carried out in 1861 by the late Mr. T. Armstrong, the contractors' agent for the greater portion of the line from Paddington to Moorgate, and the one, therefore, who had the earliest experience of the specialities of underground railway construction. At the corner of Edgware Road the arch-covered way ran foul of some important arched vaults which it was necessary to maintain intact, although the brickwork cut nearly through the arch of the railway. This case of underpinning one arch by another arch was effected without causing the slightest severance of the vaults from the buildings, and confidence in the ability to carry out such works was thus usefully strengthened. In 1867 Mr. Armstrong successfully executed the very extensive underpinning works at the Farringdon Station yard. Here the retaining-wall, 620 feet in length, 32 feet high and 11 feet thick, was underpinned to a depth of from 10 feet to 24 feet without causing the smallest movement in the ground, which was clay with pockets of very fine sand, or in the Fleet sewer running parallel to and within 15 feet of the back of the wall. At the same spot the abutments of Ray Street bridge, a heavy brick arch of 50 feet 6 inches span, were similarly underpinned (Plate 2, Fig. 22), as was also the tunnel mouth of the railway (Plate 2, Figs. 23 and 24). The abutments of Ray Street were underpinned in 4-feet lengths, containing 34½ cubic yards of excavation, which cost for labour £15 16*s.*, and for timber £5 10*s.*, or say 12*s.* 6*d.* per cubic yard, exclusive of profit and contingencies. In 1866 Mr. T. Walker underpinned sixteen houses in Conduit Street, and very many such works will be found on the "Inner Circle." Sometimes the underpinning has been attempted in long lengths, such as 12 feet, but extensive damage to property resulted.

When the original line had to be carried under a couple of houses in Park Crescent the portions of the structures immediately over the railway, weighing about 1,200 tons, were pulled down and rebuilt on wrought-iron box-girders. Some four years after, when the line was being extended through Pembridge Square (Plate 1, Fig. 24a) the houses were kept up; the side walls of the railway were constructed in short lengths, and main girders of 25-feet span slipped between the walls of the houses at convenient places, supported a number of short cross girders pinned through the walls. At Park Crescent only a floor of old ship-timber separates the kitchens from the railway, but at Pembridge Square brick jack-arches intervene.

Since the completion of the line very many buildings have been erected over it at different points. In some instances the covered way was originally constructed of sufficient strength to carry buildings, and in others it was subsequently strengthened. Where the depth was sufficient for an arch, brick-covered ways were adopted in preference to iron-girder constructions, on account of the smaller cost and increased durability. The first instance of building over the railway was at Edgware Road, where the line of frontage crossed the arched covered way on the skew for a length of 80 feet. As constructed the arch was not strong enough to carry the unequally-distributed weight of the houses, and four wrought-iron girders were consequently thrown across the 28 feet 6 inches covered way under the main walls. It was contended before an arbitrator that as part of the buildings rested on elastic girders, part on the brick arch, and the remainder on the adjoining ground, cracks would necessarily ensue from the shaking and vibration of this mixed construction. The Author held that if the walls were built in mortar and run up quickly no evil results would ensue, but clearly, in the absence of experience, no one could predict definitely what would happen. As a matter of fact no inconvenience resulted in the case referred to or in any similar cases. At King's Cross, where a 28 feet 6 inches and a 25 feet brick covered way, with central pier, are crossed diagonally by two lines of frontages for a length of 130 feet, the following plan was adopted by the Author: Over the arch, which had been built some years before, were placed wrought-iron girders spanning the 28 feet 6 inches covered way, and cantilevering over so much of the 25-feet way as the line of frontage demanded. These girders were kept a few inches clear of the arch, and upon them the main walls of the houses were built. When all deflection of the girders under the dead weight of the building had ceased, the space between the lower flanges and the arches was solidly built in, so that all live loads on the floors would be supported by the brick arch. By this contrivance, which proved quite satisfactory in practice, the weight of the girders was reduced by about one-half.

As an instance of the confidence which experience gives, it may be mentioned that although in 1861 the doubts entertained by the engineers as to the behaviour of a compound brick and iron structure were such as to lead to a timber front being put to the Edgware Road Station building, where it rested on a 49-feet span girder, yet, in 1865, when the extension to Moorgate was executed, no hesitation was felt in trusting an elaborate brick and ashlar face wall, weighing 1,300 tons, to a continuous girder 135 feet in length.

At Westminster and at Blackfriars Stations there are buildings some 80 feet in height carried on girders, spanning the rails and platforms; and at Victoria Street, Westminster, the arched covered way from eight to ten rings thick, runs for a length of 400 feet under the heavy buildings since constructed. It would be useless to tabulate the numerous cases similar to the preceding, but the Author may sum up his experience and practice as follows:—(1) In the instance of buildings carried on girders, adopt a working tensile stress of 6 to 7 tons per square inch, according to the height and solidity of the wall resting on the girder, and interpose a layer or two of tarred felt between the ironwork and brickwork. (2) In the case of buildings carried on arches, spread out the footings of the walls and assume the effective width of foundation, or length of covered way over which the weight of a wall will be distributed, as equal to double the thickness of the wall plus double the thickness of the arch; construct the curve of equilibrium due to the weight of building and arch, and so proportion the number of rings of brickwork that an ideal arch, following the form of the line of thrust, and of a thickness corresponding to a uniformly distributed stress of 8 tons per square foot, would fall within the actual arch. This empirical rule has answered well in practice, and is as scientific as any formula based on the false assumption of a constant modulus of elasticity, which the Author has never found to obtain in his own experiments. It may be added, that houses 43 feet in height from foundation to parapet, and having three floors exclusive of basement, were allowed to be built on the ordinary five-ring covered way, the footings being spread out to a width of 3 feet by brickwork or concrete.

