The effect of new tunnel construction under existing metro tunnels

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ABSTRACT: Section 2 of the Channel Tunnel Rail Link (CTRL) high-speed railway includes 36 km of 8.15 m running tunnels driven through soft ground conditions beneath east London. The tunnels pass beneath buildings, bridges, surface railways, an underground station and under six existing operational metro tunnels. The latter were considered a significant hazard due to their close proximity.

Systematic assessment was undertaken for each tunnel crossing with the capacity of each metro tunnel calculated in terms of an allowable bending curvature. The cast iron tunnels were found to be the most susceptible to the possible movements. In cases where the calculated capacity was deemed insufficient mitigation works were undertaken in advance of tunnelling. Structurally this was limited to the release of selected circle joint bolts in the existing linings.

Ground movement during tunnelling was limited through close tunnel boring machine control and the effects observed through intensive monitoring of the metros. Systems of monitoring trigger levels and associated contingency plans were prepared to manage any adverse events.

The actual movements observed were generally lower than initial expectations. Back-analysis demonstrated that the assessments of the effects had proved to be reasonably accurate. All of the metro crossings were conducted safely without disruption to the normal operation of the existing railways.

1 INTRODUCTION

1.1 *The CTRL works*

Section 2 of the Channel Tunnel Rail Link (CTRL) high-speed railway includes 36 km twin running tunnels driven through mixed soft ground conditions beneath east London. The tunnels were excavated using Earth Pressure Balance Tunnel Boring Machines (EPBM) with an excavated diameter of 8.15 m. Controlled pressure grouting through the tailskin to fill the annulus between the excavation and the tunnel lining was carried out concurrently with excavation. Additionally the annulus around the shield itself was supported with pressurised fluid (usually polymer modified bentonite or greases) to prevent the ground squeezing around the shield. A 350 mm thick steel and polypropylene fibre reinforced precast concrete tunnel lining was erected inside the EPBM tailskin to form the final lining. The lining is fully waterproofed with a gasket system. A review of the historical ground movements resulting from EPBM tunnelling indicated that a typical distribution of the volume loss to the face, body and tailskin in the proportion 25%, 25%, 50% respectively was likely and this has been broadly confirmed by the results of monitoring on the CTRL project (volume loss being the settlement trough volume as a proportion of tunnel volume).

1.2 *The metro tunnel interfaces*

The CTRL tunnels passed under or very close to about a dozen other significant tunnels. Of these interfaces six involved crossing under the existing operational metro running tunnels discussed here. Each crossing had to be undertaken twice to construct the pair of CTRL tunnels.

The London Underground Central Line was crossed between Stratford and Leyton. The remaining four metro crossings were to the south of Highbury and Islington. These four tunnels carried the London Underground Victoria Line and the national railway lines (GN&C) between Moorgate and Finsbury Park. The CTRL tunnels also passed close under parts of the underground station at Highbury and Islington including most notably an escalator shaft providing the sole public access to the low level station. As a further complication all the tunnelling at Highbury and Islington was also below busy surface railways. Close liaison with both London Underground and Network Rail was essential throughout the planning and execution of these works.

The existing tunnels included a variety of different types of metro tunnel construction. These included traditional cast iron segmental rings, tapered cast iron rings, modern precast concrete, and an unusual composite circular lining with a masonry invert and cast iron crown.

1.3 *Works objectives*

The overall objective for the crossings was of course to construct the CTRL tunnels in a timely fashion without endangering the public or staff using the metro system above. An obvious way of achieving this might have been temporary closure of the existing lines. However, all of the metro lines affected carry heavy commuter traffic into central London and operate at or very close to their capacities. This meant the railway authorities could not countenance stoppage or even disruption to services and the CTRL works had to be planned on this basis. An effort was made to time critical works to start in periods when the metro traffic was light but it was inevitable that some tunnelling took place directly below lines running at full capacity although one crossing was made when the line above was closed for unrelated reasons.

1.4 *The CTRL ground movement control philosophy*

The philosophy for the CTRL tunnelling was based on minimizing ground movement at source and systematically assessing the risks to determine if any supplementary measures were necessary. This demanded the use of much higher specification EPBMs than previous similar works but sought to avoid disruptive and costly advance works such as compensation grouting. This principle was extended to the metro crossings where the main effort was put into refining the tunnelling control and other settlement protection works were only undertaken where assessment showed the railway system's capacity to withstand likely movement was marginal.

