



Rail Accident Investigation Branch

Rail Accident Report



Derailment of a freight train at Stoke Lane Level Crossing, near Nottingham 27 August 2013

Report 02/2015
April 2015

This investigation was carried out in accordance with:

- the Railway Safety Directive 2004/49/EC;
- the Railways and Transport Safety Act 2003; and
- the Railways (Accident Investigation and Reporting) Regulations 2005.

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Any enquiries about this publication should be sent to:

RAIB	Email: enquiries@raib.gov.uk
The Wharf	Telephone: 01332 253300
Stores Road	Fax: 01332 253301
Derby UK	Website: www.gov.uk/raib
DE21 4BA	

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Derailment of a freight train at Stoke Lane Level Crossing, near Nottingham, 27 August 2013

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Summary

On 27 August 2013, at around 04:27 hrs, a freight train comprising a Class 66 locomotive and 30 fully loaded tank wagons carrying diesel fuel, derailed by two axles as it traversed Stoke Lane level crossing on the Newark to Nottingham line. The train was travelling at a speed of 53 mph (85 km/h) when the trailing wheelsets of the 26th and 28th wagons derailed. Consequential damage to the rear of the train resulted in an air leak and the automatic application of the brakes. The train came to a stop after around 1.3 km, at Carlton station. The wagons remained upright and in line, and did not foul the adjacent running line. There was no leakage of diesel fuel from any of the tank wagons. The track was damaged by the derailed wheelsets for a distance of around 800 metres. The driver was not injured. The railway remained closed for repairs until 15:30 hrs on 8 September 2013.

The immediate cause of the derailment was a severe dip in the track which developed rapidly under the leading portion of the train. After the derailment, severe dips of about 100 mm were found in both rails of the affected line, where the rails had deformed over a large void in the ground which had left the track unsupported over a length of around 3 metres. The void under the railway and other voids found later under the adjacent road surface were caused by excessive ground loss during the recent construction of a microtunnel along the road centre line. The RAIB investigation has interpreted the available evidence in order to identify the most likely cause of the voids. Although some alternative explanations cannot be completely discounted, the RAIB considers that the most likely explanation for the ground loss is that it was as a result of overmining of the ground during the construction work.

The RAIB's investigation identified safety lessons, both for those in the construction industry who build undertrack crossings and also for the railway regarding managing asset protection processes for such constructions. In line with the RAIB's remit, the improvement of railway asset protection processes to prevent recurrence has been the focus of its investigation. This is reflected in the balance of the recommendations made, which relate to the following areas:

- disseminating key learning points arising from this accident to the UK tunnelling industry, via the Health and Safety Executive and relevant industry bodies;
- improving Network Rail's asset protection standard for construction of under track crossings so that there is one unified standard applicable to both outside parties and Network Rail;
- improving the technical knowledge of Network Rail's asset protection engineers about under track crossings and increasing the time and technical assistance available to them to adequately assess risks and review documentation submitted by outside parties; and
- reviewing the suitability of the action limits in Network Rail's standard for monitoring track movement over or adjacent to civil engineering works, including under track crossings.

Introduction

Preface

- 1 The purpose of a Rail Accident Investigation Branch (RAIB) investigation is to improve railway safety by preventing future railway accidents or by mitigating their consequences. It is not the purpose of such an investigation to establish blame or liability.
- 2 Accordingly, it is inappropriate that RAIB reports should be used to assign fault or blame, or determine liability, since neither the investigation nor the reporting process has been undertaken for that purpose.
- 3 The RAIB's investigation (including its scope, methods, conclusions and recommendations) is independent of all other investigations, including those carried out by the safety authority, police or railway industry.
- 4 In line with the purpose of RAIB investigations, the focus of this investigation was to derive safety learning for the railway industry. The RAIB has only considered the construction of the Stoke Lane microtunnel as far as necessary to identify lessons for the protection of railway assets in the future. This is reflected in the recommendations made in this report. Compliance of the construction project with the relevant legal requirements is a matter for the HSE and was outside the scope of the RAIB investigation.

Key definitions

- 5 All dimensions in this report are given in metric units, except speed and locations which are given in imperial units, in accordance with normal railway practice. Where appropriate the equivalent metric value is also given.
- 6 The report contains abbreviations and technical terms (shown in *italics* the first time they appear in the report). These are explained in appendices A and B.

The accident

Summary of the accident

- 7 At around 04:27 hrs on 27 August 2013, freight train 6M35, the 02:05 hrs service from Humber oil refinery to Kingsbury oil sidings, comprising a Class 66 locomotive and 30 loaded tank wagons carrying diesel fuel, was travelling along the Newark to Nottingham line at 53 mph (85 km/h). As it traversed Stoke Lane level crossing (figure 1) the driver felt a jolt, and shortly afterwards, noted that the train had started to slow down even though it was still under power at the time. The train's brakes had applied automatically after damage to its braking system had caused an air leak and the train came to a stop around 1.3 km later at Carlton station.

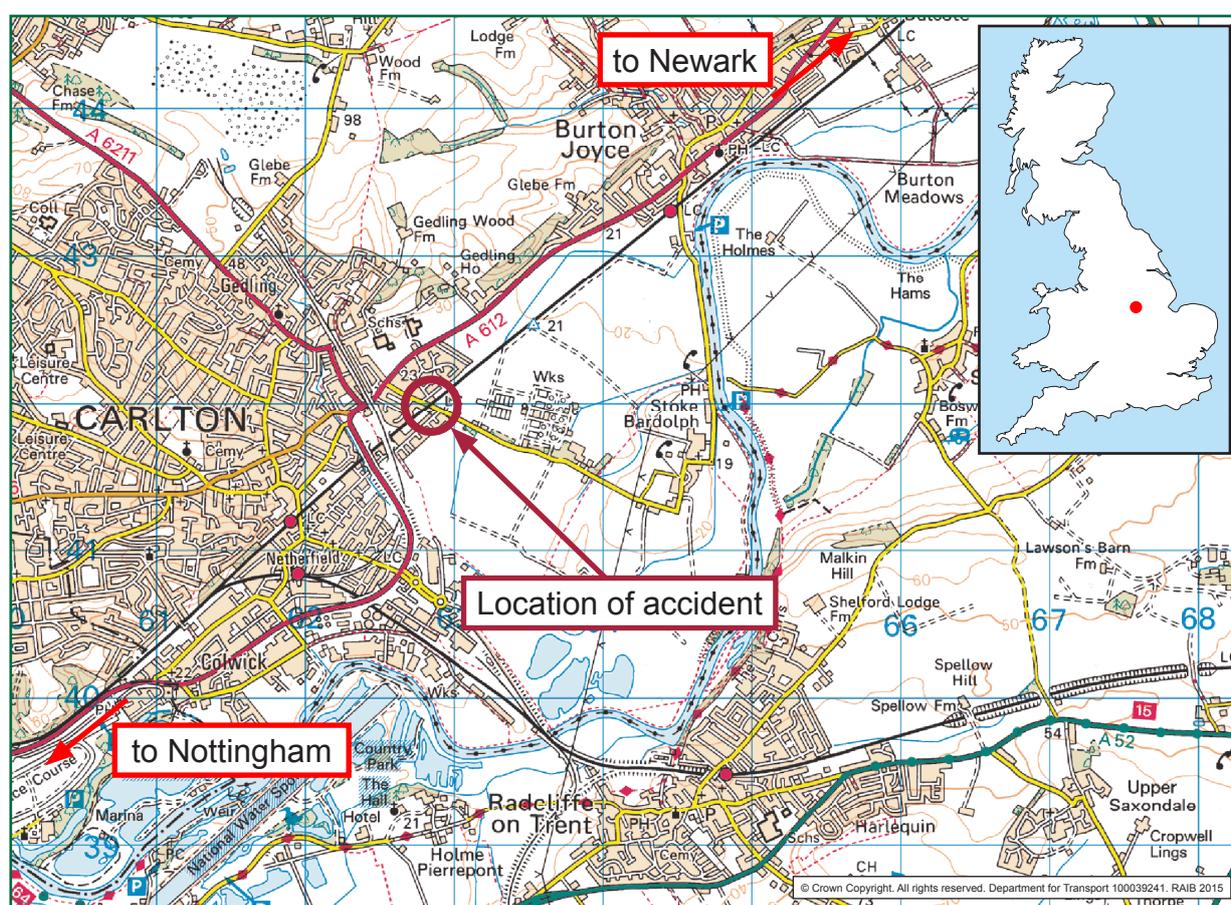


Figure 1: Extract from Ordnance Survey map showing location of accident

- 8 After informing the signaller of the automatic brake application, the driver went to investigate. He found the trailing axles of the 26th and 28th wagons had derailed toward the *six foot* (figure 2). The wagons had remained upright and in line and had not fouled the adjacent running line. There was no leakage of diesel fuel from any of the tank wagons, but the buffers on some had been damaged. The track was damaged by the derailed wheelsets for a distance of around 800 metres. The driver was not injured.



Figure 2: Train 6M35 (a) and its derailed wheelsets on 26th wagon (b) and 28th wagon (c)

- 9 Examination of the site revealed severe dips of about 100 mm in both rails of the up line at Stoke Lane level crossing (figure 3). The rails had deformed over a void in the ground. Because of this void the track was not supported over a length of around 3 metres (figure 4). The railway remained closed for repairs until 15:30 hrs on 8 September 2013.

Location and surrounding environment

- 10 The point of derailment was near the centre of Stoke Lane level crossing which is located at 3 miles 54 chains from Nottingham station and on the up and down Lincoln lines. The railway *engineer's line reference* for this section of track is 'NOB1'. The maximum line speed is 60 mph (96 km/h).



Figure 3: The dip in the rails at the point of derailment

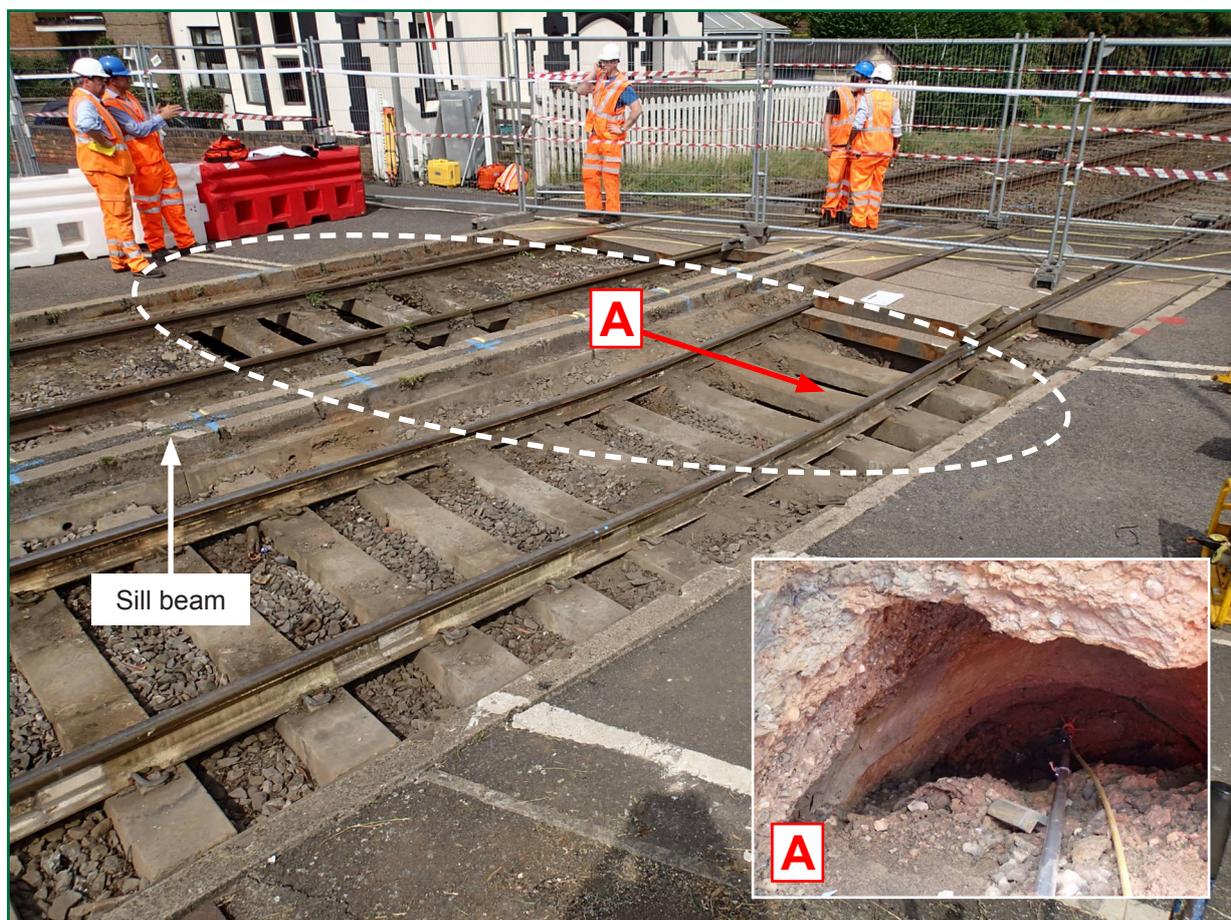


Figure 4: Extent of voiding below the track at the crossing

- 11 At this location there is an *under track crossing* (UTX) which had been built under the road and railway, seven weeks prior to the derailment (figure 5). The UTX was built to carry six 132 kV electrical cables along Stoke Lane as part of a larger project to build and connect a new substation on the east side of Nottingham at Stoke Bardolph. The UTX comprises a *microtunnel* around 53 metres long with an internal diameter of 1 metre and an external diameter of 1.2 metres. The crown of the tunnel lies at a depth of around 5.7 metres below ground level.

