Monitoring the impact of tunnel construction on existing infrastructure and its successful implementation for the Airside Road Tunnel, Heathrow

GARY WALKER[1], ALISTAIR HITCHCOCK[2], CHRIS RASMUSSEN[3] AND DAVID FARNHAM[4]

[1] *Mott MacDonald. (e-mail: Gary.Walker@mottmac.com)*
[2] *Mott MacDonald. (e-mail: Alistair.Hitchcock@mottmac.com)*
[3] *ITM Limited. (e-mail: chrisr@soil.co.uk)*
[4] *ITM Limited. (e-mail: davidf@soil.co.uk)*

Abstract: The 1200m Airside Road Tunnel (ART) was constructed in London Clay beneath Heathrow Airport. It provides an essential connection between the existing central terminals and the Terminal 5 development. Construction commenced in January 2001, with tunnelling utilising an Earth Pressure Balance (EPB) Tunnel Boring Machine (TBM). Due to existing infrastructure the tunnel alignment was constrained and the upper boundary of the London Clay was locally close to the tunnel crown giving a potential for high surface deformations.

The need for monitoring was identified early in the project and a dedicated team was set up. The monitoring team utilised an independent server and network which allowed for various modem connections to the separate instrument networks. Instrument readings were collected remotely and manually and were incorporated into specifically designed databases for the various project stages. Electronically gathered data was displayed in near real time and in order to share monitoring data between team members at various locations, data was published hourly to the internet using a 'lite' version of the monitoring package. Gathered data was reviewed in daily monitoring meetings and was used to provide control to various site activities and to observe changes in TBM operating parameters. The performance of site operations was measured against predetermined target criteria and breach of trigger values initiated predetermined actions as set out in Emergency Plans agreed with the client BAA plc and all third parties.

The principal monitoring schemes were for the East and West Portals, the tunnel drive and the Heathrow Express (HEX) crossing. These areas adopted a variety of monitoring techniques including independent robotic total stations, tilt meters, electrolevels, in-place electronic inclinometers, manually read inclinometers, borehole extensometers and manual precise level surveys. The applications of the various techniques are discussed, the data is summarised and compared to predicted values and the benefits and lessons learned in undertaking the monitoring are considered.

Résumé: Le tunnel routier Airside Road Tunnel (ART), long de 1200m, a été construit à Londres Clay sous l'aéroport de Heathrow. Il fournit une connexion essentielle entre les terminaux centraux déjà existants et le développement du terminal 5. La construction a débuté en janvier 2001 utilisant une « Earth Pressure Balance » (EPB) pour la foreuse, « Tunnel Boring Machine » (TBM). En raison des infrastructures existantes, l'alignement de tunnel a été contraint et la position de la surface enterrée de London Clay était localement proche de la couronne du tunnel conduisant à des déformations de surface potentiellement élevées.

Le besoin de surveillance a été identifié tôt dans le projet et une équipe consacrée au problème a été constituée. L'équipe de surveillance a utilisé un serveur indépendant et un réseau qui ont permis la séparation des réseaux d'instruments pour divers raccordements de modem. Les relevés des instruments ont été collectés à distance et manuellement et ont été incorporées dans des bases de données spécifiquement conçues à cet effet pour plusieurs phases du projet. Les données collectées électroniquement ont été affichées pratiquement en temps réel et pour permettre leur partage entre les membres de l'équipe à plusieurs endroits, les données étaient publiées toutes les heures sur Internet utilisant une version 'lite' du groupe de surveillance. Les valeurs recueillies étaient dépouillées chaque jour lors de réunions et furent utilisées pour le contrôle de nombreuses activités ou pour changer les paramètres d'opération de la TBM. La performance sur site des opérations a été mesurée par rapport aux objectifs prédéterminés et une série d'actions correctives ont été entreprises comme préalablement définie dans les plans d'urgence acceptés par BAA plc et tous les tiers.

Les principaux schémas de surveillance ont été appliquées sur les portails, la partie centrale du tunnel et le croisement avec le Heathrow Express (HEX). Ces zones ont nécessité l'adaptation de diverses techniques de surveillance comprenant des stations indépendantes totalement robotisées, mesureurs d'inclinaison, des « electrolevel », des inclinomètres électroniques locaux, des inclinomètres a lecture manuelle, des extensomètres de sondage et des équipements de mesure de niveau. Les applications de ces techniques diverses sont discutées et les données résumées et comparées avec les valeurs prédîtes. Les bénéfices et les leçons retenues de la mise en œuvre d'une telle surveillance sont exposés.

Keywords: infrastructure, monitoring, tunnels, settlement, retaining walls, database systems

INTRODUCTION

The ART provides an underground road link between the Central Terminal Area (CTA) at Heathrow airport and remote aircraft stands located to the west of the main airport complex (Figure 1), and in 2008 the ART will serve the new Terminal 5, following its completion. The ART is approximately 1200m long and comprises twin 8.1m internal diameter bored, segmentally lined tunnels with cut and cover portals and approach ramps formed in retained cut. Excavation of the west portal started in 2001, with the first of the two tunnel drives commencing in June 2002. All tunnelling was completed in 2003, and the tunnel opened for airport use in March 2005.