2 ENGINEERING ASSESSMENT

2.1 *Assessment principles*

The assessment process for the effects of CTRL tunnelling had been specified in general terms through the Parliamentary process which had led to the passing of the CTRL Act (1996). The process involved a three stage sequence of assessments similar in principle to that undertaken for other projects in London. The aim at the end of each stage is to reduce the number of structures assessed in the next stage by eliminating those demonstrated to be at low risk. It is important that each stage is completed even if it is obvious that a complicated structure is being assessed because the staged assessment builds up an understanding of the greenfield ground movements that is invaluable during the stage 3 detailed assessment.

2.2 *Stage 1, settlement contours*

Stage 1 assessment comprises the production of drawings showing greenfield settlement contours due to tunnelling. The contours serve only to identify, in plan, those structures potentially at risk of ground movement. For the contracts including the metro crossings contour plans were prepared by Rail Link Engineering (RLE) prior to contract award and these were subsequently adopted by the contractors. Contours were plotted for both 1% and 2% volume loss. The 2% level was a conservative starting point for assessment while the 1% was based on the contract requirement for EPBM performance. The contours were derived using the Gaussian distribution model described by New & O'Reilly (1991). A uniform trough width of $K = 0.5$ was used.

These contour plots represent a conservative upper bound condition and are not representative predictions of the expected outcome. This requires careful presentation as the distinction between prediction and risk filtering is commonly misinterpreted by third parties.

As the CTRL alignment crossed directly beneath each metro tunnel it was immediately apparent that the metro tunnels were at risk of settlement and would therefore require further consideration.

2.3 *Stage 2, damage categorization*

Stage 2 assessment comprises an assessment using standard models of the damage to the structure that is likely to occur. This methodology was originally developed to deal with masonry buildings and the CTRL project specified the application of the model described by Boscardin & Cording (1989). During the project use was also made of the more recent model proposed by Mair et al (1996) which was found to be better suited to some situations. In either case the structure is categorised into one of five risk categories ranging from negligible to very severe damage based on the predicted upper bound strains. However, the methodology recognises that there are many different types of structure and for some structures the straightforward stage 2 assessment may not be appropriate. Metro tunnels, bridges and piled structures are examples of extraordinary structures for which more detailed assessment is commonly required and this is carried out in stage 3.

2.4 *Stage 3, detailed assessment of extraordinary structures*

The stage 3 assessments were undertaken by RLE within the commercial alliance framework established for the CTRL London Tunnels (McDonald and Bowers 2005). The first step in this detailed assessment is a careful study of the structure in order to predict likely modes of failure. It is important to gather as much information as possible about the structure. For London Underground and Network Rail structures there are significant archives of old drawings and these were invaluable. It is also important to carry out an inspections and condition survey of the structures. The latter ensures that there is a record of the condition prior to the works that can act as a reference against which any change or damage can be assessed. The general approach adopted for any of the stage 3 assessments was to generate a robust model of the likely behaviour of the structure. This model can then be manipulated to determine the point at which the structure fails to perform its function. This need not necessarily mean structural failure, but could be a serviceability problem such as failed clearance affecting train operations. Once this model has been developed and tested a decision can be made on whether mitigation works are required. The model can also be used to develop monitoring and contingency plans to ensure that if unexpected behaviour occurs during tunnelling then there are pre-planned actions to protect the general public and construction workers. Finally the model becomes a tool to aid back-analysis.

2.5 *Stage 3 approach applied to the assessment of metro tunnels*

The assessment process commenced with ground movement predictions, calculated in accordance with the ground movement model proposed by New and Bowers (1994), for a credible range of volume losses and trough width parameter. The results of the calculations were then applied to the metro tunnels using simple beam and spring models. The capacity of the metro tunnel lining system was defined in terms of a limiting bending curvature (although as bending curvature is difficult to measure directly trigger levels were ultimately defined in terms of vertical settlement).

Defining the critical curvature proved to be a fairly complicated problem in the case of the bolted linings where the combination of cast iron and steel bolts results in a fairly complex strain system. Particular care must be taken when selecting the parameters for the calculations to ensure that they are compatible. Once the critical curvature had been defined, an iterative process was undertaken to determine the matching volume loss and hence the tolerable vertical settlement.