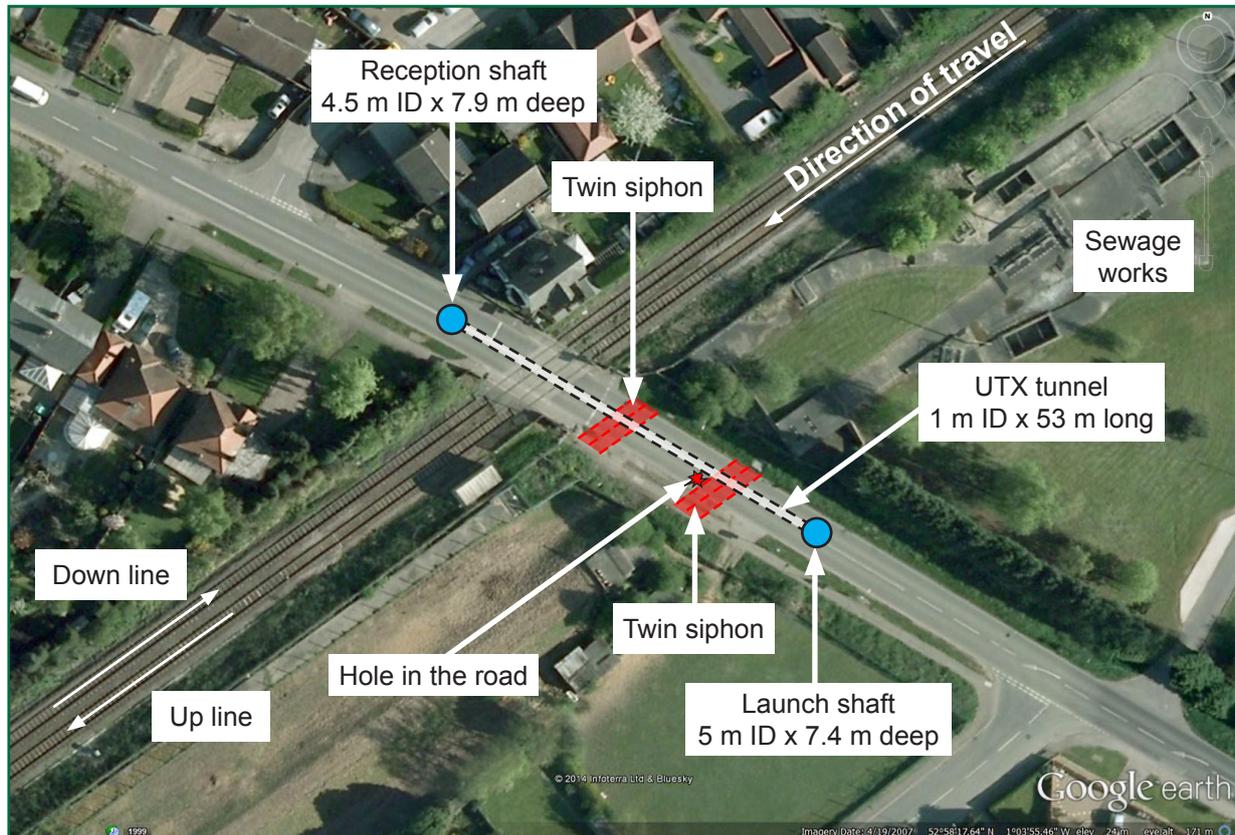


Figure 5: Google image of the level crossing, with microtunnel and construction shafts marked

- 12 The microtunnel was bored by a *slurry shield tunnel boring machine* (TBM) (appendix D) and lined with 2.5 metre long concrete pipes (called *jacking pipes*), locked together end to end. In order to bore the microtunnel, two vertical shafts had to be built first. The launch shaft was built at the south eastern end of the tunnel and used to insert the TBM into position and then drive it and the jacking pipes forwards, along the path of the tunnel. At the north western end, the reception shaft was used to retrieve the TBM. These shafts (figure 6) are also the entry and exit points for the 132 kV electrical cables. A cross section along the centre line of the road showing the position of the microtunnel and shafts in relation to the railway is shown in figure 7.



Figure 6: Launch shaft (a) and reception shaft (b) during the works (image courtesy of Morgan Sindall)

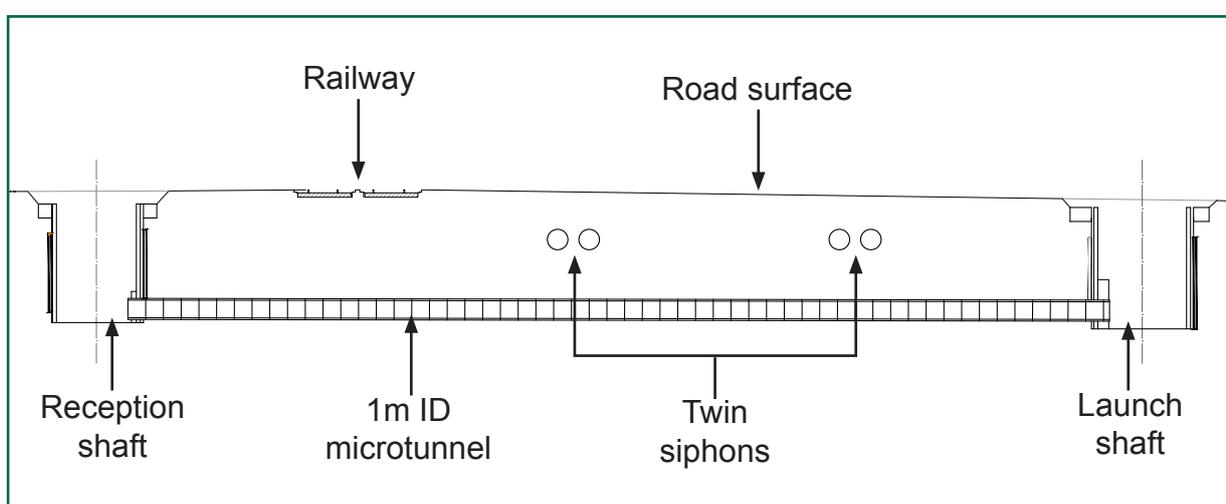


Figure 7: Schematic cross-section through microtunnel and construction shafts

- 13 Between the launch shaft and railway, two twin sewer siphons (figures 5 and 7) run across the road and parallel to the railway and carry sewerage from Nottingham into the Stoke Bardolph sewage works (figure 5). The twin siphons nearest the railway comprise two 1.2 metre diameter cast iron pipes located around 3 metres below ground level and date back to circa 1880. The twin siphons nearest the launch shaft are believed to be cast iron pipes of about 1.3 metres diameter each and encased in concrete. The two twin siphons have a combined flow capacity of around 6 m³/sec and their location was a factor in deciding the depth of the microtunnel.

- 14 Ground investigations carried out after the accident, show that the ground at the site of the UTX varies in composition and density with depth. Generally, it comprises:
- An upper layer of asphalt supported by compacted made up ground, comprising sandy clay with mudstone fragments, down to around 0.8 - 1.2 metres, representing the road formation.
 - Clayey sand with some gravel down to between 1.4 and 2.8 metres depth (typically around 2 metres), thought to be part of the alluvial deposits from the River Trent, which lies 2 km to the east. The water table lies at a depth of around 2.5 - 3 metres.
 - Sand and gravel with density generally increasing with depth and often with a marked increase in density at about 5.5 metres depth.
 - Mudstone, siltstone and sandstone below 6.8 - 7.9 metres depth.

Organisations involved

- 15 Network Rail owns, operates and maintains the track that runs over Stoke Lane level crossing. To comply with the law¹, the UTX project required the prior approval of the relevant Network Rail Asset Protection team. Initially the project was handled by the asset protection team of the London North Eastern (LNE) Route which, at the time the project started in January 2012, also covered the East Midlands area, including Stoke Lane level crossing. During the course of the project (around October 2012) the East Midlands (EM) became a separate Route of Network Rail and the project was managed by the East Midlands Route. In May 2014 a joint LNE and EM route was formed. Hereafter, the report will refer to the LNE&EM asset protection team. The team was responsible for checking, as far as was reasonably practicable, that the UTX project did not endanger railway operations and that it met Network Rail's specific requirements for UTXs. However, it was not the team's role to check and approve the design of the UTX as being fit for its intended purpose nor to carry out detailed checks of all aspects of its construction. The LNE&EM asset protection team had an agreement in place with Western Power Distribution (East Midlands) Plc to undertake the required review and approval of the UTX and to supervise the safety of staff from other organisations working near the railway.
- 16 DB Schenker was the operator of freight train 6M35. It owned the locomotive and employed the driver. The wagons were owned and maintained by others.
- 17 Western Power Distribution was building an electricity supply substation at Stoke Bardolph to reinforce the electricity supply to Nottingham.

¹ The Health and Safety at Work Act, 1974, section 3, paragraph 3 and the New Roads and Street works Act 1991 (chapter 22) Part 3 – Street works in England and Wales, section 93, 'Works affecting level crossings or tramways', paragraph 3 apply. These place a duty on anyone wanting to build near, over or under a railway to inform the infrastructure owner and comply with any reasonable requests they might make to ensure safety.

- 18 Morgan Sindall Utilities was the principal contractor to Western Power Distribution for the Stoke Bardolph cabling works. It was responsible for the design, procurement, installation and commissioning of the cables and associated structures at relevant substations. This included the sub-project to install the UTX along the route of Stoke Lane as specified by Western Power Distribution. During the tunnelling work, Morgan Sindall Utilities was responsible for general health and safety management of the site and spoil removal. Morgan Sindall Professional Services (a consultancy arm of Morgan Sindall), examined and approved the UTX design and construction in accordance with its own internal procedures. After the accident, Morgan Sindall Underground Professional Services carried out extensive ground investigations to assess the ground conditions and extent of voiding. It then carried out remedial grouting to stabilise the ground at the site of the UTX.
- 19 Bridgeway Consulting Ltd was contracted by Morgan Sindall Utilities and was responsible for the geometrical design of the UTX and shafts, and for specifying where they should be located in relation to the railway and existing services. In addition, Bridgeway Consulting was responsible for liaison with Network Rail and for making the necessary technical submissions and ground investigations to obtain approval from Network Rail for the works. Bridgeway Consulting was also responsible for monitoring the road and railway to check for any settlement during and after the tunnelling.
- 20 F&B Trenchless Solutions was contracted by Morgan Sindall Utilities to construct the UTX. It was responsible for selection of the tunnelling method and the construction of the tunnel and associated launch and reception shafts. It also provided and operated all the equipment necessary for construction, except for spoil removal from site.
- 21 Severn Trent Water owns and maintains the sewer system that crosses Stoke Lane and other water utilities that run along the road. It also owns and operates the Stoke Bardolph sewage treatment works adjacent to the level crossing.
- 22 All the above organisations freely co-operated with the investigation.

