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Embankments and Cuttings on the early Railways

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Introduction

Between 1834 and 1841 nine main lines of railway were built in England totalling 660 miles in length complete with tunnels, bridges, viaducts and stations and involving the excavation, in cuttings, of some 70 million cu.yd (54 million cu.m) of material, most of which was used in making embankments. Construction on this scale had no precedent. The earthwork quantities, in particular, are astonishing. Apart from the vast total amount, about 2 to 3 million cu.yd of excavation (and banking) was achieved on each line per year averaged over the whole period of its construction (Table 1); figures not much less than the rate of work on the Great Central Railway in the 1890s, using 40 steam navvies and upwards of 100 locomotives, and substantially exceeded, on works of a comparable nature, only with the introduction of modern earthmoving plant on the first 55 mile length of the M1 Motorway in 1958, where 11 million cu.yd were excavated and placed in (well-compacted) embankments at an average rate of 7 million cu.yd per year¹. Yet one looks almost in vain in modern histories for details of the methods employed, the results obtained or the difficulties encountered in making embankments and cuttings on the early railways.

	DATE		LENGTH	EXCAVATION		
RAILWAY	WORK BEGAN	LINE OPENED	MILES	TOTAL Million cu. yd.	VOLUME PER MILE cu. yd	VOLUME PER YEAR Million cu. yd
Liverpool & Manchester	Mar. '27	Sep. '30	31	2.7	90,000	0.8
Grand Junction	Jun '34	Jul. '37	78	5.5	70,000	1.8
London & Birmingham	Jun '34	Sep. '38	112	13.0	115,000	3.1
Great Western	Feb. '36	Jun. '41	118	9.8	85,000	1.8
Midland Counties	May '37	Jun. '40	57	5.4	95,000	1.7
London & Brighton	Sep. '38	Sep. '41	48	6.9	145,000	2.3
Great Central	Nov. '94	Jul. '89	94	13.3	140,000	3.5

Table 1: Excavation Quantities

By contrast, as these were subjects of great concern to the engineers and contractors involved, there is plenty of information available chiefly in reports and parliamentary papers, together with articles in the *Civil Engineer & Architect's Journal* and an important paper in *Proceedings of the Institution of Civil Engineers* as well as several books, all published before 1846. This material forms the basis of the present paper.

Management

The high rates of construction were achieved by good organisation and a large work force. Data are given in Table 2, where the numbers of men employed include bricklayers and masons as well as navvies, but not the brickmakers and quarrymen². Locomotives and staionary engines were used on some of the earthwork operations, and in addition there would be several small steam engines for pumping excavations.

Table 2: Workforce

RAILWAY	DATES	NUMBERS EMPLOYED				
		MEN	HORSES	LOCOS	STATIONARY ENGINES	
Great Western	Jul. 1837	6250	450	4	2	
Midland Counties	Dec. 1838	4030	460	2	1	
Midland Counties	May 1839	5140	510	3	1	
London & Brighton	Jan. 1840	4370	690	5	0	
London & Brighton	Jul. 1840	6210	960	5	0	

As for organisation, the plan adopted on the London & Brighton Railway is typical: under the engineer-in-chief John Rastrick there were three resident engineers in charge of three divisions of the line and another responsible for the tunnels, each with three or four assistants. The 48 mile length was divided into 14 contracts, plus separate contracts for three long tunnels, and on every contract there was a superintendent or agent directing the gangs, many of which worked as sub-contractors.

Excavation and End-Tipping

All 'soft ground' including clay, gravel and the softer variety of Chalk was excavated by pick and shovel. Hard rock had to be blasted. For example, in Blisworth cutting on the London & Birmingham Railway up to a ton of gunpowder was used per week in blasting the limestone (270,000 cu.yd out of a total 870,000, mostly excavated between December 1836 and May 1838)³. In an intermediate category of soft rock a (horse-drawn) plough proved to be most effective. This seems to have been introduced by the contractor Joseph Thornton in 1835 while excavating Keuper Marl in the deep cutting at Yardley, also on the London & Birmingham, where, as usual, the excavated material was taken into an adjacent embankment. According to an account written four years later:

after a few trials, and by increasing the strength and altering the form of the plough, the plan was crowned with a success far beyond what was originally contemplated; for it was found that, in addition to dispensing with a number of men employed in undermining, wedging and breaking up, it reduced the material to such small pieces that the labour of several men, who used to break it up at the foot of the embankment, was saved; and many excavations are now entirely worked with the plough.⁴

Clearly it was desirable so far as possible to balance 'cut' and 'fill', both in total and over relatively short distances. Admittedly it was not difficult to excavate a cutting and simply run the material to spoil banks nearby, or to build an embankment from borrow pits along each side of its base (the process of 'side-cutting'). But the total cost would be roughly double that involved in building embankments of material from cuttings; while extra land was required outside the normal boundaries, and useless spoil banks or pits would be left alongside the line. Locally such methods had to be adopted to overcome a deficiency of banking material or an excess of excavation, and sometimes they were used to expedite construction. But as a general rule embankments were formed from cuttings, not too far distant, the excavated material being carried in earth waggons drawn by horses or, for distances of more than about two miles, by locomotives. An integrated system of cutting and embanking was therefore achieved, capable of handling large quantities in a reasonably short time.