The cast iron tunnels were shown to be the most susceptible to the predicted movements. In cases where the calculated capacity of the metro tunnel was deemed insufficient to resist the predicted settlement mitigation proposals involving releasing circle joint bolts were developed jointly with the owners of the metro tunnels. Throughout this assessment and design process the CTRL team adopted an "open book" philosophy for dealing with the third parties and this was important in reaching agreements.

Once the assessment was agreed management systems were developed to ensure the successful passage of the tunnel boring machines. This included a high level of RLE engineering supervision during the works and preparation of special contingency measures included emergency preparedness plans for the railways that defined the actions that would follow from each trigger. Three levels of trigger were defined for each of the metro tunnel structures, tracks and escalators thus allowing an incremental planned response to movements.

3 CENTRAL LINE

3.1 *Description*

The construction of the Central Line between Mile End and Newbury Park between 1936 and 1939 has been described by Groves (1945). The assessment was concerned with the length of tunnels east of Stratford Station, which were constructed using 12ft internal diameter cast-iron bolted linings. Due to the expected poor ground conditions a special tapered ring was used without the deal (timber) packing normally used to negotiate curves. The tapered lining differs from the standard lining by having machined circumferential faces in addition to machined radial faces.

The CTRL tunnels are excavated through Thanet Sands that lie below Upnor Formation sands that in turn are overlaid by the Woolwich & Reading beds (Lambeth Group) that surround the Central Line tunnels.

3.2 *Stage 3 assessment*

The first undercrossing of the London Underground Central Line was located 35 m after the commencement of the drive east from the Stratford box. This caused a certain degree of concern, as it is a generally accepted fact that most problems occur in the first 100 metres of a drive.

The Central Line tunnel inverts are close enough to the crown of the CTRL tunnels at 4.3 m and 8.0 m for the eastbound and westbound tunnels respectively for the Gaussian distribution (O'Reilly & New 1982) to give an unrealistic result. Therefore calculations were performed to assess the greenfield movement at the Central Line invert using the formulae published by New & Bowers (1994). The results from these were used to assess the affect on the Central Line structure, track geometry and clearances.

The key settlement parameters used for the assessment were a trough width, $K = 0.4$ and initially a volume loss of 2%. A parametric study performed as part of the assessment determined that the Central Line tunnels could withstand a volume loss of 0.5% without mitigation. However it was agreed by all parties that mitigation for a volume loss of 1% would be prudent.

3.3 *Mitigation*

The primary mitigation measure adopted for the Central Line crossing was careful management and control of the tunnelling operations. However, because this was not expected to reduce the ground movements to acceptable levels and because there were already existing discontinuities that modified the expected behaviour additional discontinuities were created by undoing the circle joint bolts at key locations. This work involved local removal of the trackbed. All work was carried out during engineering hours (01:00 am to 04:00 am) when there are no passenger trains, so as to minimize any disruption to the railway timetable. In all 13 discontinuities were created in the Central Line westbound and 14 in the Central Line eastbound.

3.4 *Monitoring*

The monitoring for the Central Line undercrossing started from the portal. A series of horizontal inclinometers was installed through the diaphragm wall. These together with Borros points (subsurface settlement monitoring points) installed from the surface were necessary to measure the ground movement at the horizon of the Central Line tunnels before the CTRL tunnels reached the Central Line.

The longitudinal deflection of the Central Line tunnels was monitored using manual levelling during engineering hours to confirm the primary electrolevel based real-time monitoring system. Automatic displacement sensors and Demec studs were installed either side of each discontinuity. Measurements were taken before and after each crossing. The transverse distortion of the Central Line tunnel was remotely monitored by electrolevels mounted directly on the segments and confirmed by manual survey.

4 HIGHBURY AND ISLINGTON

4.1 *Description*

The tunnel construction types crossed at Highbury and Islington are tabulated below. The cover between these tunnels and the CTRL tunnels varies is between 12 and 14 metres.

The CTRL tunnels in this area were driven through Lambeth Group clays and localised pockets of water-bearing Harwich Formation sand with the crown mainly in the London Clay. All the existing metro tunnels were in the London Clay.

Table 1. Tunnel construction types at Highbury and Islington.