Smithfield Market.—In connection with the extension to Moorgate Street, the basement of the large Meat Market at Smithfield was constructed by the railway companies. The floor of this market, 625 feet long by 240 feet wide, affords perhaps the largest example in existence of wrought-iron girders and brick arch construction. Twenty continuous main girders, each 245 feet in length, span the width of the market, and carry longitudinal girders 630 feet in length, spaced 7 feet 6 inches apart, with jack arches two rings thick, and 1 foot 9 inches rise between them. The main girders, loaded with from 8 to 9 tons per lineal foot, are supported by wrought-iron columns at intervals ranging from a few feet to 58 feet. It is noteworthy that no provision whatever was made for expansion in any of the ironwork, which convenient course was amply justified by experience, no indications of movement being observable in the brick walls or floor. Brick vaults, in 15 feet bays, surround the market and retain the earth, the depth of which from floor to rail level is 24 feet. Extensive hydraulic plant was provided to work the sidings, turn-tables, and hoists, and a special approach road affords access for vehicular traffic to the lower level.

Bellmouth at King's Cross.—As first constructed, the single line eastern junction curve from the Great Northern Railway joined the Metropolitan Railway 150 yards west of the King's Cross Station, and the western curve, crossing the eastern curve on the level, joined the Metropolitan 80 yards further east. The whole of the works being in covered way, two bellmouths, 28 feet 6 inches span at one end and 45 feet 6 inches at the other, had to be built. When in 1867 the "widening" lines were executed, and a junction was made with the Midland Railway, it became necessary to do away with the existing bellmouth, and substitute two others; and, as this had to be effected whilst the traffic was running, the works were both novel in design and difficult of execution. Plate 2, Fig. 25, illustrates one of the peculiarities of construction. A longitudinal slice was cut off the old bellmouth, and the lateral thrust of the new arch distributed by means of castings built in the brickwork of the central pier. At other cross-sections different expedients were resorted to for maintaining temporarily and permanently the stability of the strangely-shaped covered way. Cast iron was also introduced in combination with a brick covered way on the St. John's Wood line. As the depth was insufficient for the ordinary 32-feet span covered way, the top of the arch was flattened to a radius of 40 feet, and castings, 18 feet long and 2 feet 6 inches deep, with a camber of 1 foot, were built into the brickwork every 6 feet. Cast-iron arches and struts were also built in at Baker Street and Gower Street stations, and other points where sufficient strength could not otherwise be obtained.

The Author has now finished his outline sketch of the general history and engineering features of the $11\frac{1}{4}$ miles of Metropolitan and Metropolitan District Railway, with the construction of which he was himself personally connected. He is the better reconciled to the obvious imperfections of his work by the reflection, that its very incompleteness may tempt other engineers, who have been engaged on the Inner Circle Railway, to fill in his outline sketch with such details as they individually may consider of special interest to members of the Institution. He would only add that the Chief Resident Engineers were, on the Metropolitan Railway works from Kensington to Moorgate, Mr. William Morton, and on the District Railway works from Kensington to Mansion House, Mr. Frederick Cooper, MM. Inst. C.E.

The Paper is accompanied by numerous drawings from which Plates 1 and 2 have been engraved.

Fig: 1.

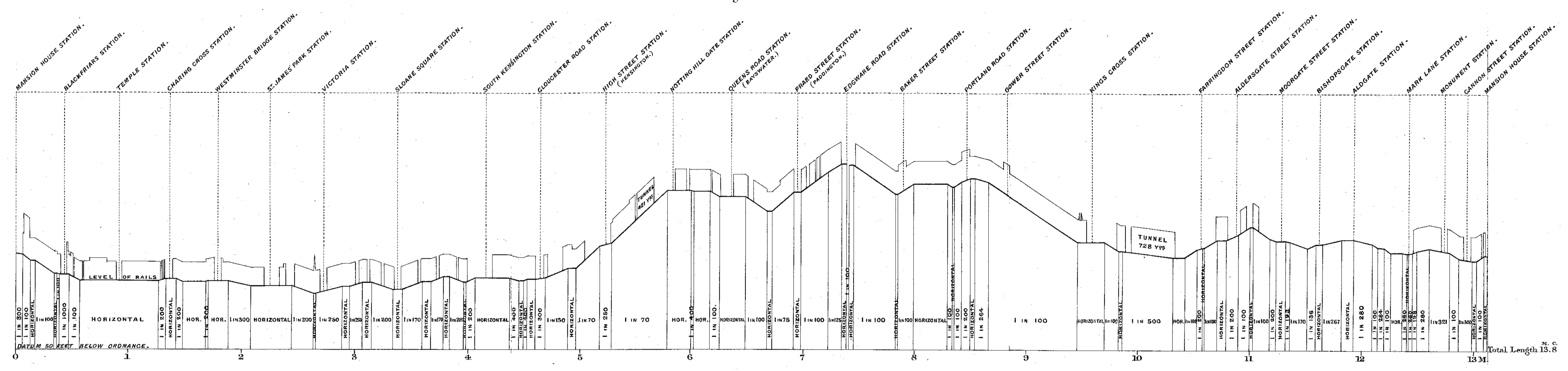


DIAGRAM OF GRADIENTS OF INNER CIRCLE RAILWAY.