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Fig 1: Cutting and embanking, from 'Resident Assistant Engineer' (J.D. Hughes), A Practical Inquiry into the Laws of Excavation and Embankments upon Railways (1840).

Now the best way of building an embankment, especially in clay, would have been to form the bank in shallow layers, say 2 to 4 ft thick, running out each of them to the full length, and following with the upper layers after each of the lower ones was laid and compacted with 'beetles' or punners. The bank is thus progressively raised and there is time for some consolidation in the bank and foundation. This was the method (with 4 ft layers) specified by John Macneill in 1836 for embankments on the Slamannan Railway in Scotland (12 miles long, built 1837-40) where the strata chiefly consists of Boulder Clay overlying Coal Measures and the total excavation amounted only to 1 million cu.yd, the largest embankment being 40 ft high with 2:1 slopes and 180,000 cu.yd. of fill⁵.

It was also quite usual to compact in layers that portion of an embankment immediately adjacent to the abutment of a viaduct⁶. But construction of the whole of an embankment in shallow layers was too slow a process, and one not well suited to the combined operations of cutting and embanking on a large scale. Instead, the method most commonly used on the railways by the mid 1830s was to run out the bank to its full height at once, by end-tipping from the advancing head of the bank on a level with the bottom of the cutting.



Fig 2: Earth waggon, from Civil Engineer and Architect's Journal 6 (1843).

be drawn back to the cutting.

The embankment in Fig. 1 is being tipped from three 'teaming roads' on a bank little wider than its finished dimension and with side slopes, at the angle of repose, which merely require

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The procedure is illustrated in Fig. 1. The cutting has been started by opening a 'gullet' 8 ft deep. Above this the 'second lift' is being worked on the face and sides with barrows. These, when filled, are wheeled over stages and emptied into earth waggons. The loaded waggons in a 'set' of six are led towards the bankhead and then drawn out singly at about 6 m.p.h. by a horse until 20 yd from the end, when the horse is suddenly detached and the waggon (Fig. 2) is precipitated against a wooden bumper and thus tilted over7. Meanwhile another waggon is 'teamed', and so on until the set is ready to

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trimming to the finished inclination of 1.5:1 in this example. More often the finished slope was 2:1. The working width at the head would then be greater (Fig. 3), allowing four or even six roads, the slopes afterwards being dressed off to the final angle and turfed and/or seeded with grass (as were the cutting slopes)⁸.

Earth waggons held about 2 cu.yd. A typical workforce would consist of 40 to 80 men

Fig 3: Cross section of Watford embankment, July 1835.

with 6 to 12 horses. Two shifts were often employed in summer, working either from daylight to dark or throughout 24 hours (with rest periods of course) the number on nights generally being less than in daytime. Only in exceptional circumstances were two shifts employed on earthworks in winter. Experience showed that work could proceed, on average, for 250 days in a year or 5 days a week, allowing for Sundays and wet or frosty weather; perhaps rather less with clays⁹.

The greater rate of construction achieved by high end-tipping, as opposed to building in shallow layers, was gained at the expense of increased settlements; but on railways (unlike canals and structured roads) settlement could readily be corrected by packing more ballast under the sleepers and, when necessary, imposing a speed restriction until the bank had become consolidated.

The method may have originated in making the 'batteries' (embankments) on colliery railways in the north-eastern coalfield, and there is a strong likelyhood that George Stephenson adopted end-tipping on the Stockton & Darlington Railway (25 miles in length, built 1822-25). Although two ridges of high ground at the western end, near Bishop Auckland, were negotiated by inclines worked by stationary engines, most of the line had fairly flat gradients suitable for locomotives, requiring cuttings and embankments up to 24 or 30 ft in height; and in his design report of 18 January 1822. Stephenson makes the point that, in contrast to a more 'undulating' line proposed by another engineer in an earlier scheme, he had arranged the levels so that the banks could be built of material excavated from cuttings and carried on not too long a 'lead', in tipping waggons on temporary rails¹⁰.