Tunnel	Type
Victoria Line southbound	12 ft 2 in cast-iron
Victoria Line northbound	12 ft 6 in expanded concrete
GN & C southbound	16 ft cast-iron crown with brick invert
GN & C northbound	16 ft cast-iron
Twin escalator shaft	Concrete Box/Cast Iron Shaft

4.2 *Stage 3 assessments*

The stage 3 assessment for the tunnels at Highbury and Islington was similar to that performed for the Central Line. As before the aim of the assessment was to minimise the mitigation. Early calculations determined that a target volume loss of under 0.5% was required to pass beneath the most sensitive tunnel, the Victoria Line southbound without mitigation. Experience already gained along the tunnel drives indicated that this was an achievable target.

The assessment of the effect on the Escalator was more difficult to assess because the range of movement although very small, would exceed the acceptable movement defined in the LUL standard. Several options for mitigation, including adjustable jacks, were considered. Ultimately it was agreed appropriate to proceed on an observational basis. This was possible because there were two escalators and only one was required to be operational to keep the station open.

4.3 *Mitigation*

During preliminary design several options including compensation grouting were considered for mitigation at Highbury. In the end no mitigation was required but Union Railways and LUL signed a protocol agreement that set out targets that should be achieved prior to crossing under the Victoria Line tunnels. The protocol set out a target volume loss that was to be achieved when passing under extensometers prior to the crossings. In the event the protocol almost stopped the tunnels because of unexpected movements. However, back analysis of the ground movement subsequently indicated that the trough width was wider than anticipated. Tunnelling continued with revised trigger levels.

4.4 *Monitoring*

The elimination of any mitigation at Highbury and Islington determined that the monitoring became very important. The monitoring scheme did not just monitor the tunnels. There was a series of extensometers and surface level points prior to the crossings. Each of the tunnels had an electrolevel string for real-time monitoring these were confirmed by manual levelling carried out during engineering hours. The escalator structure was monitored using electrolevels and manual levelling. All of the real-time monitoring was

Figure 1. EPBM Control Room at Stratford. Screens show tunnel survey, TBM operation, conveyors, metro tunnel real-time monitoring, CCTV of the TBM, and environmental monitoring of the CTRL tunnel. There is also a view of the muck pile through the window that proved invaluable.

available to the management team in the TBM control room (Fig. 1) at Stratford and at a satellite control room near Highbury. The latter was necessary because the TBM control was 4 km from Highbury.

5 OBSERVATIONS

5.1 *Central Line*

The undercrossing of the Central Line tunnels was completed successfully in February 2003. The immediate settlement results were volume losses of around 0.25%. This was achieved by intensive management of tunnelling process by a joint team with senior personnel from RLE, Costain Skanska Bachy and LUL on site 24/7.

Each crossing was deliberately started on a Friday to make the best use of the weekend to minimise the risk of disruption to passengers.

The discontinuity sensors and Demec studs were carefully examined and no movement in shear or opening was observed. There was no increase in water ingress and in fact one drip dried up.

5.2 *Highbury and Islington*

The undercrossings at Highbury were completed successfully by Christmas 2003. No significant problems were encountered and it was observed that even the masonry invert of the GN&C northbound did not show any sign of cracking. In fact the only clear sign that the tunnels had moved was that a small mortar fillet had become detached from the interface between the brick and cast iron and remained level when the brick had settled. Key results from the monitoring at Highbury and Islington are summarised in Table 2. Sample data are presented in Figures 2 to 6. Similarly movements to the escalator were so small that no adjustments to the machinery were necessary.

At Highbury the relative precision of manual and electronic became an issue. The small movements recorded are difficult to monitor by manual means.

Table 2. Results of back analysis of ground movement at the Highbury and Islington crossings. The tunnels are listed in the order that they were crossed.

	CTRL UP		CTRL DOWN	
	K	V_s (%)	K	V_s (%)
GN & C southbound	0.71	0.59	0.61	0.38
Victoria southbound	0.55	0.44	0.38	0.55
GN & C northbound	0.70	0.51	0.67	0.52
Victoria northbound	0.45	0.44	0.49	0.45

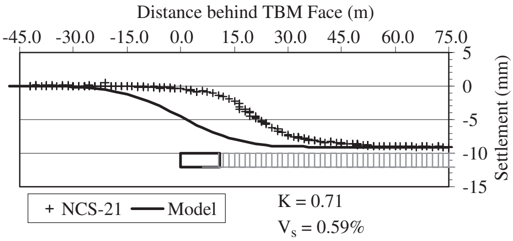

Figure 2. Settlement of GN & C southbound tunnel due to excavation of CTRL up tunnel normalized to show the development relative to CTRL TBM advance. The solid line shows the assessment. This plot confirms that the settlement in front of an EPB is small with the majority of movement occurring behind the tailskin.