Horizontal Scale for Figs 1 & 2.

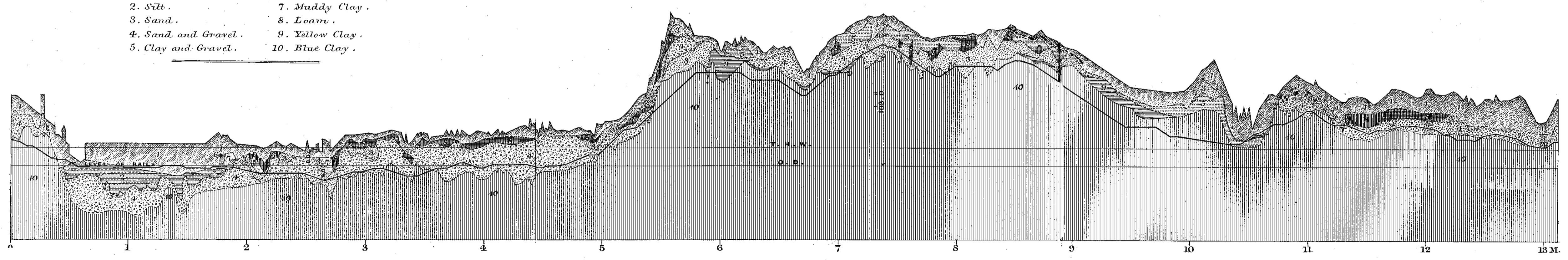
Vertical Scale for Figs 1 & 2.

Scale for Figs 3 to 9.

Fig: 2.

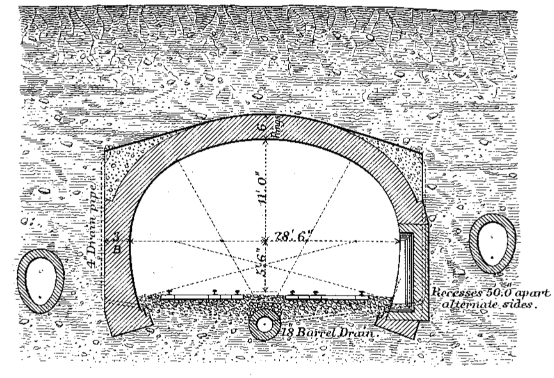
REFERENCE.

1. Made Ground. 6. Peat.
2. Silt. 7. Muddy Clay.
3. Sand. 8. Loam.
4. Sand and Gravel. 9. Yellow Clay.
5. Clay and Gravel. 10. Blue Clay.



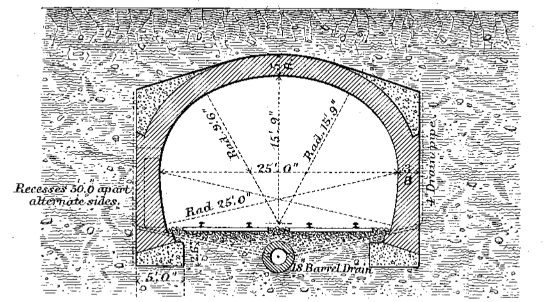
GEOLOGICAL SECTION.

Fig: 3.



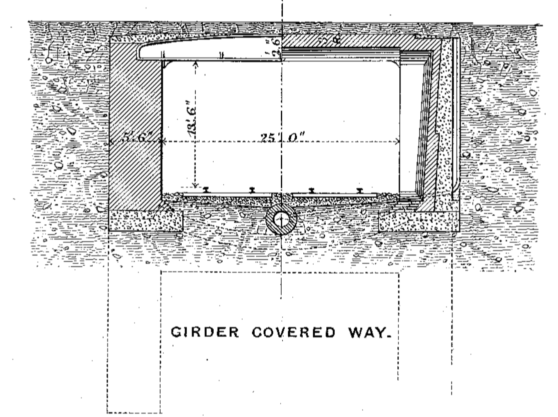
METROPOLITAN RAILWAY.
TYPE SECTION OF COVERED WAY.

Fig: 4.



METROPOLITAN DISTRICT RAILWAY.
TYPE SECTION OF COVERED WAY.

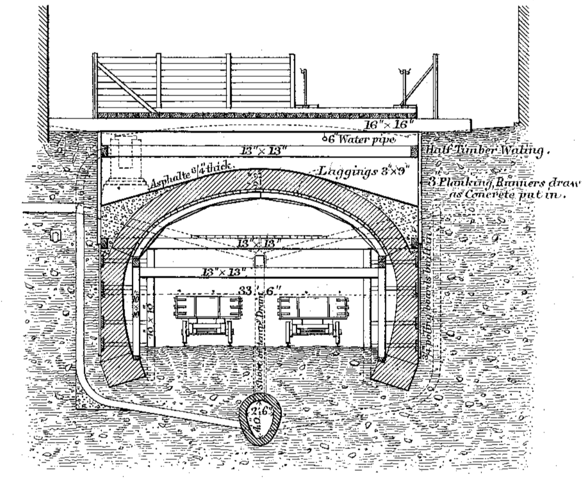
Fig: 5.