Certainly he used high end-tipping on the Liverpool & Manchester line. Earthwork operations began there in March 1827, one hundred waggons having been made to Stephenson's design¹¹. Every fortnight the three resident engineers marked up on a longitudinal section the progress achieved. Sections of Broad Green and Newton embankments at the positions reached in February 1829, published with Telford's report on the works, clearly show they were formed by end-tipping at the full height; a process, moreover, of which Telford specifically disapproved on the grounds of delayed consolidation and an increased tendency for slipping¹². At that time Broad Green embankment had advanced to a point where its head was 42 ft (13 m) above ground level, and at Newton the height was 24 ft. However, another section shows the 55 ft (17 m) bank across Sankey valley being built in 15 ft lifts, though each was formed by end-tipping. Joseph Locke, who had been resident engineer on the western district of the line, records that on Broad Green embankment, with 1.5:1 slopes and a 25 ft top width (allowing space for three roads), the utmost quantity that could be teamed in a day, employing 'as many men as we could place there', on two shifts from daylight to dark, was 800 cu.yd¹³. The material was chiefly broken-up (Triassic) sandstone brought on a mile-long lead from Olive Mount cutting.

In principle the procedure of building in two or more lifts increased the rate of construction, as

more 'roads' could be used on the lower (and wider) portion which obviously was kept in advance of those above. Locke in 1834 advocated this system¹³, but Robert Stephenson preferred the simpler, and in his view more efficient, method of tipping at the full height¹⁴, and by 1837 Brunel referred to practical difficulties in forming a bank on two lifts (let alone on three or four) which 'render it not a very general practice'¹⁵; significantly, this remark was in reply to questions on the quantity of earth that could be teamed supposing an embankment to be 'carried forward to its full height in the ordinary mode'.

Data on the rate of construction, in what by 1837 had already become the 'ordinary mode', are available from several sources. Watford embankment on the London & Birmingham line is a good example. 1.4 miles in length with a finished top width of 33 ft (10 m), a maximum height of 45 ft (13.7 m) and 2:1 slopes, the bank had a total volume of nearly 1 million cu.yd. Of this amount rather less than one-half was brought from Watford Heath cutting, a mile to the south, and about 500,000 cu.yd came, in the form of gravel and Chalk, from Watford tunnel approach cutting. Earthwork operations began about August 1834 and reached completion in March 1837. On average therefore 190,000 cu.yd were placed in the embankment in a year; equivalent to 750 cu.yd per day¹⁶.

Details are given by the resident engineer George Buck¹⁷. He records in July 1835 that the northern part of the bank had then reached a position where the height was 32 ft and the fill, tipped at its angle of repose, gave a width of 48 ft at the bankhead with space for six roads (Fig. 3). Working on a lead of 0.4 miles, a total of 160 men employed on day and night shifts moved 1000 cu.yd in 24 hours, measured as usual over a period of a fortnight which allows for time taken in extending the rails and other minor interruptions. This corresponds to a rate of 6.2 cu.yd per working day per man; a figure which, on the assumption that the workforce on this operation would be halved in the winter, translates into the long-term rates mentioned above.

For Huntonbridge embankment the same contractor, James Copeland, employed 100 men (60 on day and 40 on nights). They teamed 580 cu.yd per day on a 2 mile lead from Watford tunnel north approach cutting, also in gravel and Chalk; again measured over a fortnight in the summer¹⁸. Thus 6 cu.yd per day per man is an average performance under conditions of a well-managed contract with good banking materials. That the rate achieved at Watford was close to a maximum is confirmed by Robert Stephenson's statement in July 1836 that the greatest quality to date teamed over the end of any embankment on the London & Birmingham works had not exceeded 200,000 cu.yd per year¹⁹.

Two points should be noted: the effective amount of work done is almost double, since for every cubic yard deposited in an embankment on this system nearly the same quantity has been excavated at the same time from a cutting: and, secondly, that the rate per man is averaged for the whole workforce employed in 'getting', 'filling', 'carrying' and 'tipping', as well as those involved with other tasks such as shifting the rails, maintenance of waggons and care of the horses. This average rate should not be confused with the often quoted fact that two navvies could dig and fill into barrows or waggons up to 30 cu.yd of earth per day.

Somewhat higher rates of construction can be deduced, from figures given by the engineer Frederick Swanwick, for two embankments near Wakefield on the North Midland Railway (72 miles in length, from Derby to Leeds)²⁰. Both banks were built of sandstone and shale of the Middle Coal Measures from cuttings up to 60 ft deep. Work started about October 1837. By February 1839 a little less than half of the work had been done and 'the most vigorous means' were adopted to complete both contracts in time for opening the line at the end of June 1840; so the earthworks would have been finished by May at the latest. The bank had 1.5:1 slopes and a top width of 35 ft, providing room for four 'roads'. Oakenshaw cutting (contractor Joseph Thornton who, with John Stephenson, had worked on the Olive Mount cutting mentioned above) contained 680,000 cu.yd of which 130,000 cu.yd were run to spoil and the remainder went into the embankment (maximum height 52 ft) on a lead of about 1 mile. Thus 550,000 cu.yd of

material were taken from the cutting to the bank at an average rate of 205,000 cu.yd per year; but this volume is 'measured in the solid' and the quantity of fill would be greater, by at least 10 percent, owing to its lower density. Figures for the Altofts embankment (contractor David McIntosh) are very similar; 525,000 cu.yd taken from Normanton cutting on a 1.5 mile lead to a bank with a maximum height of 37 ft in exactly the same period of time.

