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Control of tunnelling induced movements on the Heathrow Express project (United Kingdom)

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ABSTRACT: The need to protect Heathrow airport from potential damage on the Heathrow Express project was vital for the safe operation of one of the world's busiest airports. Minimal disruption to the travelling public was paramount. This paper outlines the settlement risk management, comprehensive monitoring system and various settlement control measures implemented on an observational basis, in response to soil structure interaction, to mitigate damage. An innovative structural jacking technique and in-tunnel measures implemented to maintain three sensitive structures in service whilst tunnelling are described.

1 INTRODUCTION

The Heathrow Express is a rail project promoted by BAA plc to provide a dedicated high-speed passenger rail service between Paddington (London) and Heathrow airport. Initial planning started in 1987 and, subsequent to a number of objections, received Parliamentary Bill approval in 1991. Construction commenced in 1993 and the service was opened to the public in June 1998, only 6 months from the programmed completion date despite significant delays caused by the tunnel collapse in 1994.

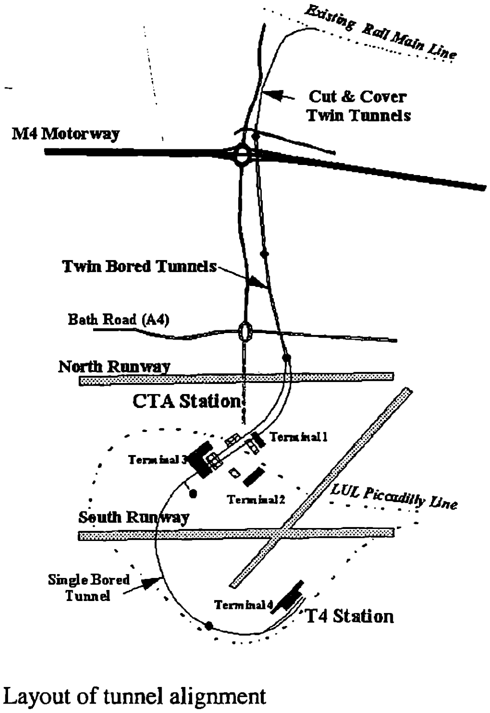


Figure 1. Layout of tunnel alignment

The Heathrow Express uses the existing main railway line out of Paddington to a new junction north of Heathrow Airport. The tracks then run into 600m of open trough/twin cell cut and cover tunnel, 5.4km of twin bored running tunnels 5.7m i.d. to link with a new station at the Central Terminal Area (CTA).

A single bored tunnel then extends the line to another station at Terminal 4 (T4). Two large junction chambers to allow for the future extension of the railway to Terminal 5 were also constructed. The layout of the overall tunnel alignment is shown in Figure 1.

The tunnels were constructed at a depth of about 20m in London Clay, bored beneath the M4 motorway, runways, terminal buildings, the London Underground Piccadilly line tunnels and numerous live services such as pressurised fuel mains.

2 TUNNELLING WORKS

- Running tunnels

The twin and single 5.7m i.d. tunnels are located 20 to 25m below ground in London Clay. The tunnels were bored using an open faced Dosco shield equipped with roadheader boom and lined with 220mm thick expanded precast concrete segments.

- CTA station

The CTA station consists of two platform tunnels 230m long 8.4m i.d. and a central concourse tunnel 300m long 8.0m i.d. at depth 24m. These tunnels were driven through disturbed soil associated with the October 1994 collapse. To restrict ground movements in the disturbed soil, a 3.3m pilot tunnel, which acts as a dowel, was driven initially and then enlarged to form the platform tunnel.

- Crossover tunnel

Leaving the CTA station, the platform tunnels continue into twin tunnels running under Terminal 3 and then intersect at a crossover tunnel (Fig. 4) below the Commercially Important Passenger (CIP) Lounge. The 95m long crossover tunnel, which has an elliptical cross section of height 11m and width 15m, was constructed using sprayed concrete linings (SCL)

- T4 station

The T4 station complex, constructed using SCL, consists of two platform tunnels over 220m long with a cross-sectional area of $62m^2$, while the central concourse tunnel located at the northern end of the station is 64m long with an area $49m^2$. The tunnels are located at 27m centres at a depth of 18m.

3 GEOLOGY

The ground conditions along the route of the tunnels are relatively uniform throughout and consist of:

- Made ground typically 2m thick
- Terrace gravels between 4 and 6m thick
- London Clay to 60m depth
- Lambeth group (Woolwich and Reading Beds).