The Train

- 23 Freight train 6M35 was made up of a class 66 locomotive and 30 TEA type tank wagons. Each wagon (figure 2) had a maximum gross laden weight of 102 tonnes and was carrying around 75 tonnes of diesel fuel. The total weight of the train was 3160 tonnes, which was within the maximum allowable load of 3212 tonnes for Class 66 locomotive hauled trains operating over NOB1. None of the wagons on train 6M35 exceeded their design gross laden weight. Due to the liquid nature of the contents, it is likely that the wheel load distribution of the wagons was reasonably uniform.

External circumstances

- 24 It was dark and foggy at the time of the derailment. The fog was starting to lift by the time the driver inspected the wagons after the derailment. The weather conditions at the time did not play a part in the derailment.

The investigation

Sources of evidence

- 25 The following sources of evidence were used:
- a) on-site inspections;
 - b) *on-train data recorder* (OTDR) from train 6M35;
 - c) signal box voice recordings;
 - d) train running data from Network Rail's *Control Centre of the Future*;
 - e) forward facing CCTV from two passenger trains which ran over NOB1 the previous evening;
 - f) wagon inspections;
 - g) interviews with relevant staff from the organisations involved;
 - h) technical specifications for the work scopes between the involved parties and relevant contractual documents;
 - i) Network Rail national and local procedures relevant to asset protection, UTXs and monitoring;
 - j) documentation submitted by Bridgeway Consulting relating to the geometrical design of the UTX and associated shafts and documentation submitted by F&B Trenchless Solutions relating to the construction of the microtunnel and shafts;
 - k) industry guidance on best practice in tunnelling (paragraphs 59 and 63);
 - l) data and reports on the post-accident ground investigations, maps of the voiding and a report on the cause of the voiding, provided by Morgan Sindall Underground Professional Services; and
 - m) expert review, commissioned by the RAIB, of various relevant technical submissions, pre and post-accident ground investigation reports and tunnel boring machine records.

Investigation timescales

- 26 Following consultation on its draft investigation report in September 2014, the RAIB decided to delay publication of its report until it had undertaken some work to further validate its conclusions regarding the most likely cause of the voids found at Stoke Lane (paragraph 51). This work was undertaken between October 2014 and February 2015 and involved reviewing submissions made during the consultation process, and undertaking further analyses of the tunnel boring machine records. Having assessed that these further investigations were unlikely to result in substantive changes to the recommendations arising from the investigation, the RAIB informed consultees on 28 November 2014 about the anticipated delay to publication, and encouraged recipients of its draft recommendations to start implementation.

Key facts and analysis

Sequence of events

Background

- 27 The contract for the Stoke Bardolph substation project and associated cabling works, which included the Stoke Lane UTX, was awarded by Western Power Distribution to Morgan Sindall Utilities on 7 December 2011. At that time the details of the tunnelling method, the number of cables and the route had not been finalised.
- 28 Discussions between Western Power Distribution, Morgan Sindall Utilities and Network Rail commenced in January 2012 and an agreement (called a Basic Asset Protection Agreement) was signed between Network Rail and Western Power Distribution on 1 March 2012. Under this agreement, Western Power Distribution undertook, amongst other obligations, to design and carry out the works in accordance with Network Rail's requirements. Network Rail agreed to provide its railway asset protection services to Western Power Distribution, on a commercial basis, to review and approve the UTX design and method statements against Network Rail's requirements. The scope of services also included the provision of staff to supervise the safety of Bridgeway Consulting personnel undertaking monitoring work around the railway.
- 29 On 8 March 2012, Network Rail issued a set of engineering conditions to Western Power Distribution and which specified the Network Rail company standards, *Railway Group Standards* and other standards that should be met. The letter also included other technical and programme management requirements. These requirements are described later at paragraph 70.
- 30 Between March 2012 and January 2013, work on the design of the UTX was progressed by Morgan Sindall Utilities and Bridgeway Consulting. Network Rail gave its initial approval in principle to the UTX design on 30 January 2013 and its final approval, upon receipt of further details, on 16 April 2013.
- 31 On 16 April 2013, Severn Trent Water arranged for trial excavations to be dug in Stoke Lane at two locations to verify the position of the two twin siphons (figure 5). The trenches were dug to a sufficient depth to locate the top and sides of each twin siphon. Following this, Severn Trent Water confirmed to Morgan Sindall Utilities on 12 June 2013 that it was satisfied that a depth of 5.5 metres below ground level to the crown of the tunnel gave sufficient clearance to its siphons. The way was now clear for the UTX construction to begin.

Events preceding the accident

- 32 F&B Trenchless Solutions began construction work on 11 June 2013, starting with the launch shaft and followed by the reception shaft on 18 June. Both shafts were completed by 27 June. This area of Stoke Lane had already been closed to road traffic by Nottinghamshire County Council since 18 February 2013, in anticipation of the works commencing earlier.

- 33 The TBM was launched from the launch shaft at 16:23 hrs on 6 July and the tunnelling was continuous until 15:25 hrs on 8 July, except for a 7.5 hour stoppage due to a pump failure, which started at around 15:00 hrs on 7 July, and periodic pauses to insert new sections of pipe. F&B Trenchless Solutions completed their work at Stoke Lane and left site on 11 July. Normal train services continued to operate over the crossing during the construction works, in line with usual Network Rail practice.
- 34 Bridgeway Consulting started full time monitoring for settlement of the road and railway when the tunnelling started. A set of base readings had been taken on 25 June. Road measurements were made at 13 equidistant points along the road centre line between the launch shaft and the south eastern railway boundary and three further points between the north western railway boundary and the reception shaft. Rail measurements were made at 22 targets located on each rail of the up and down lines at 3 metre intervals. Three measurement points on each rail were located over the level crossing. Bridgeway Consulting took measurements every 3 hours up to and including 11 July and sent these to Network Rail. By the end of tunnelling on 8 July the measurements indicated a maximum track settlement of 9.5 mm and a maximum road settlement of 7 mm (discussed further at paragraph 68). In accordance with Network Rail's instructions, the monitoring frequency was reduced in stages from two shifts per day starting on 12 July to two shifts per week starting 2 August.
- 35 On 19 July at 23:00 hrs, Network Rail started a planned blockade of Nottingham station to enable a major programme of re-signalling work to be carried out. This continued until 26 August. During the blockade, rail traffic over the level crossing was significantly reduced, amounting to a few engineer's trains per day until 10 August, when passenger services resumed. Freight traffic resumed on 26 August.
- 36 By 31 July, the maximum rail and road settlements had increased to 22.7 mm and 11 mm respectively. The rail settlement was by then was over four times Network Rail's maximum allowable predicted ground movement of 5 mm, but less than the trigger value of 25 mm at which immediate action was specified as being necessary. These limits are discussed later at paragraphs 94 and 95. Network Rail, Morgan Sindall Utilities and Bridgeway Consulting met on 1 August to discuss the increasing rail settlement and how to rectify it. At that meeting Network Rail stated that the track would need to be packed with ballast up to its normal level. In the following days its asset protection team requested an engineering *possession* as soon as possible to enable the remedial work to be carried out. Network Rail also agreed at this meeting to reduce the monitoring frequency to twice per week from 2 August (paragraph 34), in line with its practice of progressively reducing the monitoring frequency and because the settlement had levelled off. The reduction in traffic during the Nottingham blockade had been overlooked. Network Rail arranged for the remedial work to be done during a possession on 9 September. An earlier possession had been available between 24 and 26 August but Network Rail's re-signalling project team wanted to run test trains over the level crossing during that possession as part of the commissioning work. The testing work was deemed to take priority. This decision was not challenged by the asset protection team because it did not fully appreciate the severity of the problem at Stoke Lane level crossing (paragraph 70).

37 On 8 August, Bridgeway Consulting staff found a hole in the road located at one end of the trial excavation (paragraph 29) over the twin siphon closest to the launch shaft (figure 8). The position of the hole in relation to the siphons is shown in figure 5. On closer examination, the Bridgeway Consulting staff found the hole had loose material inside it which appeared to come from the reinstated road sub-base material and that there was a void below the surface which sloped downwards and toward the centre line of the road. Bridgeway Consulting called a site meeting the same day with representatives from Morgan Sindall Utilities and Nottinghamshire County Council, to examine the hole and determine the likely cause of the defect. The opinion of the two contractors' representatives at the meeting was that the hole had originated at the trial excavation due to inadequate reinstatement of the excavation and that both the hole and the void were not linked to the tunnelling activity. Nottinghamshire County Council's representative was uncertain as to the cause of the hole and subsequently sought further views from the involved parties. However no party accepted responsibility and the matter was unresolved when the derailment occurred. Severn Trent Water and F&B Tunnelling Solutions were informed of the hole. Network Rail was not informed and remained unaware of the hole until after the derailment.



Figure 8: Hole in the road found on 8 August 2013 (photograph taken on day of accident)

38 When passenger services resumed over the level crossing on 10 August, there was no increase in the maximum rail settlements, which were now being measured twice a week on Tuesdays and Thursdays. This monitoring regime continued until the derailment. Between 1 and 27 August the maximum settlement of the track varied from day to day but remained between 13 and 23 mm. However, the road settlement increased during this period to between 14 and 19 mm. The centre line of the road continued to show the greatest amount of settlement. During this period, Network Rail undertook routine track patrols on 13 and 20 August but no problems were reported over the level crossing.

- 39 Freight traffic over the level crossing resumed on 26 August, with seven trains on the up line, weighing between 2019 and 3162 tonnes, and four trains on the down line, weighing between 757 and 2359 tonnes. All these trains were within the permitted maximum weights for the track over Stoke Lane. One of the trains that went over the level crossing on the up line was driven by the driver who drove train 6M35 on 27 August. There were also several passenger trains over the crossing during the day. There were no reports from any train drivers of rough riding over the crossing. Examination of forward facing CCTV from two passenger trains which went over the crossing during the evening of 26 August, confirmed there were no obvious faults with the vertical alignment of the track over the level crossing on both the up and down lines.
- 40 On 27 August, four freight trains passed over the crossing on the up line prior to the derailment. The first was at 00:50 hrs and weighed 2856 tonnes. Subsequent trains were at 01:40 hrs (743 tonnes), 02:30 hrs (2100 tonnes) and 03:55 hrs (2068 tonnes). There were no reports from the drivers of those trains of any problems with the track at the level crossing.

Events during the accident

- 41 Freight train 6M35 departed Humber Oil refinery on time and had an uneventful journey until it reached Stoke Lane level crossing. It was the fifth train to go over the crossing that morning and it traversed the crossing at 04:26:37 hrs while travelling at 53 mph (85 km/h), which is within the maximum line speed of 60 mph (96 km/h).
- 42 The driver reported that he felt a jolt as his locomotive went over the crossing but did not think it was anything exceptional. According to the locomotive's on-train data recorder (OTDR), at 04:27:03 there was a drop in the train's brake pipe pressure, which caused the brakes to apply. The driver noticed this and his first thought was that he had inadvertently nudged the brake lever and applied the train's brake, and so he tried to release the brake. However, this action was not successful and the train started to slow down rapidly as its brakes came on automatically. The driver shut off power. Unbeknown to the driver at the time, the 29th wagon had sustained damage to an air tank and its brake equipment had been struck by debris, almost certainly from detached buffers (paragraph 43). This caused a rapid loss of air pressure from the brake pipe and resulted in the automatic application of the train brakes, starting with the rearmost wagons and progressing forward. The train came to a stop near Carlton station about one minute later at 04:28 hrs.

Events following the accident

- 43 The driver contacted the signaller and explained that he had had an unintended brake application and was going to investigate. The signaller blocked the adjacent down line to protect the driver as he examined his train. The driver found that the trailing wheelsets on the 26th and 28th wagons had derailed and that the trailing wagons had sustained various degrees of buffer damage. The buffers at the leading ends of the 24th and 26th wagons had completely detached. He then contacted the signaller a second time and declared a rail dangerous goods emergency (as required by the railway *Rule Book*) because of the nature of his load. He reported that none of the wagons were leaking and the train was not fouling the adjacent line.