Information on the rate of constructing clay embankments is available from New Cross on the London & Croydon line and from Willesden on the London & Birmingham. In the former case a mile-long embankment with 2:1 slopes and a maximum height of 25 ft (7.6 m) was built of London Clay from the deep New Cross cutting. By September 1837 the contractor William Hoof was fully organised and during the next six months, to March 1838, working double shifts for part of the time, 81,000 cu.vd were teamed into the bank²¹; thus achieving a rate of 160,000 cu.yd per year. This would seem to be an excellent performance, only 12 percent less than at Watford despite the notoriously difficult nature of the clay as compared to Chalk and gravel. But an identical figure emerges from data given by Stephenson for Willesden embankment²². This, too, was built of London Clay, here brought on a 1.75 mile lead from Kensal Green cutting. With a finished top width of 33 ft and 3:1 slopes, the bank in September 1835 had reached a position where its height was 13 ft. The clay was carried to within a few hundred yards of bankhead by a locomotive hauling 12 waggons, and typically making 25 journeys in a single 12 hours shift, when the waggons would be individually drawn and tipped in the usual manner on four roads. During the 8 months before Stephenson recorded the data in July 109,000 cu.yd had been teamed at an average rate of 160,000 cu.yd per year, which corresponds closely with $25 \times 12 = 300$ waggons a day.

Horse-runs

When all or a considerable part of a cutting went into spoil banks along the top edge, or in some nearby location, much higher rates were achieved since in this circumstance large numbers of men could be deployed along the length of the cut. The technique generally adopted was to use 'horse-runs', as illustrated in a drawing by John Bourne of the nearly completed Tring cutting on the London & Birmingham line in June 1837 (Fig. 4)²³. The contractor here was Thomas Townshend who also excavated the great Smethwick cut on Telford's Birmingham Canal improvements 1827-30.



Fig 4: Tring cutting, 17 June 1837, from J.C. Bourne, Drawings of the London and Birmingham Railway (1839).

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The cutting at Tring is 2.5 miles long with 1:1 slopes and a maximum depth of 57 ft (17.5 m) in Lower Chalk. About 60 percent of its 1.3 million cu.yd content was used in forming long, low embankments over the Gault clay vale to the north; the rest being taken to spoil along the top edge of the cut. Work began soon after September 1834 and Stephenson in February 1838 reported that the excavation and embankments on the contract had been ready for opening the line since December 1837, except for 4000 yd of permanent way, completion of which was now delayed by heavy frost²⁴; and he added that the embankments, consisting almost entirely of Chalk fill, were 'already well consolidated and little liable to subsidence'. Thus excavation had proceeded at an average rate of 400,000 cu.yd per year.

Details of a large cutting in which the whole content had to be run to spoil are given by J.U. Rastrick²⁵. This was in Contract No. 15 on the London & Brighton Railway which included a cutting in Middle-Upper Chalk nearly two miles long, between Clayton and Patcham tunnels, containing 700,000 cu.yd. Within three weeks the contractor Mark Faviell had 300 men at work with 21 horses. Six months later, in January 1840, there were 377 men and 58 horses, and during this period 325,000 cu.yd were excavated. The contract involved four bridges and a short tunnel but these works had not yet started, so the entire workforce had been engaged in excavation; at a rate of 650,000 cu.yd per year or approximately to 6.5 cu.yd per day per man.

Sonning cutting on the Great Western main line provides an extreme example of the concentration of labour. The cutting, also nearly two miles long, was one of the largest on any of the early railways with a volume of about 1.5 million cu.yd. Progress had fallen so far behind schedule by the summer of 1838 that the Company took over, and before the end of the year work was proceeding with exceptional vigour under the direction of the resident engineer John Hammond with Rowland Brotherhood as principal sub-contractor. From February to August 1839 a workforce of 1000 to 1200 men and 200 horses, with 2 locomotives, removed 555,000 cu.yd (chiefly clay) at an average rate of just over 1 million cu.yd per year²⁶. Material from the western part of the cut went into a 4-mile embankment towards and past Reading (hence the locomotives) but all the central portion was taken to spoil banks several yards behind the top edge, employing 42 horse-runs up each side working from depths down to 60 ft (18 m) on 2:1 slopes²⁷. The cutting was completed by the end of the year in time for permanent way to be laid and opening of the line through to Reading in March 1840.

