Settlement due to tunnelling on the CTRL London Tunnels

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ABSTRACT: Between late 2002 and the spring of 2004 approximately 36 km of 8.15 m excavated diameter tunnels were driven under east London for the Channel Tunnel Rail Link (CTRL) high speed railway. The tunnels were driven using earth pressure balance tunnelling machines. The tunnels were constructed through a mixture of ground conditions that included various stiff clays, sands, gravels, chalk and recent estuarine deposits. The route was entirely within the London conurbation and passed under extensive existing infrastructure. Hence settlement damage was a major risk to the project.

This paper summarises observations of ground movement made during tunnelling. Throughout much of the route settlement volume loss figures averaged around 0.5%. In the best conditions prolonged runs of normal production resulted in volume losses of around 0.25%. The actual ground movement recorded is contrasted with that assumed during the planning stage. This comparison demonstrates what can be achieved with the latest tunnelling technologies and control systems in an urban area.

1 THE LONDON TUNNELS

1.1 Route
The London Tunnels were constructed between late 2002 and early 2004. They form part of the Channel Tunnel Rail Link (CTRL) high speed railway from the Channel Tunnel to St Pancras in central London. The twin bored tunnels carry the railway underground for approximately 18 km of the route. Heading towards London the tunnels commence at Dagenham Dock in the east and pass under Barking and Newham to a station site in a 1.1 km long diaphragm wall box in Stratford. West of Stratford the tunnels continue under Hackney and Islington to the London West Portal approximately 1 km north of St Pancras (Figure 1).

1.2 Ground conditions
The tunnels were constructed through a mixture of soft ground conditions that included stiff clays of the Lambeth Group and London Clay formation, Lambeth Group sands and gravels, the Thanet Sand formation, Thames river terrace gravels, the Chalk and recent estuarine deposits including alluvium and peat.

1.3 Ground movement hazards
The route was almost entirely within the London area and passed almost continuously under urban infrastructure, much of it old and potentially vulnerable to settlement damage. The structures at risk included:

- Approximately 3000 buildings
- 67 bridges (38 road, 19 rail, 10 foot)
- 50 retaining walls
- >12 route km of surface railways
- 6 existing railway stations
- >600 pipelines (many cast iron gas and water)
- 12 existing tunnels
- various lifts and escalators
- various industrial facilities (e.g. travelling cranes).

The numerous buildings and bridges also included a significant proportion on piled foundations that presented problems largely outside previous UK experience. Overall it was clear that ground movement induced damage was a major risk for the project.

1.4 Procurement
The procurement of the CTRL London tunnels was unusual and had a material impact on the settlement produced by tunnelling. The works were undertaken under a commercial alliance between the parties to the three tunnelling contracts and the Stratford Station Box contract. Under this arrangement no party could benefit from transferring risks to another. Instead they shared the risks and had to work together to identify optimum solutions. This resulted in the management of most ground movement related issues by a single...
team that worked closely with the tunnel construction management to refine the tunnelling operations to control the risks. The procurement of the works and the commercial outturn are described further elsewhere (McDonald & Bowers 2005).

2 CAUSES OF GROUND MOVEMENT

The CTRL London Tunnels works included a number of processes with potential to cause ground movement. These included deep aquifer dewatering in the Thanet Sand and Chalk, local dewatering of the upper aquifer in the terrace gravels and in some cases confined aquifers within the Harwich Formation and Lambeth Group. The deep station box at Stratford, the cut and cover at Ripple Lane in Dagenham and the five ventilation shafts all had further potential to cause ground movements from wall and pile installation and excavation. All of these effects were locally superimposed on the ground movement due to bored tunnelling that is the primary focus of this paper.

The bored tunnelling process itself potentially gives rise to movement because of the relaxation of the in-situ stress that may occur around a tunnel headings and the slight tendency to over-excavate (i.e. to excavate a greater volume of soil than the finished tunnel volume). In soft ground it is widely recognised that a uniform tunnelling process will tend to give rise to a uniform settlement trough that can be described by a Gaussian profile (O’Reilly & New 1982).

3 MANAGEMENT OF GROUND MOVEMENT

3.1 Management strategy

The approach generally adopted on the London Tunnels was based on the premise that it was more efficient to address the problem of tunnelling-induced ground movement at source than to deal with the consequences of movements propagating into the overlying infrastructure. Thus the emphasis was placed firstly on control of the tunnelling process to minimise the amount of the movement caused. Measures to reinforce existing structures to increase their capacity to withstand movement were only developed where it could not be demonstrated that the movements induced by construction could be limited to a level that would have negligible impact. Similarly measures that aim only to prevent the effective transmission of ground movement were avoided. At tender it had been expected that compensation grouting or other intervention measures would have been used in critical locations. In the event it was found that adequate control was generally achievable through careful management of the TBMs. Where advance works were undertaken on structures these were largely because of either pre-existing poor condition or existing foundations that potentially clashed with the tunnels.