- 44 The signaller alerted the emergency services (because of the nature of the freight) and Network Rail on-call staff. The fire brigade did not attend because there was neither a fire nor fuel leakage. Network Rail and DB Schenker arranged for the leading 22 wagons to be hauled away from the site at around 13:00 hrs and the remaining 8 wagons at 17:30 hrs.
- 45 The severe distortion in the rails of the up line (figure 3) was found at around 06:00 hrs. Later that day, the *level crossing panels* were removed and this revealed the large voids below both railway lines around the centre of the road (figure 4). In the following days, a significant amount of ground investigation and repair work was carried out by Network Rail and Morgan Sindall Underground Professional Services, in consultation with the RAIB, to document the voids and repair the track before the line was reopened to traffic on 8 September 2013.
- 46 In parallel with the remedial work to the track, Morgan Sindall Underground Professional Services undertook further detailed ground investigations of the road on both sides of the crossing, in consultation with the RAIB. The purpose of this work was to determine the extent and cause of the voiding and to design a scheme for remedial *permeation grouting* of the whole site to stabilise the ground. Network Rail arranged for all four rails to be monitored during the ground investigations between 15 September 2013 and 3 January 2014, during which time further ground settlement occurred; around 17 mm and 12 mm on the up and down lines respectively.
- 47 After the ground investigations, an extensive programme of remedial grouting was carried out by Morgan Sindall Underground Professional Services to fill the voids and stabilise the ground, which was completed during February 2014. The road, which had been closed since 18 February 2013, was reopened on 14 March 2014.

Identification of the immediate cause²

- 48 **The immediate cause of the derailment was a severe dip in the track which had developed rapidly under the leading portion of train 6M35 and caused the 26th and 28th wagons to derail.**
- 49 After the derailment the maximum track dip was measured at 98 mm on the cess rail and 97 mm on the six foot rail. The actual amount of track dip that the last eight wagons of train 6M35 experienced would have been greater, due to additional deformation caused by elastic bending of rails under the weight of the wagons.

² The condition, event or behaviour that directly resulted in the occurrence.

Identification of causal factors³

- 50 The derailment occurred due to a combination of two causal factors:
- Large voids had developed under the track as a result of excessive ground loss during the construction of a microtunnel under the road and level crossing. These voids left the track unsupported at the level crossing (paragraph 49).
 - Normal train services had been allowed to resume following the tunnelling work, despite evidence of abnormal ground movement (paragraph 65).

Each of these factors is discussed below.

Voids under the track

51 Large voids had developed under the track as a result of excessive ground loss during the construction of a microtunnel under the road and level crossing. These voids left the track unsupported at the level crossing.

- 52 Examination of the track after removing the level crossing panels revealed large voids under both the up and down lines around the centre line of the road. These voids resulted in virtually all the support for the track being lost over a length of around 3 metres. The only remaining support was the concrete centre sill beam between the up and down lines (figure 4). The jolt felt by the driver as he drove over the crossing indicates that the track had already been deformed by the time 6M35 arrived, probably by the previous freight trains that morning. The track dip at that time was not so severe that the driver of train 6M35 was unduly alarmed and the locomotive and leading 22 wagons crossed without derailment. However, the type of damage to the buffers of the last eight wagons indicated that *buffer locking* had occurred as a result of severe vertical movements between these vehicles by the time they reached the crossing, and that the track had given way under the leading portion of train 6M35.
- 53 Ground investigations carried out following the derailment revealed that the voids under the railway were not isolated but were part of a series of voids which ran between the launch and reception shafts of the UTX, generally along the centre line of the road as shown in figure 9. Most of the voids were just below the road surface, but there were also voids found under the railway and the twin siphons and around the shafts. The volume of each void was estimated by Morgan Sindall Underground Professional Services from the amount of grout that had to be pumped into them during the remedial work. The combined total volume of the voids was estimated at around 63 m³ comprising:
- Voids near the surface (shown in red): 46 m³
 - Deep voids below the railway and twin siphons (shown in green): 8 m³
 - Voids around the launch and reception shafts (shown in orange): 9 m³

³ Any condition, event or behaviour that was necessary for the occurrence. Avoiding or eliminating any one of these factors would have prevented it happening.

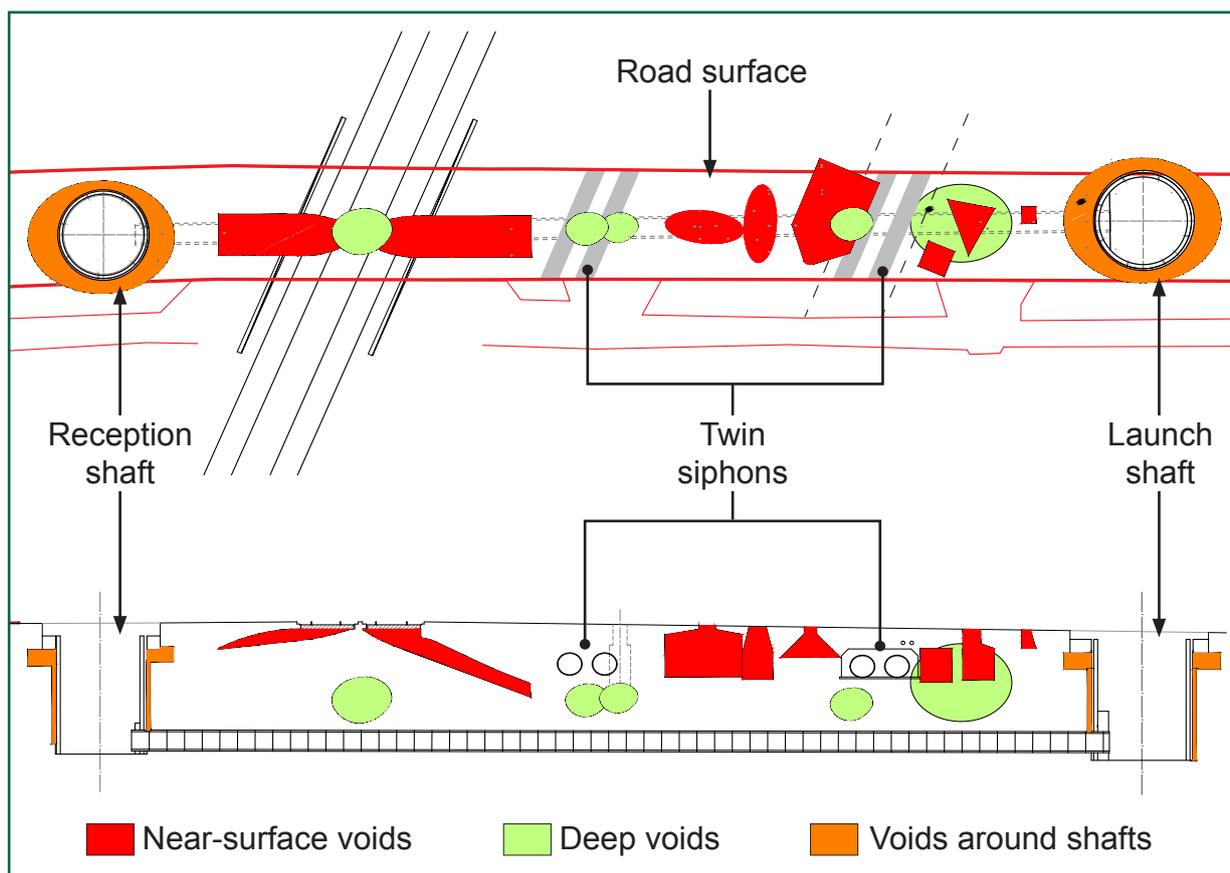


Figure 9: Map of voiding found during ground investigations undertaken by Morgan Sindall

- 54 The UTX at Stoke Lane was bored using a slurry shield tunnel boring machine (TBM), described in appendix D. The minimum amount of material that must have been removed by the 1.25 metre diameter TBM cutter head (figure 10) to bore out a 53 metre long tunnel, is around 65 m³. The combined volume of the near surface and deep voids (shown in red and green in figure 9) was around 54 m³, which indicates there had been additional ground loss⁴ of around 80%. The RAIB was advised by its consultant that a typical upper bound value of ground loss for a tunnel of this type and size would be around 5%.
- 55 Several possible causes for such a large amount of ground loss were considered by the RAIB:
- pre-existing voids caused by disused coal or gravel mining activity;
 - historic pre-existing voids caused by dissolution of rocks;
 - loss of ground due to the tunnelling operation damaging a water pipe or sewer and subsequent washing away of material;
 - overmining at the excavation face during the tunnelling operation;
 - loss of ground into unfilled annular spaces created behind the cutter head during tunnelling and during the construction of the launch and reception associated shafts;
 - loss of ground due to *dewatering* during the tunnelling operations and the associated possible loss of fines.

⁴ The additional amount of ground that was removed during the tunnelling, expressed as a percentage of the minimum volume that must be removed.



Figure 10: TBM cutter head

56 Considering first causes (a) and (b) of paragraph 55; investigations showed no evidence of any coal mining activity in the area at a depth that could have affected the UTX tunnel. There is evidence of mine workings in the area in a seam of coal at a depth of 350 metres but the extent of the working was restricted to protect the sewers that run along the railway into Stoke Bardolph sewage treatment works. The nearest recorded mine shaft is located around 2.5 km to the north west of the level crossing. Although there are sand and gravel workings in the Trent valley, there are no records of any such activity in the area around the level crossing. There are also no recorded soluble rocks in the area which might have had associated dissolution cavities. Had there been any pre-existing voids, it is very likely that some would have risen to the surface and manifested themselves as subsidence of the road and railway a long time ago. It is very unlikely that any pre-existing voids created by natural or man-made means could be so aligned to the UTX as the voids found along Stoke Lane. Therefore, the RAIB has concluded that pre-existing voids are unlikely to have caused the voiding observed at Stoke Lane.

- 57 The RAIB considered the possibility of ground loss arising from damage to a water pipe or sewer during the tunnelling work (paragraph 55c). Although there are a number of services that lie below ground at the site, there are no confirmed records of any current or disused services existing at the depth of the UTX. Severn Trent Water carried out CCTV inspections of its services in the vicinity of the UTX after the accident and reported that it had not detected any leaks or damage. Had there been a breach of a sewer or water pipe, any resulting erosion of the surrounding ground would be expected to form a void local to the breach and not a series of voids along the length of the tunnel and on both sides of the railway. Hence, the RAIB has found no evidence to support the possibility that ground was lost into a damaged underground service and this mechanism of void formation is considered unlikely.

Overmining (mechanism (d))

- 58 The positioning of the voids above the path of the microtunnel (figure 9) is the strongest indication that the voids had been caused by overmining of the ground during the tunnelling activity. Most of the voids along the road and across the railway between the launch and reception shafts had migrated from the depth of the tunnel to a level just below ground level. Normally such voids would be expected to break through the surface soon after the tunnelling had been completed but the road and its foundations effectively bridged the voids, except for one hole which appeared in the road on 8 August (paragraph 37). The deep voids found below the railway and each of the twin siphons do not appear to have risen higher because they were bridged by those structures.
- 59 Overmining, to the extent seen at Stoke Lane, is rare (paragraph 101). Typically the upper bound value of ground loss expected for this type and size of tunnel is around 5% of the tunnel volume (paragraph 54). The only way to accurately check that the amount of ground being excavated is in line with expectation, is to measure the volume of material extracted. Best practice for using closed face tunnelling machines is published by the British Tunnelling Society in association with the Institution of Civil Engineers⁵. The guidance states that it is essential to have a management system to compare the volume of spoil excavated against the theoretical value for each section of pipe installed. For slurry shield tunnelling machines it recommends the use of a flow meter and a density meter in both the slurry feed line and return lines. From this data any overmining can be identified during the tunnelling process and appropriate action taken by the operators.
- 60 F&B Trenchless Solutions did not have density meters in the slurry feed and return lines. The TBM it used was fitted with flow meters only and so the operators would not have been able to accurately measure the amount of material excavated. F&B Trenchless Solutions reports that it visually monitored the quantity of spoil removed by applying its usual rule of thumb that it expected to fill a 9 tonne capacity dumper truck with spoil for each 2.5 metre length of tunnel excavated. Morgan Sindall Utilities was responsible for disposing the spoils and it took the excavated material in the 9 tonne dumper truck to a holding area about 2 miles away. Here the spoil became mixed up with spoil from other sources. Neither F&B Trenchless Solutions nor Morgan Sindall Utilities kept any records of the volume of spoil removed from the tunnel excavation, and therefore it has not been possible to verify how much ground was extracted.

⁵ Closed-face tunnelling machines and ground stability – a guideline for best practice, published by Thomas Telford, London, 2005, ISBN 0727733869.