Side-cutting

The converse process of banking from side-cuttings is exemplified by Swindon embankment on the Cheltenham & Great Western Union Railway (Fig. 5). The bank is 1.8 miles long, averaging 20 ft in height and nowhere exceeding 24 ft (7.3 m), with 2:1 slopes and a volume of about 480,000 cu.yd. It was built of brown and some blue (unweathered) Kimmeridge Clay wheeled up from side-cuttings and deposited in layers from barrows²⁸. No large cutting on the line itself existed within a reasonable distance. Work began in the summer of 1839²⁹; a few small slips occurred in the following winter, but were easily repaired, and by November 1840, with the bank nearly completed, opening of the line (from Swindon to Cirencester) was planned for January 1841³⁰. However, rain delayed the work by two months, and in early spring (probably in March) a slip occurred on the east side; sliding into the side-cut over a length of 330 ft with an initial drop of 8 ft in the bank top. This was eventually stabilised by the simple but tedious method of back-filling the side-cut, and after repairing the bank the line was opened on 31 May 1841.

Assuming that work began in May 1839 and the bank was practically finished in November 1840, the average rate of construction in this 18 month period is about 300,000 cu.yd per year; almost double the rate achieved by teaming at New Cross and Willesden but, of course, no 'useful' cutting had been accomplished.



Fig 5: Cheltenham and Great Western Union Railway Swindon embankment. Built 1839-41: slips, March and June 1841.

Embankment Slips

Shortly after opening the line another very similar slip occurred in the Swindon embankment. As a quick first-aid measure Brunel had a row of timber piles driven at the toe of the slope, penetrating 8 ft into undisturbed ground below the level of the bottom of the side-cutting. They were soon sheared off by the relentless movement of the slip. On the suggestion of the resident engineer Charles Richardson pits 6 ft square were then excavated near the toe, 24 ft apart, to a depth of 2 ft below the slip surface – which was clearly seen during this operation as a smooth polished plane – and filled with ragstone brought from a cutting several miles further north. These rubble-filled pits could have been doubled in number but in fact the first set proved effective in stopping the slip, allowing repairs to the bank to be started before completing the more lengthy process of back-filling the side-cut.

The slips in Swindon embankment were essentially foundation failures, though of an unusual kind. Normally, failure occurs simply by the weight of the bank causing shearing and upheaval of the foundation material. A spectacular example is provided by Hanwell embankment on the Great



Fig 6: Great Western Railway Hanwell embankment. Built 1836-8: slip started 21 May 1837.

Western Railway, on the west side of Wharncliffe Viaduct, which failed during construction in May 1837³¹. Composed of end-tipped gravel fill 54 ft (16 m) high with 1.5:1 slopes, it is founded on a thin layer of gravel over London Clay (Fig. 6). Gravel was added, and continued to be added, in an effort to maintain a level for further progress, but to no avail; and Brunel then ordered a counterweight berm to be built. By December, when a state of equilibrium had been

Table 3: Slips in Embankments

LINE	EMBANKMENT	HEIGHT m	DESIGN SLOPES	METHOD OF CONSTRUCTION	MATERIAL	DATE OF SLIP	TIME
							CONSTRUCTION
London & Birmingham	Bugbrooke	10	2:1	end-tip	Upper Lias	1838	
Great Western	Wotton Bassett	12	2:1	end-tip	Oxford Clay	1841	during
London & Brighton	Earlswood	14	2:1	side-cut	Weald Clay	1841	construction
Eastern Counties	Colchester	15	2:1	end-tip	London Clay	1842	
London & Birmingham	Blisworth	14	2:1	end-tip	Soft mudstone	Jan. 1840	2 years
Great Western	Tockenham	10	2:1	side-cut	Oxford Clay	Jan. 1843	2 years
London & Brighton	Salfords	15	2:1	side-cut	Weald Clay	Nov. 1844	3 vears

achieved, the slip extended over a length of 400 ft (120 m), with a subsidence of 30 ft at the top^{32} . Distortions of the strata were recorded in exploratory trenches sunk to the depth shown in the section.

Slips within the body of an embankment were nearly always restricted to clay fills (poorly compacted by modern standards) and resulted principally from softening of the clay lumps by absorption of rain water. This process could be quite rapid, leading to failures during construction, but might continue for a year or more after completion of the bank. Examples of both types are given in Table 3.

Obviously the embankment could not be protected from rain, but at least the worst effects could be avoided by not placing clay fill in wet winter conditions. This rule was not always followed, but experience showed that, even with reasonable care, difficulties attended the building of stable clay embankments with heights of more than 10 or 12 m by end-tipping or uncompacted barrow work.