4 SETTLEMENT RISK MANAGEMENT

The risk management process, set up to control settlement effects on the airport infrastructure, is indicated in Figure 2.

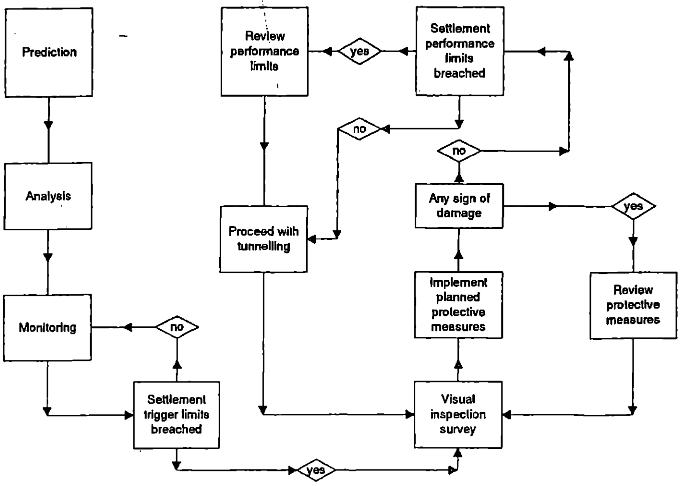


Figure 2. Process mapping of settlement risk management

4.1 *Settlement prediction*

The potential settlements associated with the tunnelling works were assessed using empirical methods based on field observations (O'Reilly & New, 1982). Volume losses of 1.2% (running tunnels) and 1.1% (SCL) were generally used. Since SCL tunnelling technique in London Clay had not been used before in the UK, BAA had commissioned a trial tunnel to evaluate 3 different construction sequences and determine the volume losses associated with each type. Surface settlement contours were produced and settlement/slope of buildings/services assessed. Buildings and services with settlements less than 10mm and a maximum slope not exceeding 1/500 were generally considered to be at negligible risk of damage and were eliminated from further considerations.

4.2 *Second-stage assessment*

The remaining buildings were taken to a second-stage assessment based on the method proposed by (Boscardin and Cording, 1989). Settlements were evaluated at foundation level and corresponding tensile strains and angular distortion assessed. The buildings were then categorised according to risk of damage and those found to be in the "moderate or higher " categories were selected for settlement mitigation measures.

4.3 *Contractual performance criteria*

The risk of damage to buildings and services is directly associated with tunnelling induced movements, which in turn is largely dependent on the tunnelling methods. This risk was allocated to the Contractor on grounds of being the best party able to control settlements by the use of good tunnelling techniques. As a consequence, the tunnelling contract was let on a performance specification basis requiring the contractor to maintain the buildings and services within a set of contractual performance control limits. This contractual agreement allowed a single point of responsibility. BAA undertook to repair any damage caused before the performance control limits were reached whilst the contractor was responsible for damage beyond these limits.

4.4 *Instrumentation and monitoring*

A comprehensive array of instrumentation and level survey points were installed on buildings and paved areas to provide settlement data for the Client, Contractor and interested Third Parties. The data was also used to compare actual settlements with predicted settlements and contractual performance control limits. The monitoring package known as, the Employers Monitoring System, included the installation, data collection and processing which was awarded to Mott MacDonald, who operated as a contractor under the New Engineering Contract (Cook, 1996).

The remote-data capture monitoring system for the buildings comprised electrolevels supplying real-time readings backed up by manual levelling survey. Some 750 electrolevels, each fixed on beams (about 2.5m long) formed continuous string lines and 1850 precise levelling points were installed.

4.5 Visual inspection

The airport infrastructure was inspected regularly for any sign of damage during the tunnelling period to obtain feedback on observed behaviour. Daily inspections were carried on buildings with settlements approaching the trigger control limits and those undergoing live preventative measures.

5 PROTECTIVE MEASURES

The Contractor was contractually required to maintain the overlying structures within the performance control limits. Suitable preventative measures were evaluated during the design stage and recommendations were made for each structure categorised to be in the 'moderate or higher' risk damage category. The Contractor chose compensation grouting as the main form of protective measure. However, other measures including structural jacking and in-tunnel measures were developed during the construction stage to deal with unexpected grouting difficulties at Terminal 4 and restrictions imposed by the Health and Safety Executive (HSE) after the collapse.