- 61 The TBM used for the UTX and the cutter head were appropriate for the ground conditions at Stoke Lane. Examination of the data recorded by the TBM control unit during tunnelling (called the machine protocols) indicates that it was driven to an accurate line and level. Key operating parameters did not indicate anything obviously amiss. However, detailed analysis of the volume flow rates (measured by flow meters) in the feed and return lines of the TBM, and the likely range of fluid densities in these lines (assessed by the RAIB's consultant), suggests that, most likely, there had been overmining to the extent reported at paragraph 52.
- 62 A key factor that increased the risk of overmining was that F&B Trenchless Solutions did not add *bentonite* to the slurry used in the TBM. The fluid it used comprised only water. Bentonite is added to water (at a concentration of around 5%) in slurry shield TBMs for certain types of ground, such as wet sands and gravel below the water table, because it offers support to the excavation face and minimises the risk of overmining.
- 63 The use of a bentonite slurry with polymer additives for spoil conditioning is recommended by the British Tunnelling Society and the Institution of Civil Engineers⁵ to establish a film (called a 'filter cake') on the tunnel face to stabilise it and prevent slurry loss into the ground. British Standard 6164:2011⁶, section 7.4.2.2 also explains that a pressurised heavy slurry with bentonite not only supports the sand and gravel but also negates the effects of the ground water by equalising the ground water pressure. The use of bentonite is not mandated in British Standard BS6164:2011 but is recommended to minimise the risk of overmining in *unstable ground* conditions. The RAIB has concluded that, although it is not possible to be certain about the cause of the voiding, the most likely explanation is overmining. The RAIB has taken into consideration all available evidence, expert advice and possible alternative explanations put forward by an involved party who disputes the RAIB's conclusion.

Loss of ground into unfilled annular spaces (mechanism (e))

- 64 In addition to the likelihood of ground loss at the tunnel face due to overmining, two other possible causes of ground loss, associated with unfilled annular spaces, were identified:
- a) During the tunnelling process, a void space is normally created between the concrete pipes which form the tunnel and the cut ground, because the cutter head has a slightly larger diameter than the trailing part of the TBM and concrete pipes. This void space should be filled with bentonite or a polymer to avoid the ground collapsing onto the pipes as the tunnelling progresses and also to lubricate the outside of the pipes so that they slide more easily relative to the ground. F&B Tunnelling Solutions reported that it pumped 6 m³ of bentonite into the void space. If this had been the case, this should have filled the void space around the pipes if there had only been the minimum over-cut (of about 25 mm around the pipes). However, the forces required to drive the TBM forward indicate a high level of friction between the pipes and ground, which indicates that bentonite was either not used or was not effective in preventing the ground closing onto the pipes. If the void space had not been filled effectively, as appears likely was the case, the ground would have collapsed around the pipes and contributed to the overall ground loss.

⁶ BS 6164:2011; Code of practice for health and safety in tunnelling in the construction industry; page 34.

- b) The launch and reception shafts were constructed from concrete rings which were jacked down into the ground while the ground within the rings was excavated. The process leaves an annular void between the concrete rings and the ground. It was estimated by Morgan Sindall Underground Professional Services that the volume of this annulus was around 9 m³ for the launch shaft and 8 m³ for the reception shaft. This annular space should have been filled with a grout to prevent the ground moving in. F&B Tunnelling Solutions build records indicate each shaft was pumped with 3 m³ of bentonite which would not have been sufficient to prevent some ground loss into the void spaces around the shafts.

Dewatering (mechanism (f))

- 65 The launch and reception shafts were built with a concrete base around 300 mm thick with a sump in the bottom to allow ground water to enter the shaft. This was to ensure the whole shaft was not forced up by ground water pressure. Because the shafts were not sealed from the surrounding ground water, it was necessary to pump the shafts out (or dewater) at various times during the tunnelling work. F&B Trenchless Solutions used a standard 4 inch (100 mm) 'Hydrainer' pump which was discharged into a nearby manhole in the road. Interview evidence provided to the RAIB indicates the period of dewatering was between 5 and 7 days, including 24 hrs per day dewatering during the tunnelling activity. During this period a significant amount of water was pumped out of the ground and would have been replaced naturally by the water table.
- 66 This dewatering activity, which should have been the subject of a separate approval by Network Rail according to its procedures (discussed later at paragraph 79), could have caused fine grained particles to be washed out of the ground and thereby contributed to the loss of ground. There are no estimates of how much ground was actually lost as a result of the dewatering at Stoke Lane. F&B Trenchless Solutions reported that although it did not use a silt separation plant while dewatering the launch shaft, it did use such a plant for the reception shaft and that did not pick up a significant quantity of fines. Severn Trent Water also reported it did not find unusual quantities of fines at its pumping station next to the sewage treatment works, into which water pumped from the shafts would have been routed. Therefore, the available evidence indicates that the amount of ground potentially lost through dewatering was likely to have been small and mainly from the area adjacent to the shafts. Dewatering could also have caused a small amount of general settlement of the area around the shafts (because soil grains move closer together when there is a reduction in the water pressure holding them apart) but this would not be expected to have contributed significantly to the voiding.

The resumption of normal train services

67 Normal train services had been allowed to resume following the tunnelling work, despite evidence of abnormal ground behaviour.

68 As detailed at paragraphs 34 to 38, monitoring of the railway showed a trend of increasing track settlement from 9.5 mm on 8 July when the tunnelling operations finished, to around 23 mm on 31 July. A graph of settlement against time from the start of tunnelling (6 July) for the six foot rail of the up line at the road centre line (which generally showed the greatest amount of settlement) is shown in figure 11. After 31 July, this measurement position and some others around it indicated some fluctuation⁷ between 23 mm and 12 mm. The last measurements taken before the derailment were on Thursday 22 August when the settlement recorded for position LX5 was 14 mm and those at other rail measurement positions at the centre of the level crossing were similar. The next set of readings were due on the day of the derailment. By 29 July, the monitoring had been reduced in frequency to three times per week (paragraph 34). The Nottingham station blockade, which had started on 19 July and continued until 26 August, had resulted in reduced rail traffic over Stoke Lane level crossing. Despite the reduced rail traffic flows there had been a further increase in settlement up to 31 July.

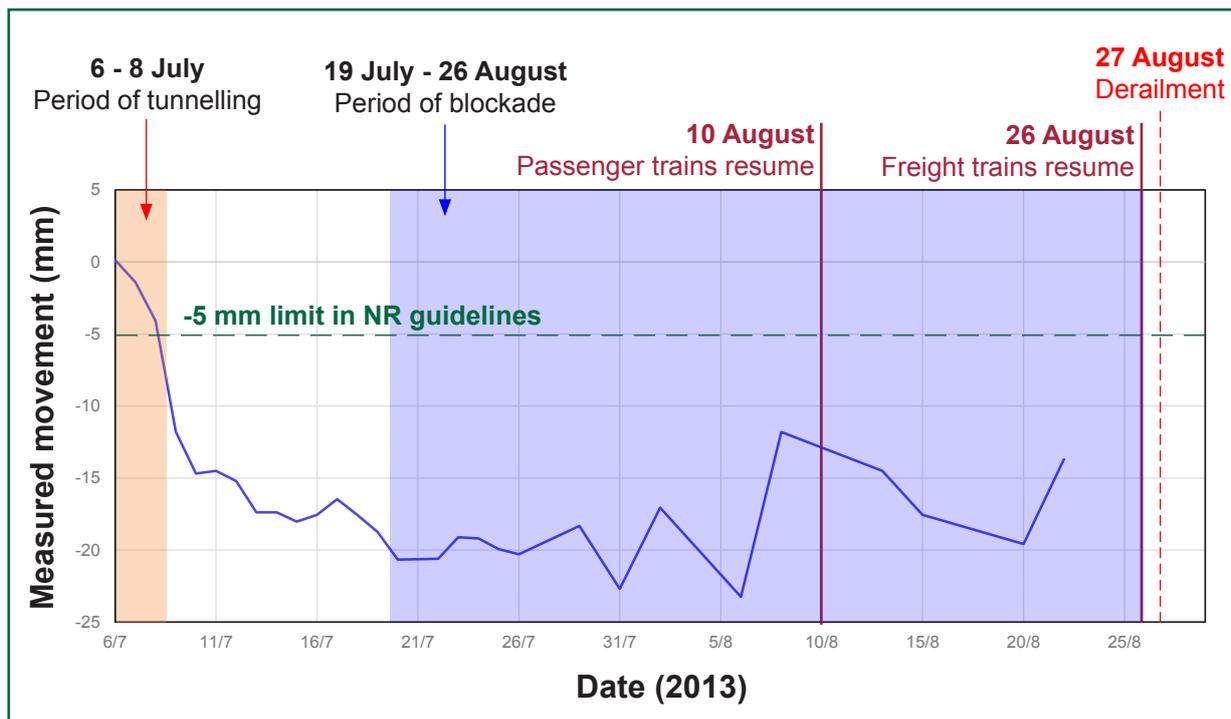


Figure 11: Movement of rail during and following tunnelling (on six foot rail of up line at road centre line)

⁷ The precise reasons for the fluctuation are not known, but the RAIB considers it is unlikely that the ground level itself fluctuated by the amount indicated in the measurements. Other factors which could have contributed are the passage of a trains around these dates, natural expansion/contraction of the rails due to temperature changes and measurement errors (estimated by the surveyors to be around +/- 3mm).

- 69 Bridgeway Consulting and Network Rail assessed the measured settlements in accordance with Network Rail standard NR/BS/LI/045, 'Monitoring track over or adjacent to civil engineering works: procedure and intervention levels', August 2008. According to the criteria in that standard, the 23 mm of vertical movement recorded on 31 July and subsequently again on 8 August did not require immediate action. Nevertheless, Network Rail's construction manager had become increasingly concerned about the settlement during late July. There had been discussion between the asset protection team and the track maintenance team during 9 to 16 July during which the track team reportedly indicated that it was not too concerned with the amount of settlement because the values were still below the track maintenance limits specified in Network Rail standard NR/L2/TRK/001 and the settlement was still being monitored. The use of track maintenance limits to assess settlement from construction activity is discussed later at paragraph 90.
- 70 Network Rail's construction manager called the meeting on 1 August with Morgan Sindall Utilities and Bridgeway Consulting (paragraph 36), to discuss action to remedy the situation. The agreed plan was that the track at the level crossing would be packed to its normal level as soon as possible to avoid the need to apply temporary speed restrictions. This led to arrangements for remedial work to pack the track during a possession on 9 September. Earlier possessions had been available but the nature of the problem at Stoke Lane was not fully appreciated by the asset protection team. Had it been, and the opportunity taken to inspect the track under the crossing before the derailment, it is possible that the voiding under the track might have been found.
- 71 There were two other factors which affected the decisions made by the involved parties about the severity of the settlement problem:
- a) The hole that was discovered in the road on 8 August (paragraph 37) was not reported to Network Rail by either Morgan Sindall Utilities or Bridgeway Consulting, despite the joint meeting on 1 August to discuss Network Rail's concerns about the settlement. Interview evidence indicates that the reason it was not communicated to Network Rail was because it was considered by the parties at the site meeting of 8 August, that the hole had been caused by poor reinstatement of the trial excavation carried out prior to the tunnelling work and because it was quite far from the crossing. Examination of the hole after the derailment revealed that the trajectory of the void was steeply downward towards the centre of the road and the tunnel and not into the remainder of the trial excavation. Had more rigorous consideration been given to the cause of the void, a possible link to the tunnelling operation should have been apparent. This was a missed opportunity to provide potentially valuable information to Network Rail about what was happening at Stoke Lane almost three weeks before the derailment. Had Network Rail been informed about the hole in the road, and the trajectory of the void below, it may have led to lifting the level crossing panels sooner than the planned 9 September possession.

- b) The settlement affecting both the up and down lines was not severe enough to be noted by the track patrollers on 13 and 20 July. Even if any voiding had been present directly under the track around 20 July, it would have been concealed by the level crossing panels and the only way track patrollers would have found a problem would have been if the settlement had been severe enough to have significantly deformed the panels. The lack of any rough riding reports by other drivers and the evidence from the forward facing CCTV of two passenger trains during the evening of 26 August indicate no visible distortion of the panels nor any noticeable jolt as the trains ran over the crossing.