An instructive case record comes from the embankments north and south of Wolverton viaduct on the London & Birmingham Railway³³. Both had a maximum height of 48 ft (14.5 m). On the north side the materials were mostly glacial sand and gravel with some Boulder Clay. The bank stood well, except for a minor foundation slip in the underlying alluvium. The south embankment, in its early stages, was built with similar materials, brought by locomotive from Denbigh Hall cutting 3 miles away, again without trouble. But as the cutting progressed it yielded 'black, soapy clay' (Oxford Clay) and despite care to mix sand with the clay a large slip developed in the bank. More and more material was added on the top in the hope that a flatter, stable slope would be formed by continued displacement. But as fast as material was placed on top the toe moved out, and after several weeks the bank was still 12 ft below its proper level; even though the slope had now decreased to about 4:1. A temporary timber bridge was then erected to allow end-tipping to continue at bank head. The state of affair in June 1837 is depicted in Bourne's drawing (Fig. 7), about three months after the slip started.³⁴

Later in the summer the bridge was removed to try again the effect of adding material, but the response was just the same; so the only remedy was to build a counterweight berm by barrow work. Meanwhile, ahead of the advancing bank, earth was excavated to a depth of 5 ft across nearly the full base-width and used to form mounds on each side as pre-existing small berms, perhaps about 12 ft high with a top width of 20 ft. They proved to be effective, demonstrating that





London & Croydon Railway

Fig 7: Wolverton embankment, 28 June 1838, from J.C. Bourne, Drawings of the London and Birmingham Railway (1839).

it is easier to prevent a slip than to stabilise one after it has occurred. This is due to the fact that the 'residual' strength on a slip surface is much smaller than the strength of the unsheared clay³⁵. In February 1838 Stephenson reported that work at Wolverton had for some time been advancing in the most satisfactory manner, and would be completed in eight weeks time, as indeed it was.³⁶ The very flat slope required for final stability after a slip in clay fill is illustrated by Colchester embankment on the Eastern Counties Railway. Two slips totalling 380 ft (115 m) in length developed during construction of this end-tipped 50 ft (15 m) high London Clay embankment, in the autumn of 1842. Material was added on the top, as usual, but in this case the process was continued until stability had been achieved, by outward displacement of the toe, with a slope of 6:1³⁷; an operation in which 34,000 cu.yd of additional fill was 'swallowed up'³⁸. Trestle bridges were then built across the top, still much below its proper level, and the bank left to consolidate until July 1843, when it was completed without further slipping³⁹.

Slips in Clay Cuttings

Superficial slips were common in clay cuttings (and embankments) either in rainy seasons during construction or in the first or second winter afterwards. They usually required for their repair no more than trimming and a few shallow trench drains. In an altogether different category were deep slips which took place, almost without warning, several years after excavation. Three well-documented cases are summarised in Table 4.

The first of these 'delayed slips' occurred on 2 November 1841 at 8.30 p.m. in the west side of New Cross cutting on the London & Croydon Railway, with an effective depth of 48 ft (14.5 m) in brown London Clay, 3 years after excavation (Fig. 8). It had a length of 360 ft and involved the movement of a mass containing about 50,000 cu.yd of clay. A slip on the opposite side

Table 4: Delayed slips in clay cutting

LINE	CUTTING	EFFECTIVE DEPTH m	SLOPE	MATERIAL	DATE OF SLIP	TIME AFTER EXCAVATION
I ondon & Crovdon	New Cross	14.5	2:1	London Clay	2 Nov. 1841	3 years
Great Western	Sonning	13	2:1	Reading Clay	24 Dec. 1841	2.5 years
London & Birmingham	Bugbrooke	14	2:1	Upper Lias Clay	24 Sep. 1842	4.5 years

Fig 8: London and Croydon Railway New Cross Cutting, excavated 1837-8.

followed three weeks later, with an extension of the first one in January 1842. The slips, by their magnitude and unexpected nature, attracted much attention in the technical press and formed the principal subject of a paper by Charles (later Sir Charles) Hutton Gregory, the resident engineer under whose direction the remedial works were carried out.⁴⁰ Within hours of the first slip a coach service had been organised between New Cross and Forest Hill, the next station down the line, and remarkably the railway was closed only for a total of 12 weeks while dealing with a succession of three of the largest slips ever encountered in British transport history. The slopes were benched back in stages to an overall inclinatin of 4:1, and during these operations the polished nature of the slip surface and its shape were observed (Fig. 8).

On a smaller scale at about the same time (November or December 1841, the exact date has not been found) a slip occurred in Wootton Bassett cutting on the Great Western line: 42 ft (14 m) deep at 2:1 in the Oxford Clay⁴¹. And this was followed on 24 December by a slip on the same line in Sonning Cutting, which lead to a train de-railment with the loss of eight lives⁴². At the slip the cutting, with 2:1 slopes, had an effective depth of 42 ft (13 m) in clay of the Reading Beds and a total depth of 58 ft⁴³.