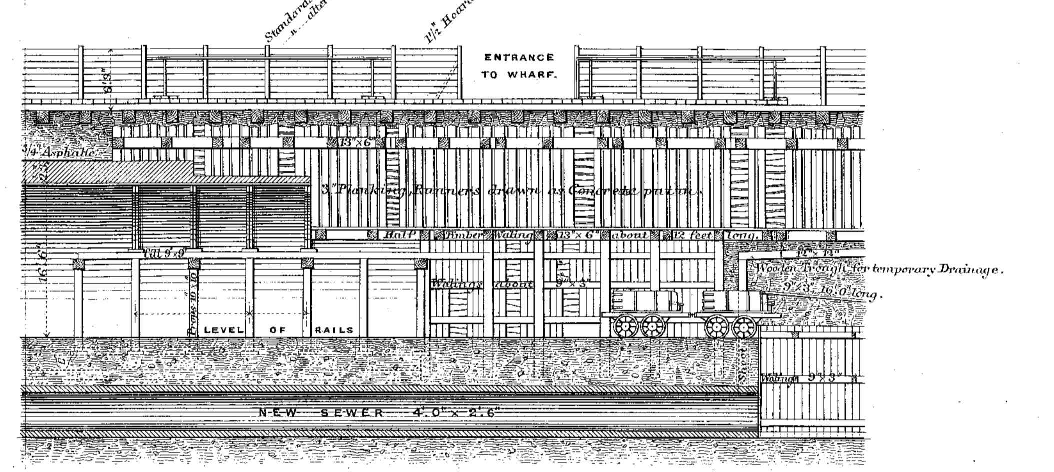
GIRDER COVERED WAY.

Fig: 6.

TIMBERING AT SOUTH WHARF ROAD.

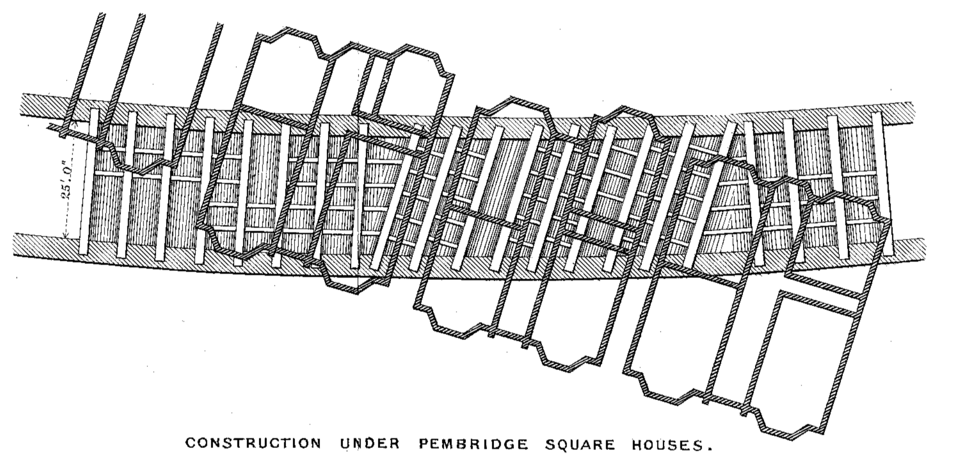


CROSS SECTION.



LONGITUDINAL SECTION.

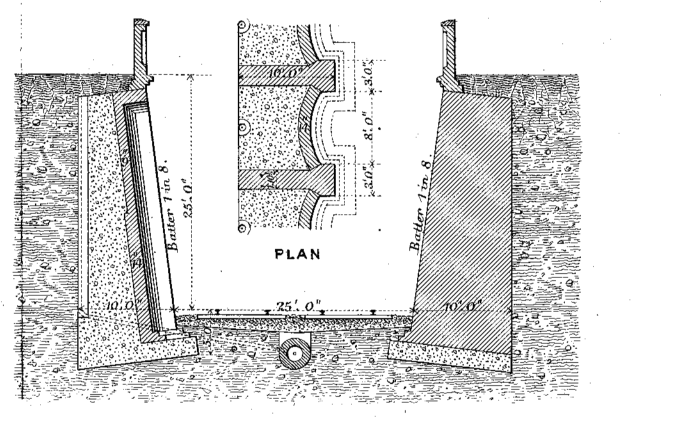
Fig: 24a.



CONSTRUCTION UNDER PEMBRIDGE SQUARE HOUSES.

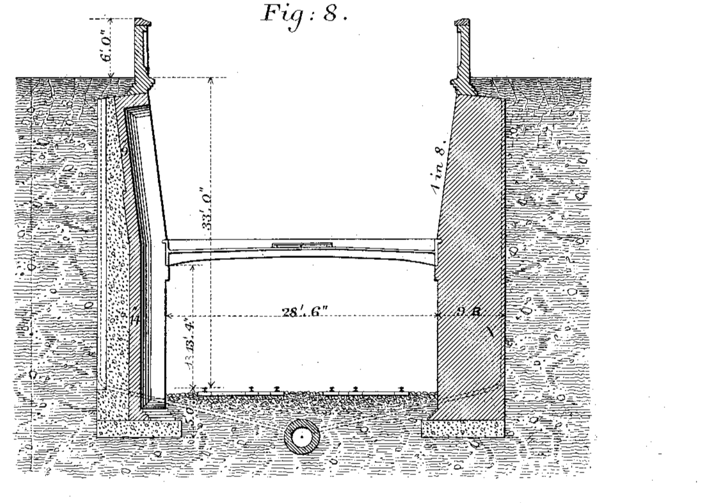
Scale of Feet.

Fig: 7.