Identification of underlying factors⁸

Relevant Network Rail standards

- 72 As a preface to the following sections of this report, the key Network Rail standards applicable to the construction of the Stoke Lane UTX are summarised below.
- 73 Standard NR/L2/CIV/003, 'Engineering assurance of building and civil engineering works', is Network Rail's high level document which sets out the process that should be followed for all construction work undertaken by Network Rail on outside party property and work undertaken by outside parties on Network Rail property. It requires the completion of three forms:
- a) F001, 'Approval in principle', which signifies that Network Rail is satisfied that the design solution identified is the preferred option for achieving the objectives of the project and is acceptable to Network Rail.
 - b) F002, 'Statement of design intent', which defines the basis of the design for the works and is submitted by the contractor's responsible engineer acting for the outside party making the submission. This is reviewed by a Network Rail asset protection engineer.
 - c) F003, 'Certificate of design and check', is the detailed design submission and should include drawings, schedules, performance criteria, materials, workmanship specifications, testing and inspection plans, risk registers and other documents which form the design. It should be signed off by a responsible engineer to confirm that the design has been carried out in accordance with form F002 and checked in accordance with the agreed method of checking, whether in house or by an independent company.
- 74 Standard NR/SP/CIV/044, 'Design and construction of undertrack crossings', August 2004, is the mandatory standard for both Network Rail and outside parties who wish to build a UTX. Those responsible for the design and construction of UTXs, and also those involved in the management of its design and construction, are required by Network Rail to comply with this standard. It includes certain requirements for design, risk assessment, details of precautions that should be taken and what should be submitted to Network Rail.

⁸ Any factors associated with the overall management systems, organisational arrangements or the regulatory structure.

- 75 There was also a guidance document which was used within the LNE route of Network Rail entitled 'Guidelines for design and construction of undertrack crossings under Network Rail infrastructure'. Its purpose was to assist Network Rail construction managers in providing advice to outside parties on how to comply with its requirements for UTXs. It was not issued to other parties involved in the design and construction of the Stoke Lane UTX. It expanded on the requirements specified in standard NR/SP/CIV/044 and included the following extracts relevant to the Stoke Lane UTX project:
- a) 'Positioning of UTXs beneath level crossings is strongly discouraged due to the problems of installing an effective monitoring system and disruption to road and rail traffic should corrective action (packing of track) be needed.'
 - b) 'If using 'O'Reilly and New'⁹ formulae for settlement calculations, any reduction factors applied during determination of 'Volume of losses' shall be justified within the F002 and F003 submissions.'
 - c) 'It is expected that drilling works will include the use of bentonite (or similar) drilling fluid under pressure head to maintain stability of the drill bore. Any proposal to omit this is subject to Network Rail approval. This shall be identified within the F001.'
 - d) 'Network Rail's Engineering Conditions states that dewatering is not permitted within the vicinity of the Railway. In extreme cases this may be relaxed where good engineering reasoning has been used to demonstrate there is no practicable alternative. Forms F002 & F003 will be required for any dewatering proposal.'
 - e) 'The predicted settlement, pipe strength and temporary ground support calculations (if required) shall be subject to a Cat 3 Independent Check. Pipe ovalisation shall be considered. Cat 3 Independent design check is carried out by an independent consultancy organisation that is a separate legal entity to the designer.'
 - f) 'The maximum allowable calculated settlement/heave is 5 mm. Certain exceptional circumstances will allow for slightly higher values ie line speed, track category, etc.'
 - g) 'All UTX installations require Network Rail full time supervision for works within the *zone of influence* of the railway infrastructure.'

⁹ O'Reilly M.P, New B.M, 'Settlements above tunnels in the United Kingdom, their magnitude and prediction'. Proc. of Tunnelling '82 Symposium, London. pp.173-181.

Compliance with Network Rail's asset protection standards

76 Network Rail's asset protection standards and guidance were not fully complied with, which introduced risks to the Stoke Lane UTX project.

- 77 Standard NR/SP/CIV/044 is mandatory, and both Bridgeway Consulting and F&B Trenchless Solutions were aware of the document and its requirements. However they did not comply with some of the requirements of that standard (paragraph 78) and Network Rail did not adequately check compliance. Network Rail's LNE route guidance document for UTXs contains important additional requirements (paragraph 79), but these appear to have been overlooked by Network Rail and not communicated to Bridgeway Consulting or F&B Trenchless Solutions. As a result important factors, which are detailed below, were not addressed during the planning and approvals stages.
- 78 The investigation identified the following issues with respect to the application of Network Rail standard NR/SP/CIV/044:
- a) Use of the standard: Network Rail's engineer responsible for reviewing the design submission, who had previous experience of reviewing UTX submissions, considered that the standard was for outside parties to follow and sign that they were compliant, in line with custom and practice. He did not consider there was any need for Network Rail to perform checks that the standard had been followed and there is no explicit instruction in the standard for Network Rail to carry out a clause by clause check.
 - b) Competence of designers and construction managers: the standard requires that the skill, expertise, training and experience of those employed on a design shall be appropriate to the nature and complexity of the UTX being designed, and in line with the competency requirements of the Construction, Design and Management regulations, 1994¹⁰. The Stoke Lane UTX design required a good understanding of *microtunnelling* and the associated risks and mitigations at level crossings. Bridgeway Consulting submitted curriculum vitae (CVs) of its competent responsible engineer and competent responsible manager to Network Rail, as part of its technical submissions for approval of the UTX. Neither CV demonstrated relevant experience with UTXs but they were accepted by Network Rail without challenge. Network Rail did not check the CVs of key F&B Trenchless Solutions staff involved in the construction of the UTX.
 - c) Use of appropriate standards: the standard requires that UTXs are designed 'in accordance with Railway Group Standards, Network Rail Company Standards, European and British Standards, relevant industry standards and industry good practice'. Network Rail did not pass on to Bridgeway Consulting and F&B Trenchless Solutions some important requirements, because they were contained in the internal guidance document. Network Rail did not check against its own requirements in the guidance that key precautions against ground loss were in place.

¹⁰ The Construction, Design and Management (CDM) regulations, 1994 was the predecessor to the current CDM regulations, which were introduced in 2007. Standard NR/SP/CIV/044 pre-dates CDM 2007. These regulations set out the legal duties on organisations involved in construction projects to ensure that the project is safe to build and use and maintain. (see <http://www.hse.gov.uk/construction/cdm.htm>). Compliance of the Stoke Lane UTX project with CDM 2007 is a matter for the Health and Safety Executive (HSE) and its investigation, and is outside the scope of the RAIB's investigation.

- d) Monitoring of excavated material: the standard requires that the quantity of material excavated during construction of a UTX shall be monitored by the outside parties to ensure that the volume is compatible with the progress of the work. There is no requirement for Network Rail to undertake its own checks. As explained at paragraph 60, neither F&B Trenchless Solutions nor Morgan Sindall Utilities kept any records of the amount of material that was excavated. Network Rail did not check that either party was keeping records.
- 79 The following deviations with respect to the application of the LNE&EM guidance document for UTXs were evident:
- a) Position of UTXs: the guidance strongly discourages positioning UTXs beneath level crossings, due to the problems of installing an effective monitoring system and potential for disruptive remedial works to road and rail traffic. Given that Network Rail were faced with such a UTX, it did not then take adequate heed of the difficulties of setting up an appropriate monitoring system for a level crossing, by for example, specifying the inclusion of sub-surface measurements of ground settlement.
- b) Use of bentonite: the guidance states an expectation that bentonite will be used to maintain stability of the tunnel bore and that the volume of bentonite used will be monitored against the anticipated amount required. Any deviation from using bentonite should have prior approval from Network Rail. F&B Trenchless Solutions' method statement was clear that only water would be used without bentonite. Network Rail did not challenge this because it did not consider this specific aspect of the method statement. Its focus was on checking whether the predicted settlement was acceptable.
- c) Dewatering: the guidance states that dewatering is not permitted within the vicinity of the railway but that in extreme cases this may be relaxed where good engineering reasoning has been used to demonstrate there is no practicable alternative. A separate set of forms, F002 and F003, should be used for any proposal to carry out dewatering. The guidance does not define 'vicinity of the railway' but the issue of dewatering was not considered until there was concern about the measured settlements. At that point Network Rail requested that dewatering be stopped. No engineering assessment was done as to the possible effects of the dewatering and no controls were put in place during the tunnelling work. It is possible that had forms F002 and F003 been submitted for the dewatering, Network Rail would have put some controls in place.
- d) Design checking: the guidance clarifies the requirements specified in standard NR/SP/CIV/044, that calculations submitted as part of the approvals process for a UTX, including predictions of ground settlement, should be checked by an independent organisation (called a 'cat 3' check). For the Stoke Lane UTX project, Network Rail's design reviewer decided that it was sufficient for Bridgeway Consulting to check its own calculations, which represents a lower level ('cat 2' or 'cat 1') check. In the event, there was an issue with the calculation of ground settlement which is discussed later at paragraph 95.

80 Network Rail's LNE&EM asset protection team had not been subjected to any audit to check compliance with Network Rail's procedures and guidance related to the approval of UTXs. The RAIB has found no evidence of a process for such auditing.

Assessment of the risk posed by the Stoke Lane UTX

81 **There was insufficient assessment of the risks posed by the UTX at Stoke Lane.**

82 F&B Trenchless Solutions submitted four risk assessments to Morgan Sindall Utilities, the first three of which were passed to Network Rail as part of the approvals process for the works. These assessments covered:

- a) General site risks which could cause injury to people working on site and passers-by, dated 10 October 2012. It included risks such as working at height, manual handling, transport, operating equipment, fire and environmental pollution.
- b) Risks associated with construction of the launch and reception shafts, dated 10 October 2012. This covered hazards of the excavation, groundwater, flooding, methane, working at height, lifting, and grouting.
- c) Risks which could cause injury to F&B Trenchless Solutions staff during the microtunnelling, dated 10 October 2012. This covered risks such as working at height, lifting operations, construction of the shaft walls, *pipe jacking*, operating machinery, use of lasers, transport, and excavation around buried services causing collapse. It included consideration of the collapse of unsupported ground around the shafts, to be mitigated by monitoring and management of the ground water.
- d) Risks associated with the effect of the microtunnelling on the railway, dated 4 June 2013. This is the most relevant to the voiding found at Stoke Lane. It included consideration of the following risks:
 - 'cant or displacement of the rail': precautions listed are monitoring the amount of soil mined against pipes installed, and monitoring of settlement.
 - 'unexpected ground conditions': precautions listed include monitoring of excavated material and TBM controls at all times, and modifying operation of the TBM as necessary.

83 Network Rail had given its approval to the UTX project and associated method statements by 16 April 2013, by which time it had received risk assessments (a) – (c) above. It had not received the final risk assessment done by F&B Trenchless Solutions (listed (d) above) which was the only one that considered the risk of ground loss affecting the railway. Therefore Network Rail's approval was given without an adequate assessment of the risk to the railway. Had Network Rail reviewed the final risk assessment of 4 June 2013, and applied its guidance procedures correctly, it would have realised that key mitigations in its standard NR/SP/CIV/044 and the LNE&EM UTX guidance document had not been adequately addressed.

- 84 There were two other factors which probably affected Network Rail's consideration of the Stoke Lane UTX submissions and its consideration of risk to its infrastructure:
- a) There was some confusion about roles and responsibilities between Network Rail's design reviewer and construction manager, regarding who was responsible for checking the risk assessments submitted by F&B Trenchless Solutions. The design reviewer thought this was the responsibility of the construction manager and vice versa.
 - b) At the time of the Stoke Lane UTX project there was a shortfall in staff resources in the asset protection team for various reasons. The workload of the construction manager and his assistant was high due to several dozen other projects they were handling at the time. Witness evidence indicates that this did not allow them sufficient time to focus on the Stoke Lane UTX and its particular risks.
- 85 No party involved in the Stoke Lane UTX, other than F&B Trenchless solutions, carried out any risk assessments of their own for the tunnelling works. Although not a mandated requirement of the CDM regulations 2007, Bridgeway Consulting did not undertake a designer's risk assessment for the works or the routing of the UTX (as required by Network Rail standard NR/SP/CIV/044), because it was not specifically requested to do so. Morgan Sindall Professional Services approved the F&B Trenchless Solutions tunnel construction method statement on 8 July 2013, by which time the tunnelling had been completed.
- 86 The Network Rail and Morgan Sindall Utilities construction managers had not received any formal training on UTXs and had limited knowledge of the particular issues regarding UTXs at level crossings. Neither organisation sought to procure the expertise required, nor use the facilities of other departments within their own organisations. Consequently the risk assessments and other documentation put forward by F&B Trenchless Solutions were not properly scrutinised and the lack of important controls against overmining (eg such as the use of bentonite in the slurry, grouting of void spaces, and monitoring of spoil removal) were not addressed.

Adequacy of Network Rail's procedures for UTXs

87 Network Rail's procedures for UTXs and the way they were used, did not provide adequate guidance for those involved in the design, scrutiny and construction of the UTX.