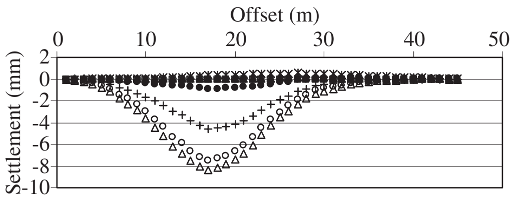

Figure 3. Transverse settlement of GN & C northbound tunnel due to excavation of CTRL up tunnel. The profiles represent 12 hour increments during the passage of the TBM.

A precision of ±2 mm is the best that could be achieved in the difficult circumstances presented by working in engineering hours. The real-time (electronic) monitoring worked particularly well with a low noise threshold.

6 CONCLUSIONS

The metro crossings described in this paper were all completed successfully. The approach adopted allowed the work to be completed without any requirement for disruption to railway operations.

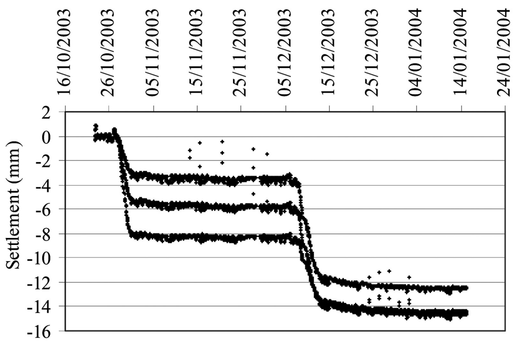

Figure 4. Settlement Time-history of GN & C northbound tunnel due to excavation of CTRL tunnels. Two events are apparent reflecting the separate passage of the two TBM's.

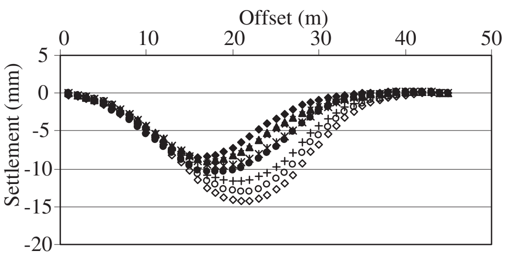

Figure 5. Transverse settlement development for GN & C northbound tunnel showing the effect of excavation for the CTRL down tunnel. The profiles show how the centre of the combined trough migrated laterally with the passage of the second TBM.

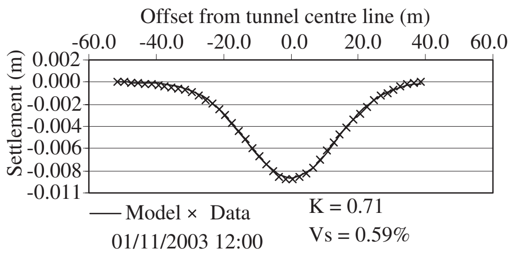

Figure 6. The result of back analysis of settlement for G.N & C southbound using Excel solver. The curves demonstrate the close agreement between the data and the model.

The metro crossings had originally been considered to be major risks to completing CTRL Section 2 to time and budget. The detailed specification of the tunnelling machines and the systematic risk based engineering assessment of the effect of tunnelling resulted in substantial savings compared to the allowances made in the tenders and were major contributors to completing the London tunnels to time and budget. All of the assessments were originally included in the contractor's scope of work; however it very quickly became apparent that this resulted in an inappropriate allocation of risk. Therefore the assessments and mitigation design were transferred back to RLE where the risk could be managed economically. The overall team performing these works comprised representatives from RLE, the contractors and the third party owners of the infrastructure. All parties worked together using an open book philosophy to safely complete the tunnelling without disruption to the normal operation of the existing railways.

Back analysis of the monitoring data to provide direct comparison with the predictions shows that the assessment of ground movement distribution proved to be reasonably accurate. The actual magnitudes of movement observed were generally lower than initial expectations when the works were planned.

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