3.2 TBM and tunnelling specifications

Early in the planning process it was decided that the London Tunnels running tunnels should be driven using a total of six earth pressure balance (EPB) tunnel boring machines (TBM). The need to minimise settlement was an important factor in this decision. A specification for these machines was included within the contract documentation. This specification was significantly more sophisticated than any previous UK practice and included a requirement that the TBMs should limit volume loss to 1%. The contractors procured the TBMs after contract award. The machines eventually chosen were manufactured by Kawasaki (contract 220), Wirth (240) and Lovat (250).

The specification required that the TBMs be capable of driving as EPBs with fully pressurized faces. It was assumed from the outset that this would be essential for
control of the ground over the parts of each drive where granular soils were to be encountered. The specification also required the provision for a system of viscous fluid injection around the TBM shield to provide positive support to the ground between the face and the rear of the shield.

At the ends of the route the tunnels pass through several kilometres of various stiff clays. These were expected to provide self-supporting faces and so would not require closed mode (i.e. pressurised face) EPB operation. Hence the machines for these contracts were specified with the option to operate in an open (i.e. unpressurised) mode. To achieve mucking out in this mode the Kawasaki machines were equipped with a belt conveyor while the Lovat machines were equipped with a screw conveyor.
on the settlement being achieved that was used as a basis for refining both the tunnelling process and also the advance works requirements later in the drives. Through this process it was demonstrated that much of the originally expected advance mitigation works would not be required. This lead to substantial savings and in particular the deletion of a large number of utility diversions that had been planned but which would have been costly and disruptive to undertake.

4 OBSERVATIONS

4.1 Types of ground movement

The ground movements attributable to soft ground tunnelling processes may be divided into two basic categories. Firstly there are the movements associated with formation of the normal settlement trough. The mechanism by which they may cause problems is the development of ground strains that are transmitted into structures. The second category of movements tend to be much larger, more erratic in form and highly localised. These movements may relate to specific failure events in the tunnel (e.g., collapse of the face) or other effects such as the uncontrolled interception of below ground structures or geological features or the uncontrolled flow of groundwater.

In general the CTRL works produced a fairly uniform settlement trough of a magnitude that was imperceptible to the casual observer. In the 36 km of tunnelling there were, however, some isolated instances of the second type of movement. These included problems when TBMs had to be driven in peat and alluvium containing pockets of water, problems with the interception of foundations in the Stratford site and difficulty stabilising Upnor gravels in the tunnel face. There was one serious incident in a residential area when a large hole was formed in gardens between two terraces. No injuries were sustained in these events but they inevitably created adverse publicity and costs. No damage occurred to the TBMs or tunnel in any of these cases. All of the events were investigated and detail changes made to the tunnelling systems including to varying degrees more control room based TBM management. However, the fundamental tunnelling specification remained unchanged.

4.2 Observed settlement magnitude

The volume losses achieved throughout the route tended to be significantly less than had been considered during the assessment phase. Typically volume losses were in the range of 0.25% to 0.75% in the London Clay. In the Thanet Sand and Upnor Formation sands volume losses were in a similar range although more measurements tended to be at the lower end. When continuous bentonite injection was used around the TBM in addition to close control of face pressure and tailskin grouting an average of around 0.25% was achieved over long distances in the Thanet Sands. The overall average was around 0.5% across the whole of the drives.

The width of the settlement trough in relation to depth was generally in line with past experience of tunnelling in London soils although there was some evidence that the troughs were of a slightly wider and flatter form than those observed in the past. It may be speculated that this was a function of the lower ground strain levels incurred in these relatively low volume loss conditions.

Figures 2 to 4 illustrate the volume loss results obtained from transverse surface movement monitoring arrays. The letters marked on these three graphs relate to points of particular note discussed below.

Figure 2 shows volume loss on contract 220. Early in the drive tunnelling was in mixed clays and sands of the Lambeth Group. At (A) an experiment was conducted on the first TBM under a vacant site to determine the effect of reducing progressively the face pressure. This resulted in a rapid increase in the settlement up to almost 3% volume loss and the test was discontinued. Later, at around chainage 7600, further tests were conducted on the progressive reduction of soil conditioning to the TBM cutterhead. This resulted

![Figure 2](image-url)
in a progressive increase in volume loss until the 1% contract limit was breached. In both cases reverting to normal operating procedures immediately resulted in recovery to acceptable movement levels.

For approximately the next 2.5 km (C) the drive was substantially in sand and the TBMs were driven in closed mode with bentonite injection around the shield body. This resulted in consistently very low settlement. Tunnel production was fast with up to around 30 m driven in a typical 12 hour shift.