88 Standard NR/SP/CIV/044 does not provide Network Rail or those required to comply with it, a clear and straightforward list of requirements. It does not include important additional requirements contained in the UTX guidance document. The guidance is not listed as a mandatory document and therefore outside parties did not have the full set of Network Rail requirements to work to in this case. However, the requirements in the guidance document are generally consistent with good microtunnelling industry practice and should have been familiar to experienced parties.

- 89 Neither standard NR/SP/CIV/044 nor the UTX guidance document provide a logical risk based approach to dealing with applications for UTXs. For instance the UTX guidance document states that UTXs under level crossings should be strongly discouraged, but it does not explain what procedure to follow or what additional precautions to take if a UTX has to be located under a level crossing.

Criteria for monitoring settlement at UTXs

90 The criteria used for monitoring settlement were not appropriate for a UTX under a level crossing and did not adequately alert the asset protection team as to the severity of the developing problem.

- 91 This factor adversely influenced the decisions made by Network Rail about the severity of the settlements, the urgency of the situation and the associated risk to the railway. The monitoring regime was a key safeguard for the safety of the railway.
- 92 Network Rail had specified that the monitoring of settlement during and after the tunnelling should comply with its standard NR/BS/LI/045, 'Monitoring track over or adjacent to civil engineering works: procedure and intervention levels', August 2008. This standard sets criteria for horizontal and vertical movement of the track, track cant and track twist over a 3 metre base.
- 93 The assessment of the measured settlements by Network Rail and Bridgeway Consulting's surveyors was generally in accordance with its standard NR/BS/LI/045. However, it did not help Network Rail to correctly assess the severity of the voiding at Stoke Lane for the reasons discussed below.
- 94 Bridgeway Consulting's surveyors calculated the changes in each parameter monitored and compared them with the limits specified in standard NR/BS/LI/045 by means of colour codes, and then emailed the results to Network Rail's construction manager as soon as they were compiled. Vertical rail movement was the main issue in this accident, the limits and actions for which were:
- 0 – 15 mm: no action;
 - 15 – 25 mm: note but no action necessary; and
 - 25 mm or greater: report fault.

These criteria are consistent with Network Rail maintenance standard, NR/L2/TRK/001, 'Inspection and maintenance of permanent way. The purposes of that standard are:

- to prescribe the inspections, limits and actions required to prevent track caused derailments; and
- to describe the inspections, limits and actions required to optimise track performance, cost and asset life.

By using the criteria in standard NR/BS/LI/045 there was an inherent assumption that the track, even if it was settling, always had solid ground below it. This cannot always be assumed. Standard NR/BS/LI/045 did not take cognisance of four important factors which were present at Stoke Lane. These are described in the following paragraphs.

- 95 Firstly, standard NR/BS/LI/045 did not require the size of the settlement to be compared to the predicted settlement. The maximum vertical settlement was 23 times the settlement predicted by Bridgeway Consulting, which was 1 mm. Bridgeway Consulting's prediction had been based on an unrealistically optimistic assumption that the amount of ground lost during the tunnelling would be 0.6% of the volume of the tunnel. A more realistic value of ground loss in the conditions at Stoke Lane would have been around 2.5%¹¹ which would have given a predicted settlement of around 4 mm. Even compared to this value, the actual settlement was still nearly 5 times more. The high ratios between predictions and measured settlements was a strong indication that something had gone wrong during the tunnelling operations.
- 96 Secondly, it did not require any consideration that the roadway and railway might have been bridging voiding beneath them and thereby masking the severity of the problem. The possibility of this occurring is recognised in Network Rail's LNE& EM guidance document for UTXs (paragraph 79a) but this warning had not been incorporated into standard NR/BS/LI/045. The track monitoring at Stoke Lane used the rails as the targets and would have been compromised from the outset because the settlements seen by the rails lying on the surface were unlikely to reflect the settlement affecting the ground below the foundations of the road and railway¹².
- 97 Thirdly, the standard did not require any assessment of the rate of settlement of the track in relation to the type and frequency of trains running over it. Had this been considered, it would have become apparent that the settlement continued to increase between 20 and 31 July although there was no rail traffic over the level crossing in that period except for two freight trains on 29 July. This should have increased the concern about the safety of the line over Stoke Lane when normal services resumed, even if the cause of the settlement was not clear.
- 98 Finally, it did not provide any advice on when and how to reduce the frequency of monitoring. At Stoke Lane the frequency of track monitoring was being reduced progressively while the settlement was increasing with the volume of rail traffic decreasing. It would have been logical to increase the frequency of monitoring in preparation for and following the resumption of normal rail services on 26 August. This could have shown further settlement as trains started running over the crossing and led to the closure of the line before the derailment.

Factors affecting the severity of consequences

- 99 The consequences of the derailment could have been worse if the wagons had rolled over and the tanks had ruptured or if a passenger train had derailed at the crossing.

¹¹ This value applies if the void space between the cutter head diameter and concrete pipes is filled with an appropriate grout. The cutter head diameter is necessarily slightly greater (by about 50 mm) than the outer diameter of the tunnel pipes. If the space is not filled with grout, the ground loss would be closer to around 8.5%, excluding any ground loss due to overmining at the tunnel face.

¹² To capture subsurface ground movements in such conditions, the targets would need to be attached to rods drilled deep into the ground.

Observations¹³

- 100 Although not linked to the cause of the derailment, the RAIB has noted a number of issues related to the submissions that were made to Network Rail. In particular, it was observed that submissions from Bridgeway Consulting were not updated as the design evolved during the project, both in relation to the type of tunnelling to be used and the geometry of the UTX and its associated shafts:
- a) The submission made to Network Rail by Bridgeway Consulting on 18 December 2012 stated that the tunnel would be built by *auger boring* even though it was known by then that F&B Trenchless Solutions intended to use a slurry shield TBM. Although this was a typographical error, it was never corrected and meant the documentation approved by Network Rail was not consistent with tunnelling method that was used at Stoke Lane.
 - b) The UTX design approved by Network Rail was different in geometry to what was actually built in respect of tunnel length and depth, diameters of the launch and reception shafts and their position with respect to the railway. Changes to the design were not notified formally to Network Rail nor was re-approval sought. Document control of the design drawings was not up to normal engineering standards, resulting in different drawings with the same revision number and no list of amendments or dates.
 - c) The reception shaft was built closer to the railway than shown in the design drawings sent to Network Rail for approval. The decision to move the shaft closer to the railway was taken on site by Morgan Sindall Utilities and F&B Trenchless Solutions just before construction of the shaft was started, in order to ease the blockage of a driveway to a nearby house. However, the movement encroached slightly into the 'zone of influence' of the railway and should have been formally notified to Network Rail. However, Network Rail was verbally informed of the move.

Previous occurrences of a similar character

- 101 Network Rail reports that 83 UTXs were constructed on its infrastructure nationally during December 2012 to December 2013. There have not been any previous derailments caused by subsidence following UTX installations.
- 102 There have been previous occasions where the track has had to be packed to its normal level following settlement resulting from the installation of UTXs:
- a) In May 2003 at Prestonpans (near Edinburgh), a temporary speed restriction was applied until four sleepers were packed to correct the vertical alignment of the track.
 - b) In 2009 near Staythorpe power station, Nottinghamshire, continuous track settlement was noted and corrected by regular packing, during the installation of 17 ducts to the power station, each of 450 mm diameter, by auger boring. The total of the incremental settlements was estimated at 256 mm. The settlement was attributed to overmining.

¹³ An element discovered as part of the investigation that did not have a direct or indirect effect on the outcome of the accident but does deserve scrutiny.

Summary of conclusions

Immediate cause

103 The immediate cause of the derailment was a severe dip in the track which had developed rapidly under the leading portion of train 6M35 and caused the 26th and 28th wagons to derail (**paragraph 48**).

Causal factors

104 The causal factors were:

- a) Large voids had developed under the track as a result of excessive ground loss during the construction of a microtunnel under the road and level crossing. These voids left the track unsupported at the level crossing (**paragraph 51, Recommendation 1**).
- b) Normal train services had been allowed to resume following the tunnelling work, despite evidence of abnormal ground behaviour (**paragraph 67, Recommendation 4**).

Underlying factors

105 The underlying factors were:

- a) Network Rail's asset protection standards and guidance were not fully complied with, which introduced risks to the Stoke Lane UTX project, (**paragraph 76, Recommendation 2**).
- b) There was insufficient assessment of the risks posed by the UTX at Stoke Lane level crossing (**paragraph 81, Recommendation 3**).
- c) Network Rail's procedures for UTXs and the way they were used did not provide adequate guidance for those involved in the design, scrutiny and construction of the UTX (**paragraph 87, Recommendation 2**).
- d) The criteria used for monitoring settlement were not appropriate for a UTX under a level crossing and did not adequately alert the asset protection team to the severity of the developing problem (**paragraph 90, Recommendation 4**).

Additional observations

106 Although not linked to the cause of the derailment, the RAIB observed that changes to the design of the UTX as it evolved were not formally notified to Network Rail and were not captured in the design drawings (**paragraph 100, Recommendation 2**).

Actions reported as already taken or in progress relevant to this report

- 107 On 3 March 2014, Network Rail LNE&EM route issued a document, 'Guidance for the installation of undertrack crossings using horizontal directional drilling (HDD) and other micro tunnelling/thrust boring techniques'. This is an enhanced version of the LNE&EM guidance document for UTXs that existed prior to the derailment. It stresses certain key points such as the need to avoid UTXs under level crossings as far as possible, ensuring adequate communication between all parties, demonstrating competency of the designer and tunnelling contractor, the need for a designer's risk assessment and analysis of possible failure modes.
- 108 Network Rail reports that it is in the process of delivering training for its LNE&EM route asset protection teams to bring them up to date with the latest microtunnelling techniques in relation to UTXs.

Learning points¹⁴

109 The RAIB has identified the following learning points for the construction industry:

- a) A detailed risk assessment should be carried out which includes careful consideration of the prevailing ground conditions and the consequences of excessive ground loss or heave, and appropriate control measures should be implemented during the works.
- b) UTXs should not be routed under level crossings unless absolutely necessary, due to the difficulties of reliably monitoring both the road and railway for settlement and the potential risk from settlement.
- c) Bentonite or other appropriate additives should be used in the slurry where ground conditions require it, or best practice suggests it should be used.
- d) The volume of spoil excavated from a tunnel or microtunnel under construction should be carefully monitored, to a level of accuracy that is achievable for the method of tunnelling being used, and compared to the expected volumes. Records of the spoil volumes extracted should be retained.
- e) The method and frequency of measurement for monitoring ground settlement during and after tunnel construction should take cognisance of any nearby civil engineering structures such as level crossings, bridges, stations (which may mask the severity of any subsequent voiding or settlement) and any temporary changes to traffic conditions. For the specific case of UTXs at level crossings, consideration should be given to monitoring subsurface movements because surface measurements alone can be unreliable and give optimistic results.
- f) Where there is an unexpected event such as the appearance of a surface hole in the vicinity of a tunnel, this should be investigated immediately and thoroughly, to identify the cause and any associated risks.

¹⁴ 'Learning points' are intended to disseminate safety learning that is not covered by a recommendation. They are included in a report when the RAIB wishes to reinforce the importance of compliance with existing safety arrangements (where the RAIB has not identified management issues that justify a recommendation) and the consequences of failing to do so. They also record good practice and actions already taken by industry bodies that may have a wider application.

Recommendations

110 The following recommendations are made¹⁵:

- 1 *The intent of this recommendation is that the HSE, as the investigatory and regulatory authority for the construction of UTXs, disseminates the key learning points from this accident to the UK tunnelling industry. It is intended that the tunnelling companies then review their methods of working and make any necessary changes to prevent similar future accidents or incidents.*

The Health and Safety Executive (HSE) should:

- a) disseminate the key lessons from this accident (paragraph 109 refers), to UK organisations representing tunnelling companies (eg The Pipejacking Association, British Tunnelling Society, UK Society for Trenchless Tunnelling), and request them to further disseminate the learning points to their members, so that individual companies can review and improve their working practices as necessary.
- b) assess the need to carry out monitoring checks at UTX construction sites, as part of its audit programmes, to verify that the procedures being followed on site are in line with industry good practice and lessons learned from this investigation (paragraph 104a).

continued

¹⁵ Those identified in the recommendations, have a general and ongoing obligation to comply with health and safety legislation and need to take these recommendations into account in ensuring the safety of their employees and others.