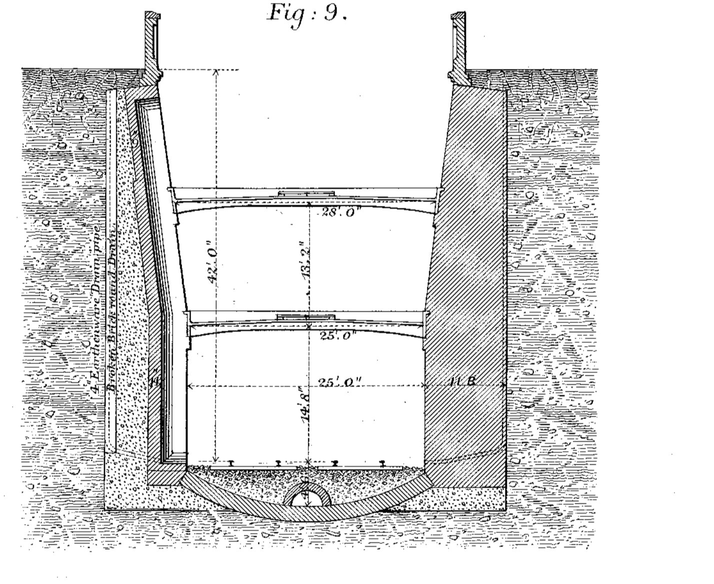
CROSS SECTION OF OPEN CUTTING.

Fig: 8.



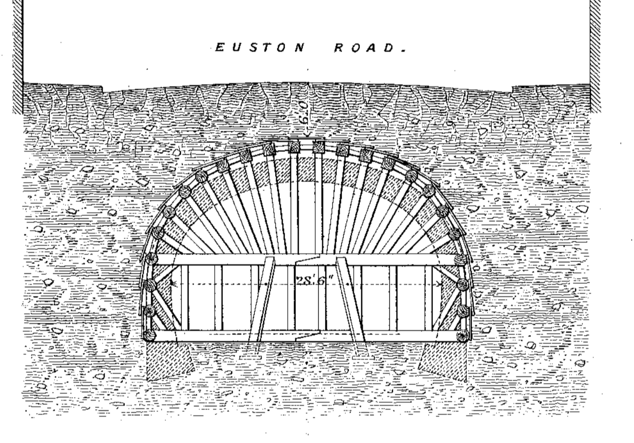
OPEN CUTTING WITH SINGLE STRUT.

Fig: 9.



OPEN CUTTING WITH TWO ROWS OF STRUTS.

Fig: 6a.



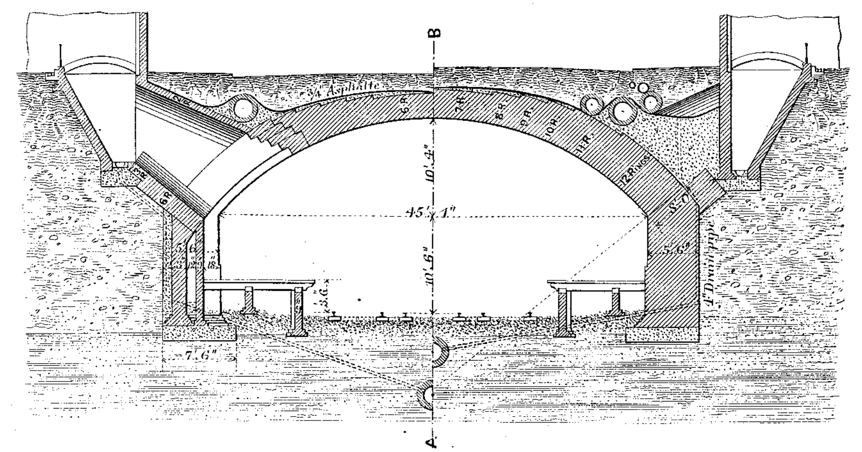
TIMBERING OF TUNNEL.

B. BAKER, Del.t

THOS KELL & SON, LITH. 40, KING ST COVENT GARDEN.

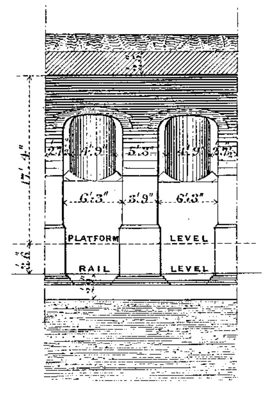
Fig: 10.

BAKER STREET STATION.



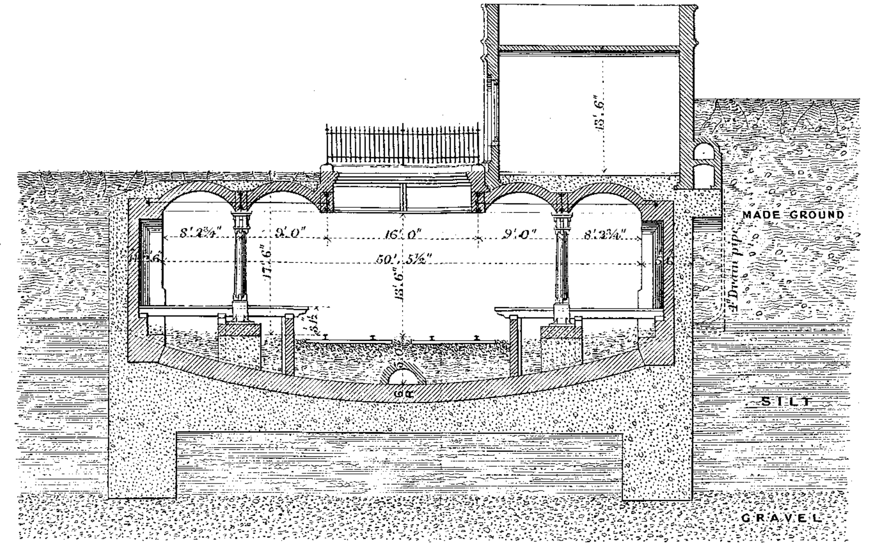
HALF CROSS SECTION THROUGH LIGHT. HALF CROSS SECTION THROUGH PIER.