Beyond chainage 4500 the drive passed gradually into the very stiff Lambeth Group clays. These proved hard to mine and production declined rapidly. Eventually settlement again reached the 1% contract limit. The machines were stopped and the cutterheads reconfigured to better suit clay. When driving resumed production was faster and settlement dropped to around 0.5%. Volume loss generally remained between 0.3% and 0.8% through the remaining 2 km or so driven largely in the London Clay (E) although a low result of about 0.15% was achieved at the Caledonian Road (F) where special management measures were put in place to pass 3 m below major water mains and a key highway.

Contract 240 experienced various difficulties in the early part of the drive. These related in some cases to pre-existing ground disturbance and in at least one place to the interception of redundant foundations within the CTRL site (G). Intensive management and high pressure face support at the crossing under the London Underground Central Line reduced volume loss to around 0.3% (H) but was not a sustainable process for long term production. These drives were then delayed for some time following a ground loss event that extended to the surface but that was isolated between survey arrays and so is not directly reflected on the graph. After the restart the volume loss due to both 240 TBMs averaged around 0.5% (I).

Contract 250 had a very difficult launch with the upper part of the tunnel face being in alluvium and peat. This resulted in some large movements (J) and localised disruption to the overlying ground on both drives. Once the drives were fully in the London Clay volume loss averaged around 0.5% (K). The scatter in this data is probably partly a reflection of the instability of the saturated surface alluvium in which the survey points had to be established rather than the performance of the TBMs in the clay at depth.

Figure 3. Volume loss along contract 240 derived from transverse ground surface settlement monitoring profiles. Square markers represent the up line drive and triangular markers the down line.

Figure 4. Volume loss along contract 250 derived from transverse ground surface settlement monitoring profiles. Square markers represent the up line drive and triangular markers the down line.
Around chainage 18000 to 17500 (L) the graph shows a rise in the apparent volume loss. This is in an area affected by other contemporaneous tunnelling and dewatering works the effects of which cannot be completely isolated from TBM induced movement. Past this area the tunnels moved into predominantly sand conditions and the volume loss reduced to around 0.5% (M). Data is limited from the final part of the drive because this was under multiple track railway where track was monitored directly but full ground surface settlement arrays were difficult to establish (N).

4.3 Observations on TBM performance

Ground movement may arise at the TBM face, around the shield or at the tail (or further back along the tunnel due to lining flexure or soil consolidation). To optimise control it is important to know which of these sources of movement are the major contributors. Previous studies have shown that on open face TBM settlement is dominated by movement at the face (Burland et al. 2004). On the CTRL EPBs it was found that movement near the face was greatly reduced and at times almost eliminated by consistent maintenance of face pressure (Figure 5). Experience also showed it was not just the mean pressure that mattered but also the minimum level to which pressure dropped. Effective control of this and also the grout delivery depended heavily on operator skill as these processes were manually controlled.

Similarly maintaining constant fluid (bentonite) pressure around the shield had a positive effect. Where similar machines were driven in similar ground with and without this measure the comparison suggested that it reduced volume loss by around 0.25%.

There was some evidence to suggest that the area of the TBM system with greatest scope for improvement in movement control is the tailskin grouting. An increase in movement was sometimes observed as the tailskin was pulled clear of measurement points.

4.4 Effective impact of the works

It is apparent from the observations that the project was broadly successful in minimising the impact of tunnelling through the strategy of minimising ground movement at source. There were no adverse impacts on the railway operations due to tunnelling induced ground movements. Similarly no significant problems attributable to tunnelling have been reported by the utilities. Movement within acceptable limits was apparent at several of the major bridges and useful experience was gained of the behaviour of piled structures directly over the tunnels (Jacobsz et al. 2005).

The severe ground loss incident described earlier caused severe damage to part of one masonry building and significant cracking to several others. Aside from this and one other instance of damage to a retaining wall the impact on structures along the route was minimal and did not result in any significant costs at a project level. In general property occupiers were unaware of movement during the passage of the tunnels although tunnelling was sometimes audible.

5 CONCLUSIONS

The observations from the CTRL London Tunnels demonstrate the extremely low levels of settlement that can be produced by modern mechanised tunnelling without the need for extensive mitigation works outside the tunnel.

Throughout much of the route settlement volume loss figures averaged around 0.5%. In the best conditions prolonged runs of normal production resulted in volume losses of around 0.25%. The results demonstrate that the initial assessment level of 2% was very conservative. This level could probably reasonably be halved for future similar works.

The observations have also improved the understanding of complex EPB TBM performance and helped to identify areas where future development would be beneficial. The current machines have some weaknesses particularly in grout delivery and the high dependency on operator skill. Addressing these is a challenge for the future.

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