5.1 Installation of grouting arrays

An area of about 25,000m^2 was covered with grouting arrays of Tube à Manchette (TAMs) installed from permanent and temporary shafts. The TAMs, up to 75m in length, were generally located within the London Clay, positioned midway between the tunnel crown and building foundation level to minimise the effects of grouting pressures on both the tunnel below and the overlying structures. The grouting process was carried out in stages.

5.2 Conditioning

The conditioning consisted of grout injections in low volumes, typically 20 litres, through alternative sleeves in alternate TAMs in a series of passes. This operation was carried out in advance of tunnelling to tighten the ground until a nominal controlled heave (about 5mm) was discernible. This ensured an effective response of the structure for the next stage of grouting.

5.3 Compensation grouting

To control settlements, grout was injected between the tunnel and building foundations to compensate for ground loss and stress relief caused by the tunnel excavation. Grout injections were carried out during tunnelling and the intensity was directly related to the predicted settlements, rate of tunnel advance, observations from the monitoring system and the response of the tunnel lining to the grouting pressures.

5.4 Grouting strategy

The grouting strategy was based on the principles of the observational method proposed by (Peck, 1969). The main criteria used to decide the frequency and amount of grouting were 1) observed settlement/angular distortion and 2) visible sign of damage.

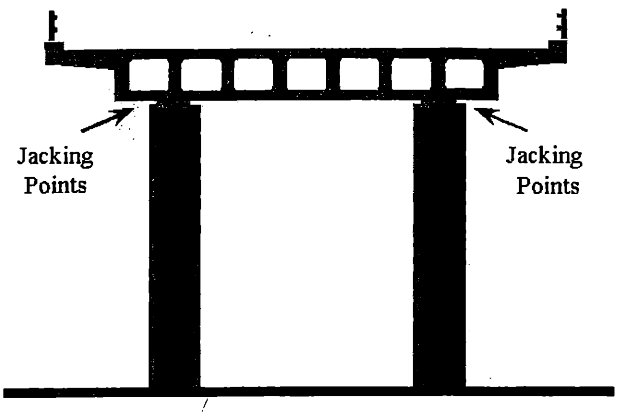
After the conditioning phase, compensation grouting was targetted at areas where the worst predicted settlements, based on design or back-analysed volume losses, were anticipated. The structure movements and angular distortion were assessed daily as the tunnel face advanced and the results compared with the performance control limits. Since progress of the tunnel was relatively slow, there was adequate time to maintain the structure within the specified limits by interactive grout injections. The Contractor prepared grouting proposals whenever the trigger levels were reached and these were reviewed, discussed and approved in the afternoon prior to the night shift grouting.

After the collapse, the HSE raised concerns on tunnel face stability. This led to restrictions being imposed on grout volumes and the distance above the advancing face that the grouting could take place. To alleviate these concerns, controlled preheaving of the structure based on anticipated settlements was employed for the remaining tunnel operations, obviating the need for compensation grouting during tunnel advance.

6 JACKING TO STRUCTURES

6.1 Terminal 4 – West Departure Ramp

This structure is located above the south end of Terminal 4 platform tunnels, in an area congested with ventilation tunnels, cross passages and vertical shafts. The structure consists of an in-situ reinforced concrete voided slab, supported via spherical bearings on circular reinforced concrete columns. The columns are generally supported on pad foundations. Figure 3 shows the structure and jacking point above the columns.



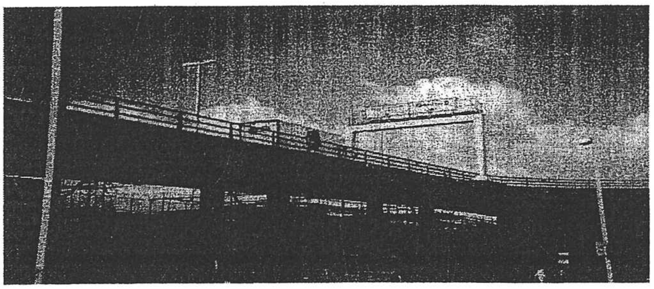


Figure 3. Jacking to West Departure Ramp

Compensation grouting was chosen by the Contractor to control settlements, which were restricted to 10mm. During tunnel construction, repeated attempts to offset settlements by grouting under the pad foundations when the structure was approaching this performance limit were only partially successful. It became clear that settlement limits originally imposed to protect the structure would be exceeded and alternative measures had to be devised. Possible causes of this unexpected grouting behaviour include (a) heavy foundation loads under the TAMs (b) grout ports not located beneath the foundations and (c) TAMs not at correct levels.