Fig: 11.



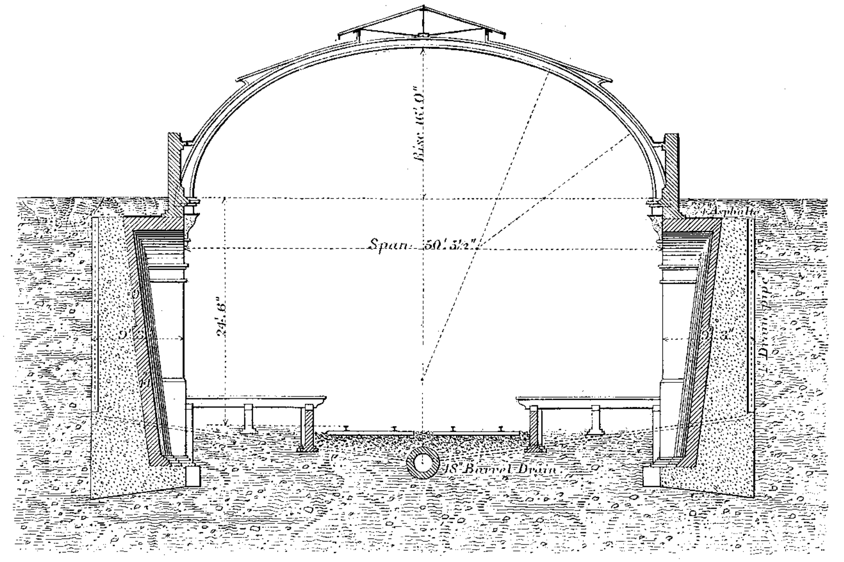
SECTION ON LINE A.B.

Fig: 13.



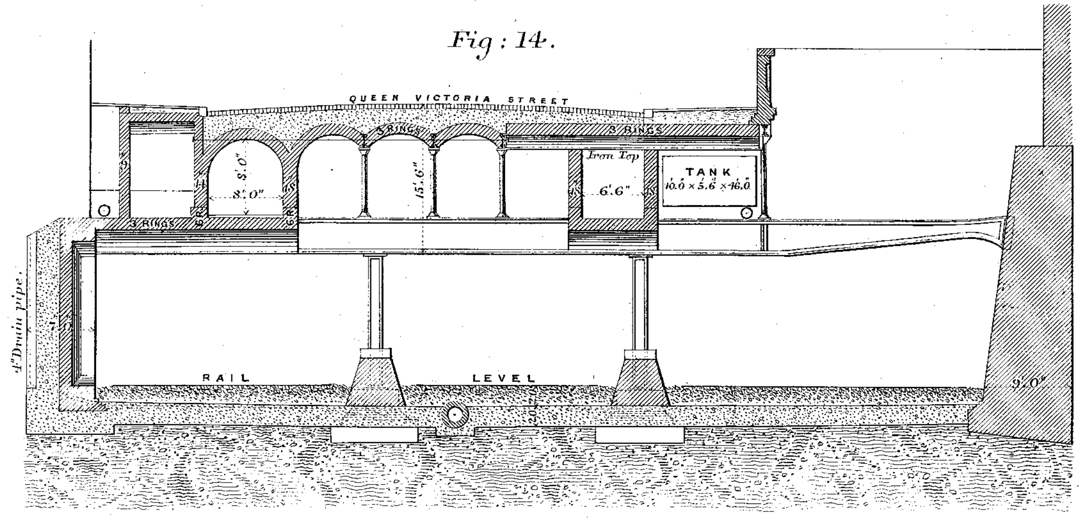
TEMPLE STATION.

Fig: 12.



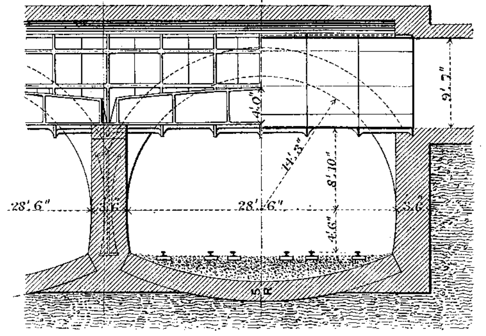
SLOANE SQUARE STATION

Fig: 14.



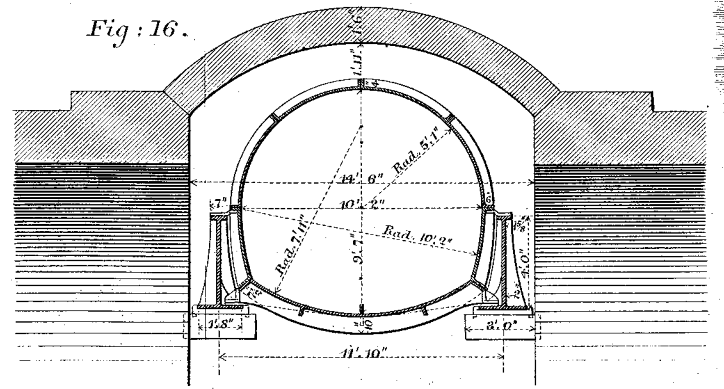
MANSION HOUSE STATION.