In his report on the New Cross slips Charles Pasley, Inspector-General of Railways, having examined and approved the remedial work then in progress, goes on to say:

The original slope of the sides of the deep cutting was two of base to one of height, and they had stood for more than two years without any slip [of significance] until lately, when continued rains have produced this unfavourable effect, which I do not think that any engineer could have anticipated; for it is only our late experience that has developed the disadvantage of deep cuttings and high embankments in certain kinds of clay, even at very moderate slopes. No blame therefore attaches to the original construction of this railway, though the extraordinary slips that have occurred recently will be a lesson to put engineers on their guard for the future in working in such soil.⁴⁴



Fig 9: London and Birmingham Railway Bugbrooke Cutting. Excavated 1835-7: slip 24 September 1842.

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Thus, while Pasley emphasises the delayed nature of the slips (and he had in mind Sonning as well as New Cross) he attributes their occurrence to heavy rain; an opinion generally held at the time.

In the sense that rain can trigger a slip, this is true. But in his 1844 paper Gregory postulated that additionally a more fundamental process must be involved: deep-seated progressive softening of the clay, connected in some way with the effects of stress release caused by excavation, and he thought that the fissured nature of London Clay played a significant role. This foreshadows the explanation of delayed slips in stiff fissured clays put forward by Terzaghi in 1936⁴⁵, from which stemmed a long series of investigations leading, very recently, to a proper understanding of the complex process of pore pressure change and progressive failure involved⁴⁶.

The early winter of 1841, however, was indeed exceptionally wet. But in September 1842 a slip occurred on the London & Birmingham line at a time of only moderate rainfall and in a cutting which had remained stable for more than 4 years. This was at Bugbrooke, in Northamptonshire: a cutting 47 ft (14.3 m) deep with 2:1 slopes in Upper Lias clay (Fig. 9) completed before February 1838 and which had survived the winter of 1841-42 (and, like Sonning and New Cross, the scarcely less wet winter of 1839-40).

The circumstances are described by Pasley who now realised that some deep-seated effect must be acting, and he began to wonder if deep cuttings in 'London Clay and other plastic clay formations' were always liable to slip sooner or later.⁴⁷ Subsequent experience has shown this view to be not far from the truth. Cuttings with slopes steeper than 3.5:1 in London Clay or 2.5:1 in Upper Lias clay, for example, are prone to slip 10 to 50 years (or even longer) after excavation⁴⁸.

While developing his ideas on delayed slips Gregory would no doubt have been influenced by the failure at Bugbrooke, and also by further slips on the Croydon line south of New Cross, in cuttings at Brockley (9 m deep) and Forest Hill (12 m deep): both in brown London Clay.

Remedial Measures

The usual method of stabilising a deep clay slip on the early railways was to flatten the slope, either by trimming or benching back, or in extreme cases by removing the slip mass entirely, as at New Cross. Slope flattening required the removal of considerable volumes of clay (25,000 cu.yd at Wotton Bassett) and the purchase of land outside this existing boundary fence (nearly an acre at Bugbrooke, 1.7 acres at Forest Hill).



Plan and section of counterforts, redrawn from a sketch by Gregory (1844)

Counterforts were an alternative remedial measure, except perhaps for very large slips. They consist of trenches,

Fig 10: Plan and section of counterforts, redrawn from a sketch by C.H. Gregory, Min. Proc. Insti. of Civ. Eng. 3 (1844).

typically 6 ft wide at 24 ft centres, dug into the slope to a depth of 2 or 3 ft below the slip surface and backfilled with gravel or rubble stone rammed in tight (Fig. 10) and act both as an internal buttress and as a deep drain. Introduced by Robert Stephenson in 1839 to stabilise the Jurassic clay slopes above the limestone in Blisworth cutting⁴⁹, counterforts were used by Joseph Locke early in 1842 in the cuttings adjacent to Tapnage tunnel on the Gosport Branch of the London & South Western Railway⁵⁰ and later that year by Gregory in Brockley cutting. At Tapnage the slips occurred within a year of excavation; not surprisingly, as the cuttings were made at 1.5:1 in London Clay! In this case the slopes were cut back before installing the counterforts.

It appears that Gregory in 1844 gives the first published description of counterforts, though by that time they were quite well known; as clearly emerges from the discussion on his paper. They became practically a standard remedial measure on the railways, and remained so for the next hundred years.