Furthermore, concerns were raised on the adverse affects, which continued grouting would have on the completed tunnel lining. The ground around the column support also heaved, which in turn could have been damaging to the buried services. Several options to remedy the situation were considered (a) Install new TAMs under the foundations (b) Jacking of the deck (c) Analysis of the concrete deck to assess the effects of the recorded and anticipated settlements from the remaining tunnels. Options (b) and (c) were chosen.

Based on available as-built drawings and specifications, structural analyses of the structure were undertaken to assess the effects of the supports settling as tunnelling progressed. Settlement contours of recorded settlements combined with the anticipated settlements (based on back-analysis of completed platform tunnel) for the remaining tunnels were produced to assess the likely deflection scenarios of the deck. These settlements were then used to check the structural adequacy of the deck and develop a jacking contingency measure designed to lift the concrete road deck from the supporting column to supplement the compensation grouting. The planned actions and contingency measures were as follows:

- Record the daily movement of the structure.
- Assess the observed movements and issue recommendations to the site team confirming the structure is satisfactory and tunnelling can continue.
- If settlement reached unacceptable levels before the jacks were put in place, then traffic weight restrictions up to 17 tonnes imposed.
- If the daily review of settlements showed the structure taking up a different profile from that anticipated, then the bridge engineers provided a new set of acceptable settlements.

A jacking system was installed on the columns where maximum settlement was anticipated and shims prepared for insertion into the bridge bearing configuration. At the end of tunnel construction in the area, total recorded settlements stopped short of the revised acceptable limits and the jacking system, though ready for implementation, was not put into operation.

6.2 *Central Terminal Area - CIP Lounge*

The CIP lounge 76x32m constructed in 1992 consists of a three-storey steel frame structure externally clad with Eternit fibre cement sheeting and glazing. This structure is supported on a wide reinforced strip footing 1000x750mm deep with large brackets welded to the base of the stanchions. This in-built arrangement was originally designed to allow jacking of the structure, if required, for the then future HEX tunnelling works. The lounge is used as a transit facility for business class passengers and includes finishes and decorations, which are sensitive to settlements. The structure is immediately above the large SCL crossover at Terminal 3 (Fig. 4.)

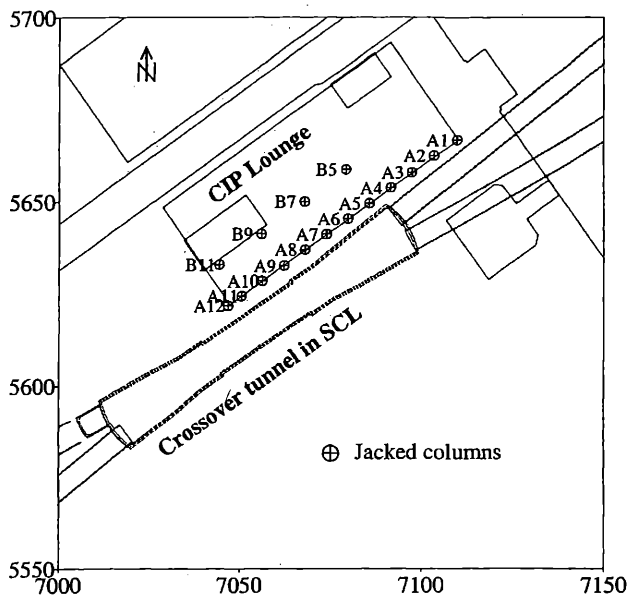


Figure 4. Jacking to CIP Lounge at Terminal 3

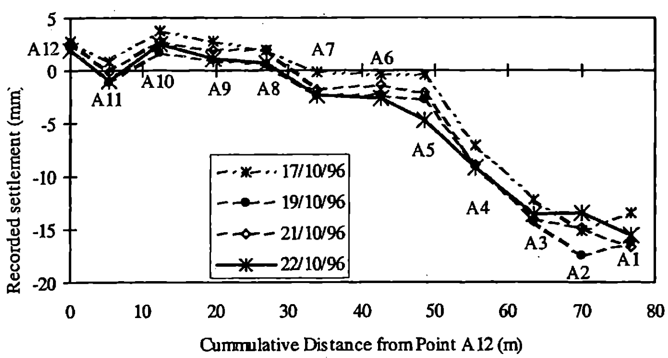


Figure 5. Recorded settlements to columns A12 to A1

6.2.1 Potential settlements

Based on a conservative design volume loss of 1.5% for the SCL construction, settlements of up to 50mm were calculated based on green field site conditions. This settlement was within the acceptable limits set by the original designer. However, in view of concern raised relating to likely damage of internal finishes and the need to minimise disruption to the occupants, all parties subsequently agreed a more stringent settlement limit of +/- 5mm and/or an angular distortion 1:500 to the structure.