Fig: 15.



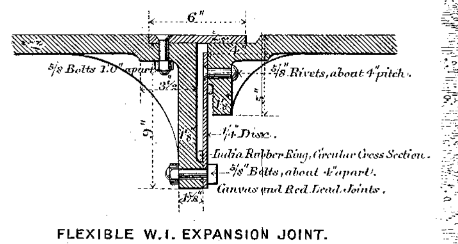
FLEET SEWER CROSSING AT FREDERICK STREET.

Fig: 16.



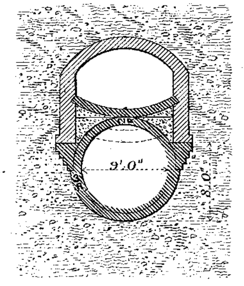
CROSS SECTION OF FLEET SEWER.

Fig: 17.



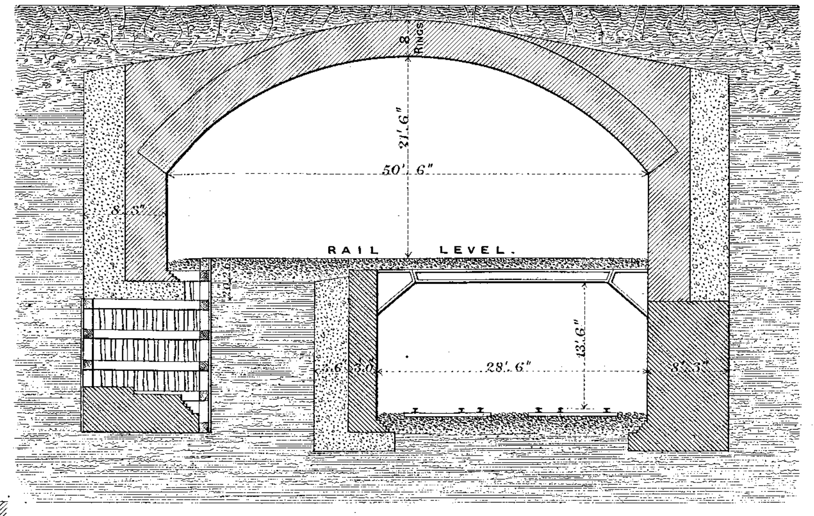
FLEXIBLE W.I. EXPANSION JOINT.
RANELAGH SEWER, SLOANE SQUARE.

Fig: 18.



UNDERPINNING OF RANELAGH SEWER AT GLOUCESTER ROAD.

Fig: 22.



UNDERPINNING OF RAY STREET BRIDGE.

Fig: 23.

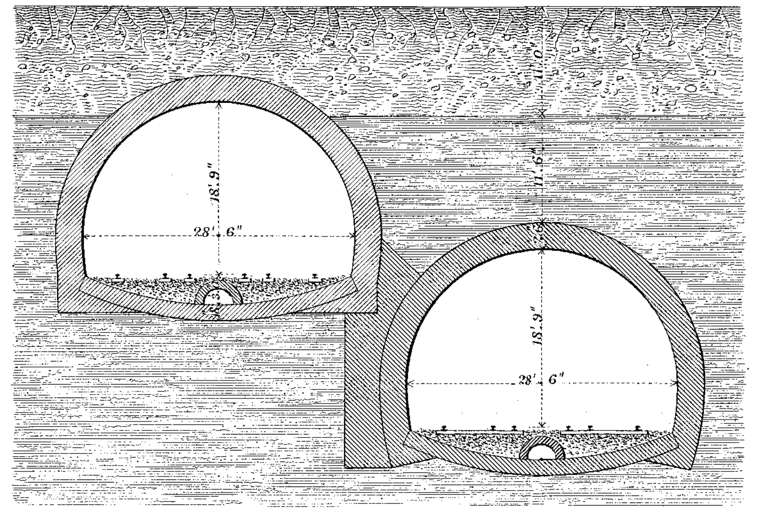
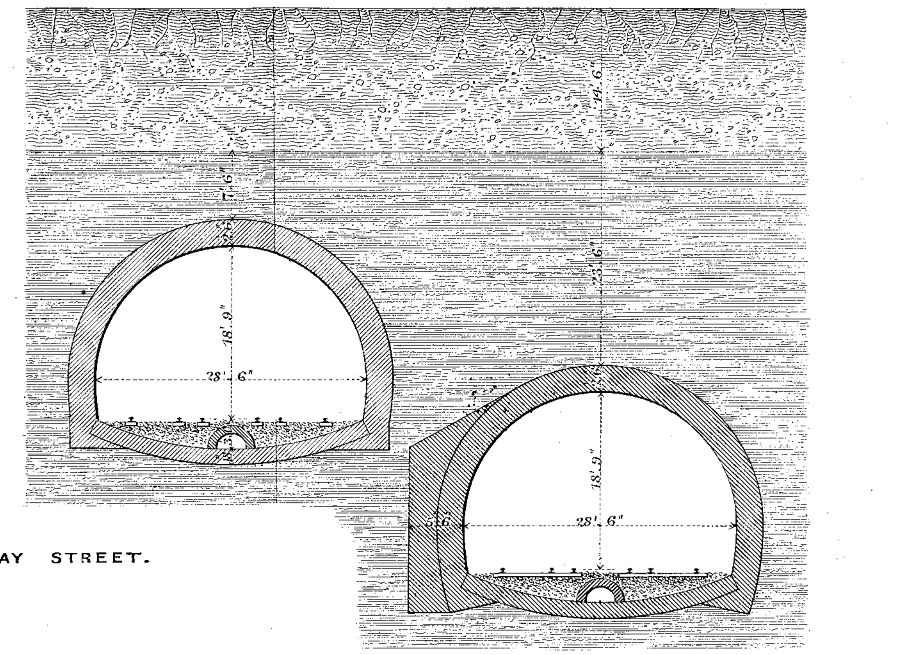


Fig: 24.