Additionally, for the purposes of regulation 12(1) of the Railways (Accident Investigation and Reporting) Regulations 2005, Recommendation 1 is addressed to the Health and Safety Executive, and Recommendations 2, 3 and 4 are addressed to the Office of Rail Regulation, to enable each to carry out their duties under regulation 12(2) to:

- (a) ensure that recommendations are duly considered and where appropriate acted upon; and
- (b) report back to RAIB details of any implementation measures, or the reasons why no implementation measures are being taken.

Copies of both the regulations and the accompanying guidance notes (paragraphs 200 to 203) can be found on RAIB's website www.gov.uk/raib.

- 2 *The intent of this recommendation is that there is one consistently applied Network Rail standard for UTXs, applicable to both outside parties and Network Rail, so that in future there is clarity about Network Rail's complete requirements and expectations and the checks its engineers should undertake.*

Network Rail should review how its current processes related to the construction and approval of UTX works are being applied, and consider the most effective way of merging its national standard and local route guidance documents into a unified set of requirements for UTXs. These requirements should:

- a) include improvements to cover lessons learned from this accident as detailed at paragraph 109, and be included in a process of periodic review to check that they remain up to date;
- b) list the main sources of risk to its infrastructure from the construction of UTXs (eg ground settlement, heave or voiding) and how it expects those risks to be mitigated;
- c) provide clarity on roles and responsibilities within Network Rail, and its expectations of outside parties, particularly with respect to assessing and managing risk and communication for matters affecting safety of the railway; and
- d) seek to use a risk based approach which leads users to additional control measures for higher risk UTXs, such as those at level crossings.

Once developed, the requirements should be the subject of appropriate briefing and training to relevant Network Rail staff and made available to outside parties installing UTXs. Compliance with the requirements should also be subject to a system of periodic internal audit (paragraphs 105a, 105c and 106).

- 3 *The intent of this recommendation is that Network Rail's asset protection engineers have sufficient knowledge about UTXs, and the time to properly assess and manage the associated risks to its infrastructure.*

Network Rail should:

- a) review the working knowledge of its asset protection engineers with respect to UTXs and where necessary provide appropriate training, which should include information on types of UTX, methods of construction, best practice, failure modes, seeking specialist assistance; and
- b) review the resourcing in its asset protection teams to check that engineers have sufficient time allocated to carry out their duties and access to specialist technical assistance when required, and where necessary, make any appropriate changes (paragraph 105b).

continued

- 4 *The intent of this recommendation is that Network Rail has a procedure for monitoring settlement in the vicinity of UTXs and other civil engineering works adjacent to its infrastructure, which can be relied upon to accurately measure ground movements that could adversely affect the safety of the line.*

Network Rail should:

- a) review the suitability and action limits of its standard for the monitoring of track movement over or adjacent to civil engineering works, including UTXs. This should take into account calculated predictions of settlement, rates of movement and the potential for the movements to be masked by existing structures, and not rely upon inappropriate track maintenance standards; and
- b) make any necessary changes to its procedures and brief these out to relevant staff (paragraph 105d).

Appendices

Appendix A - Glossary of abbreviations and acronyms

LNE&EM Route	London North Eastern and East Midlands Route
OTDR	On-train data recorder
TBM	Tunnel boring machine
UTX	Under track crossing

Appendix B - Glossary of terms

All definitions marked with an asterisk, thus (*), have been taken from Ellis's British Railway Engineering Encyclopaedia © Iain Ellis. www.iainellis.com.

Auger boring	A method of cutting small diameter tunnels (typically up to around 1 metre diameter). A rotating auger within a circular casing is used to transport the cut spoil from the cutter head at end of the auger to a pit at the other end, from which the spoils are removed. The casing around the auger provides support to the ground while the tunnel is cut and then forms the tunnel itself.
Bentonite	Bentonite is a processed form of a naturally occurring clay (called montmorillonite). It is used in the slurries of slurry shield TBMs (see appendix D) for tunnelling in certain types of ground where it helps to stabilise the excavation face (to minimise the risk of overmining) and assist in the transport of spoil away from the face to the surface. It is also used to lubricate the movement of the tunnel pipes during pipe jacking and to provide support for the ground around annular spaces resulting from the tunnel boring process.
Buffer locking	A phenomenon in some rail accidents involving rolling stock fitted with end buffers. Severe vertical movements can cause the buffers of one vehicle to ride over and lock against the back of the buffers of the adjacent vehicle.
Cant (of track)	The amount by which one rail of a track is raised above the other rail, measured over the rail centres.
Cess	The part of the track bed outside the ballast shoulder that is deliberately maintained lower than the sleeper bottom to aid drainage, provide a path and sometimes (but not always) a position of safety.*
Control Centre of the Future	A computerised system used by Network Rail and train operating companies as a source of real time train running and performance information.
Dewatering	The process of pumping out water from the ground at a construction site in order to artificially lower the ground water level, (where needed) or to keep an unsealed sunken structure dry while people are working in them.
Engineer's line reference	A unique reference, used by railway engineers, given to each route on the national network.
Jacking pipes	Concrete pipes used in a method of microtunnelling. See 'pipe jacking'.
Level crossing panel	A constructional unit, which together with other units, forms a level crossing surface suitable for carrying road traffic over the railway.

Microtunnel	A tunnel which is too small for an on-board operator during tunnelling; typically up to around 1.5 metres diameter.
Microtunnelling	A method of tunnelling in which an unmanned tunnel boring machine is remotely controlled from a control cubicle on the surface.
On-train data recorder	Equipment fitted on-board the train which records the train's speed and the status of various controls and systems relating to its operation.
Permeation grouting	A means of stabilising ground and filling up voids using a low viscosity grouting fluid to permeate into the inter-granular pores of the soil and any voids. As the grout hardens, it improves the strength and stability of the soil.
Pipe jacking	A method of installing underground pipes using a tunnel boring machine (TBM) which is driven forwards by hydraulic jacks installed in a launch shaft. The jacks drive the TBM forwards via a series of concrete pipe sections (called jacking pipes) which are dropped into position at the launch shaft as the TBM advances.
Possession	A period of time during which one or more tracks are blocked to trains to permit work to be safely carried out on or near the line.*
Railway Group Standard	A document mandating the technical or operating standards required of a particular system, process or procedure to ensure that it interfaces correctly with other systems, process and procedures.*
Rule Book	Railway group Standard GE/RT8000, which sets out most of the rules to be observed by railway staff for the safe operation of the main line network.
Sewer siphon	A pipe or pipes used to carry waste water under a road or other obstruction. Such siphons are designed to run full, with the flow being driven by a difference in hydrostatic pressure.
Six foot	The term for the space between two adjacent tracks, irrespective of the distance involved.
Under track crossing	A service, such as a cable, pipe or pipeline, which passes below the sleepers of the track.
Unstable ground	In the context of this report, ground in which a vertical excavation face is liable to collapse if there is not adequate support.
Zone of influence	A region directly below the track and extending laterally up to 3 metres from the cess rails horizontally and thereafter at a downward angle of 45 degrees.

Appendix C - Key standards current at the time

Network Rail standard NR/L2/CIV/003, Issue 4, 2 June 2012.	Engineering assurance of building and civil engineering works
Network Rail standard NR/SP/CIV/044, Issue 2, August 2004.	Design and construction of undertrack crossings
Network Rail standard NR/BS/LI/045, Issue 3, 26 August 2008.	Monitoring track over or adjacent to civil engineering works: procedure and intervention levels
Network Rail standard NR/L2/TRK/001/mod11, Issue 6, 1 December 2012.	Track geometry - Inspections and minimum actions

Appendix D - Slurry shield tunnel boring machine (TBM)

Slurry shield tunnel boring machines (TBMs) are a type of tunnelling machine suited to unstable ground where there is a high ground water pressure¹⁶. A schematic of the type of machine used at Stoke Lane is shown in the figure D1.

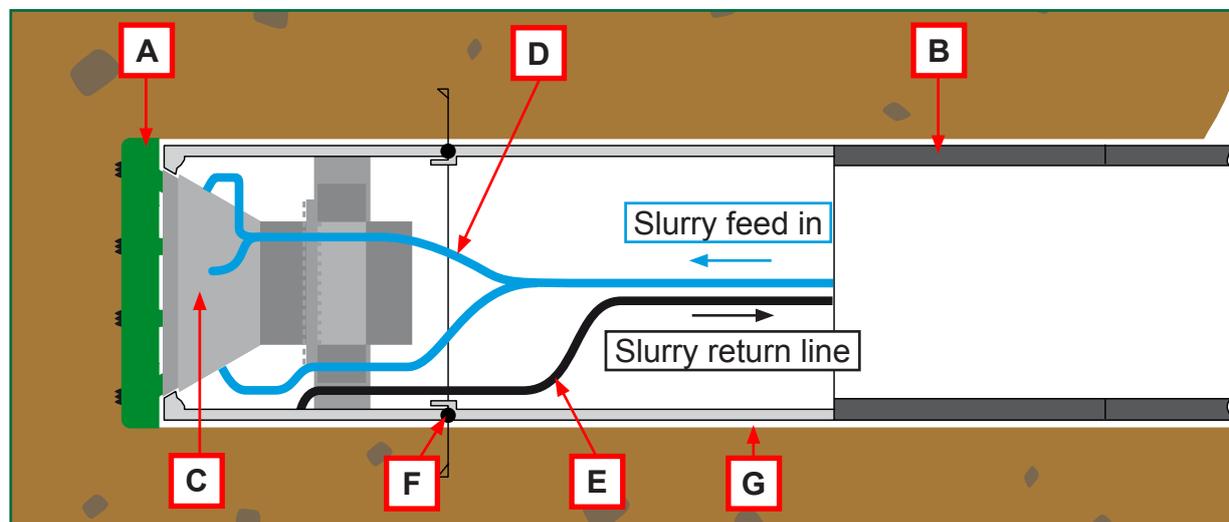


Figure D1: Schematic of a slurry shield TBM

The machine is remotely operated from a control cubicle at the surface. It works by cutting the ground with a rotating cutter head (A), which has rollers, scrapers and teeth, and which is pushed from behind by a series of concrete pipe sections (B). The pipes are pushed along the microtunnel by hydraulic jacks installed in the launch shaft. The process has to be paused periodically to insert a new pipe; at Stoke Lane this was every 2.5 metres. The cut ground falls into the excavation chamber (C) of the TBM. A crushing device (called a 'cone crusher') in the excavation chamber breaks up any large lumps as the cutter head rotates.

If the machine is being used in unstable ground such as wet sands and gravel below the water table, the excavated face must be supported while the TBM is operating, to prevent uncontrolled collapse of the ground into the excavation chamber, potentially leading to overmining. According to industry best practice this is achieved by feeding in a pressurised slurry (D), comprising water mixed with bentonite (or a polymer), into the excavation chamber. The pressure in the excavation chamber (called the face pressure) forces the slurry into the tunnel face in front of the cutter head, where it permeates into the ground, leaving a thin layer of bentonite (called a filter cake) on the surface of the ground. This layer of bentonite impregnated ground supports the areas of the tunnel face which are exposed as the cutter head (figure 10) rotates, while the slurry pressure counterbalances the ground water pressure. For excavation in some types of soil, such as clays, bentonite may not be required. In such cases the slurry may simply comprise water and a proportion of suspended clay material from the excavation face.

Material excavated from the ground falls into the excavation chamber where it is mixed with the incoming slurry and pumped into the slurry return line (E) to a separation plant at the surface (figure D2).

¹⁶ <http://www.ita-aites.org/en/how-to-go-underground/construction-methods/mechanized-tunnelling/slurry-shield>.

The plant separates the cut ground from the slurry, which is then recycled back to the TBM. The TBM has an articulation joint (F) which allows it to be steered by means of hydraulic jacks within the TBM (not shown) to maintain horizontal and vertical alignment as the TBM is driven forwards, using lasers and targets.

The cutter head diameter is slightly larger than the diameter of the main body of the TBM and the pipes and this results in an annular void space around the pipes (G) which, in accordance with industry best practice, should be filled with bentonite to prevent the ground closing in on the pipes.



Figure D2: Slurry separation plant (image courtesy of Morgan Sindall)

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Any enquiries about this publication should be sent to:

RAIB	Telephone: 01332 253300
The Wharf	Fax: 01332 253301
Stores Road	Email: enquiries@raib.gov.uk
Derby UK	Website: www.gov.uk/raib
DE21 4BA	