6.2.2 Protective works

By using the in-built brackets to the base of the columns, structural jacking was employed to control settlements. This option was more cost effective and least disruptive to the occupants. Preliminary works to isolate the ground floor columns from masonry walls were implemented prior to tunnelling. The Contractor considered the need to jack several columns in tandem to maintain the structure within the specified limits. However, this was not considered necessary, since the movements were assessed to be slow and would allow sufficient time to move one set of 4 Nos. 100 tonne jacks where required. As another precautionary measure, safety plastic film was applied to the glazing to hold any shattered glass in place and prevent injury.

6.2.3 Observations

By adopting the observational method, all the columns, anticipated to settle more than 5mm, were jacked on several occasions and shims not thicker than 6mm (to limit angular distortion) were inserted under the base plates. During tunnel construction, a decision was taken to apply the angular distortion criteria only, together with observed damage, when it was seen more economical to leave columns A1 and A2 attached to masonry walls and apply limited jacking. Figure 5 shows the recorded settlements to the external columns A1 to A12 with angular distortion being limited to 1:500.

On completion of tunnelling, only minor damage was reported. Existing hairline cracks to ceiling finishes opened to 1mm width and one panel of the Eternit fibre cement external cladding was cracked whilst jacking.

7 IN-TUNNEL MEASURES

7.1 Terminal 4 - Foul Pumping Chamber

This 10m diameter r.c Foul Pumping Chamber was located immediately above the Up line platform tunnel at Terminal 4 with only 1.85m cover to the crown of the tunnel as indicated in Figure 6.

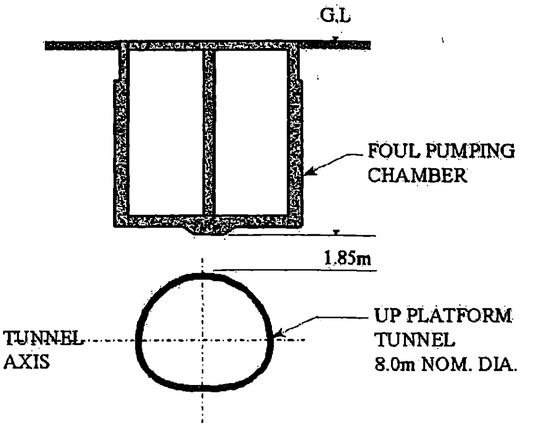


Figure 6. Platform tunnel below Foul Pumping Chamber

The settlement of the chamber was predicted to be 55mm and protective measures were required to minimise damage and maintain the operations of this essential facility. Given the limited clearance with the platform tunnel, compensation grouting was not possible and alternative solutions were sought. The chosen measures included: -

- soil nailing
- reducing the exposed face of the SCL
- decoupling the inlet and outlet pipes from the structure to cater for differential settlements with the structure

In view of concerns raised about the stability of the shaft by punching failure into the tunnel, although calculations had indicated that there was sufficient skin friction in the London Clay, tunnelling under the shaft was considered a high-risk event. Consequently, the top heading sequence of SCL was adjusted to a split top heading to reduce the exposed face and temporary faces were sealed with 100mm shotcrete. The invert was also closed more quickly to provide maximum support to the shaft prior to breakout from underneath the base. Fully grouted face dowels 25m long were also employed to enhance face stability. With these measures in place, the recorded settlement was limited to 30mm.

8 CONCLUSIONS

The ground movements associated with the extensive tunnelling works on the Heathrow Express could undoubtedly have led to severe structural damage to the buildings and disruption without the protective measures that were put in place. The risk management strategy was successful in limiting damage to the infrastructure and provided a set of carefully planned actions to be taken to deal with unexpected settlement related issues.

Compensation grouting was generally effective in minimising damage to the airport buildings. The grouting control process which included detailed monitoring, interpretation of the data, observed structure response and use of controlled pre-heaving in anticipation of settlements were essential for the overall success of this protective measure. The innovative structural jacking system also proved to be very successful in limiting settlements and angular distortion to CIP lounge at Terminal 3 and Victor Pier at Terminal 4 with no disruption to the occupants.

9 ACKNOWLEDGEMENTS

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