TUNNELS NEAR RAY STREET.

Fig: 19.

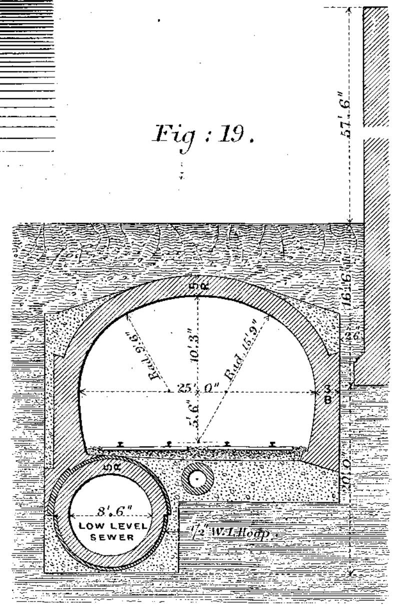
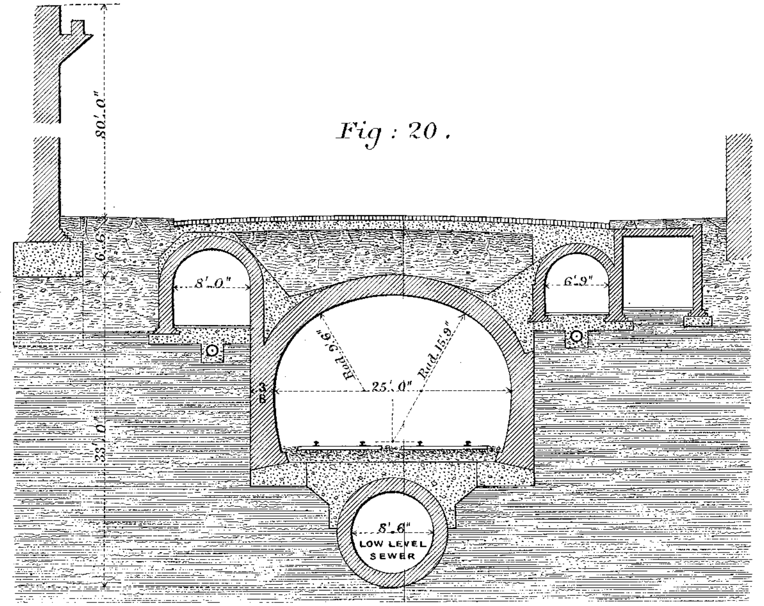
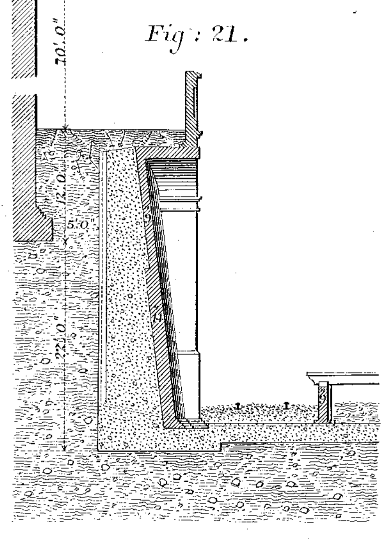


Fig: 20.



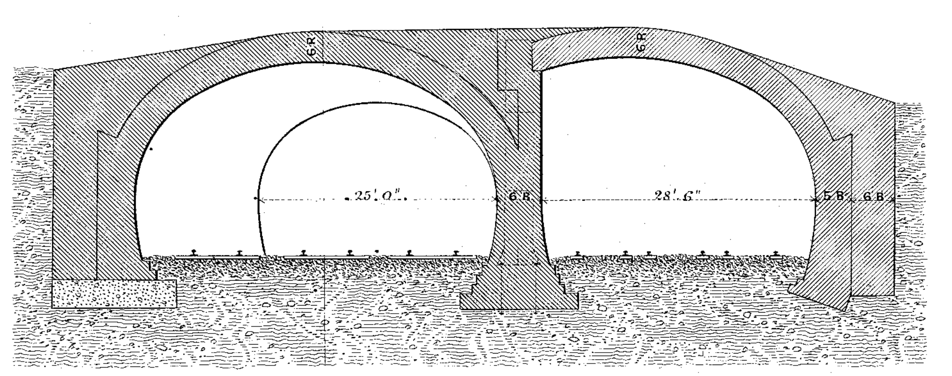
CONSTRUCTIONS IN QUEEN VICTORIA STREET.

Fig: 21.



RETAINING WALL AT MANSION HOUSE STATION.

Fig: 25.



BELLMOUTH AT KINGS CROSS.

Scale for Figs 10 to 15 & 18 to 25. 20 Feet = 1 Inch.

Scale for Fig 16. 8 Feet = 1 Inch.

Scale for Fig 17.

B. BAKER, DELT

THOS KELL & SON, LITH 40, KING ST COVENT GARDEN.