Note on Steam Power

It has been mentioned above that stationary engines were sometimes used on earthworks. An example is provided by the cutting (600,000 cu.yd) and embankment (430,000 cu.yd) at Leire on the Midland Counties Railway. This was part of a big contract carried out by David McIntosh on the 20 miles length between Leicester and Rugby. In the summer of 1838 on this contract he had nearly 2000 men at work with about 150 horses, and as the engineer Thomas Woodhouse reports:

The spirited manner in which Mr Macintosh is working his heaviest cuttings, shows his determination to complete the works in the time specified in his contract, the 1st of May 1840 ... The excavation at Leir Hill is the most extensive piece of earthwork on the whole line of railway; and here he is erecting a steam-engine to facilitate his operations; he has an inclined plane from the cutting to the embankment (on a lead of 0.75 miles) where the material is to be deposited. The plane descends at an angle just sufficient for the gravity of the waggons to overcome their friction and the resistance offered by the rope. The waggons, when emptied, are drawn back by the engine; by this means, more earth may be removed expeditiously than by any other vet practised.⁵⁰

McIntosh continued with great vigour, his workforce by the following year having increased to 2600 men and 260 horses, and despite the wet winter of 1839-40 he managed to complete the whole contract, involving upwards of 3 million cu.yd of excavation as well as the Avon viaduct, at the specified time after 2.5 years work; thus averaging at least 240,000 cu.yd per year in the Leire cutting, practically the full depth of 60 ft (18 m) being in Boulder Clay⁵¹. The embankment, with 2:1 slopes and a maximum height of 40 ft (12 m), was already well consolidated on opening the line in July 1840 and there is no record of any slips in the bank⁵².

Other than a fairly restricted application of stationary engines the sole use of steam power for excavation on the early British railways was on the Eastern Counties line when John Braithwaite in 1843 carried out successful trials of the 'American Steam Excavator'. Powered by a 10 h.p. (nominal) engine, this was the fourth machine of its kind made by Carmichael, Fairbanks & Otis and used from 1838 on the Western Railroad (from Worcester, Mass. to Albany, N.Y.). It dug and loaded into waggons about 500 cu.yd of sand per day: equivalent to the work of rather more than 30 men, and at roughly half the cost⁵³. Nevertheless, even in America, where labour was less plentiful, steam navvies came into their own only so late as the 1880s with the introduction of far more powerful machinery⁵⁴. In England they were first used on a grand scale on the Manchester Ship Canal (1887-93) where 58 large and 17 smaller steam navvies excavated 54 million cu.yd in 6 years⁵⁵.

Conclusions

Cuttings and embankments on the early railways were planned on the principle of designing for normal, expected conditions and dealing with the abnormal when it is encountered. Slips, in the latter category, gave a lot of trouble but mostly in deep clay cuttings and high embankments where previous experience scarcely existed. They should be seen in relation to the great majority of the earthwork which was carried out rapidly and successfully on an unprecedented scale by the methods and with the results described.

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- 2. Details of the London & Birmingham Railway workforce have not been found, except that the numbers of men employed were upwards of 10,000 in July 1836 and 12,000 in June

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1837; as reported in Railway Magazine.

- Peter Lecount, The History of The Railway Connecting London & Birmingham (1839) p. 42. Quantities are given by Arthur Freeling, The Railway Companion from London to Birmingham, Liverpool & Manchester (1828) p. 12 and sections of the cutting by F.W. Simms, Public Works of Great Britain (1838), pls. 20-35.
- 4. *Civil Engineer & Architect's Journal* 2 (1839), pp. 224-225. In a note on p. 252 R.B. Dockray says this method was in full operation before he took up his post as resident engineer (in December 1835) on this section of the line.
- The specification, dated August 1836, is quoted in S.C. Brees Railway Practice (1837) pp. 93-108. Macneill worked from 1826 under Telford on the London-Shrewsbury division of the Holyhead road; his specification for the Salamannan embankments may reflect this experience.
- 6. For example, Robert Stephenson specifies layes not exceeding 3 ft in thickness, each being 'closely packed' previous to succeding layers being laid on, for a viaduct on the Slatley contract, London & Birmingham Railway, 1834. Townshend collection, Inst. Civ. Eng. archives. See also Vignoles' specification of 1836 for the Avon viaduct on the Midland Counties Railway in Brees pp. 85-86.
- 7. "Resident Assistant Engineer" (J.D. Hughes), A Practical Inquiry into The Laws of Excavations and Embankments upon Railways (1840) pl. 1 (see Fig.1) and pp. 163-165. Details of end-tip waggons are given by "O.T." "On Earthworks, Excavation, Cutting and Embankment upon Railways", Civil Engineer & Architect's Journal 6 (1843) pp. 265-268 (see Fig.2) and by G. Drysdale Dempsey, Railways, Papers on the mechanical and engineering operations and structures combined in the making of a railway, (1846) pl. 9.
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Gibbs, Railway Magazine, (March and September 1837; March 1837).

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