At approximately mid-point the ART passes over the existing Heathrow Express (HEX) tunnel with a clearance of only around 3.5m. The tolerance of operating railway lines is such that small track movements can take the track out of serviceability and affect safety. This situation may necessitate imposition of a temporary speed restriction subsequent realignment of the track. Such disruption would have major implications for the rail operator. Consequently, there was significant concern that construction of the ART could cause unacceptable movement of the existing tunnels because of the limited tunnel separation.

This paper discusses the monitoring systems that were implemented during portal construction and the first ART tunnel drive, and describes the observed ground behaviour resulting from construction, with the aim being to:

- Demonstrate how a fully integrated monitoring scheme can help to both control the impact of tunnelling on airport operations and third party infrastructure (e.g. existing rail tunnels and airfield infrastructure), and improve project delivery in terms of site operations and health and safety;
- Demonstrate that high levels of accuracy and repeatability are achievable for the instrumentation used in safety critical monitoring;
- Demonstrate the benefits of automated monitoring systems.

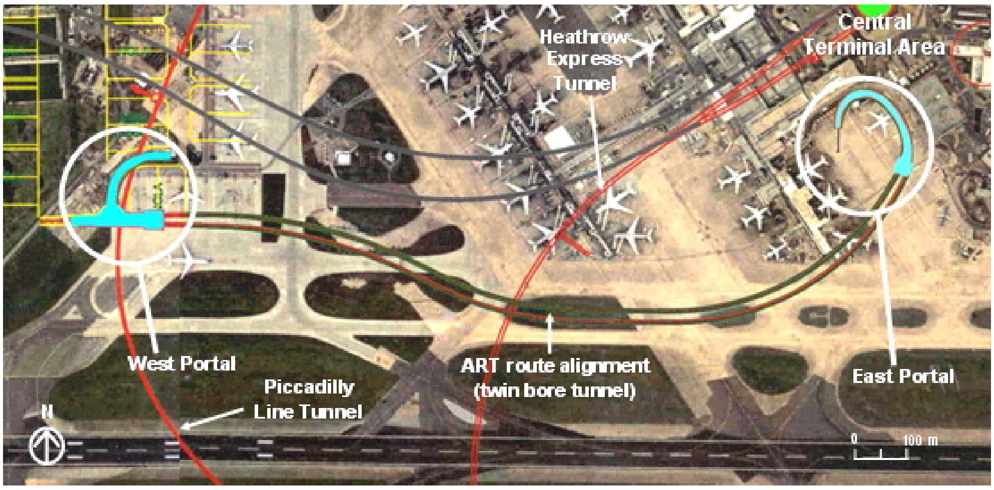

Figure 1. Location plan of the Airside Road Tunnel (ART) at Heathrow Airport

GROUND CONDITIONS

An extensive site investigation was carried out to determine the ground conditions along the alignment of the ART and this supplemented the existing database of information on the geological conditions at Heathrow Airport. Over much of the route, the investigation identified that Terrace Gravels overlie a considerable thickness of London Clay. However, the location where the HEX crosses the ART lies at the edge of a backfilled borrow pit where the Terrace Gravels have been extracted. The geological profile at the location of the crossing is as given in Table 1.

Table 1. Geological profile at HEX-ART crossing

Stratum	Thickness (m)
Borrow Pit Materials /Terrace Gravels	4.3
London Clay	55.4
Lambeth Group	Undefined

The Terrace Gravels comprise a dense to very dense, sandy medium to coarse gravel, becoming progressively more clayey towards the ground surface. The London Clay is a stiff to very stiff overconsolidated fissured silty clay with an average undrained shear strength, measured in triaxial tests, increasing from about 100 kPa at the London Clay surface to about 350 kPa at a depth of 30m below ground level. The surface of the London Clay is weathered, but along the route of the ART the depth of weathering is no more than 1m. The Borrow Pit materials typically comprise slightly sandy, slightly gravelly clay with occasional layers and/or pockets of silty, sandy gravel. The SPT N values within the deposit vary between 2 and 9. It is believed that the Borrow Pit materials are derived from a mixture of London Clay and Terrace Gravels. The water table is located at 2.2m below existing ground level and the water pressures are assumed to be hydrostatic through the Borrow Pit materials, Terrace Gravels and London Clay.

MONITORING SYSTEMS AND IMPLEMENTATION

The need for comprehensive monitoring of ground deformations around and above the tunnels and portals was recognized as being an essential requirement of the risk management process at an early stage in the project inception (Williams 2005). Monitoring was to provide assurance for and protection of the existing airport and third party infrastructure.

To provide the appropriate level of confidence in the monitoring process the ART team, comprising BAA (client), Mott MacDonald (designer) and Morgan-Vinci jv (constructor) developed a monitoring scheme, managed by Mott MacDonald, that would evolve with the needs of the project and be able to provide, where necessary, 24 hour coverage. This approach led to the establishment of a central Monitoring Office (MO) within the ART project team, which designed, procured and supervised installation of a number of monitoring packages as part of the project. Table 2 summarises each package, of which three: the West Portal TBM chamber; the ART surface monitoring and the HEX Crossing form the basis of this paper.

Table 2. Summary of the ART monitoring packages

Scheme	**West Portal* (TBM Chamber and Cut&Cover)**	**West Portal (LUL Piccadilly Line Interface)**	**ART Surface Monitoring***	**HEX Crossing***	**East Portal (TBM Chamber and Cut&Cover)**
Primary System	Tape extensometers	Electrolevels crown and track	Precise Level surveys	Robotic Total Station	Tape extensometers
Secondary System	Robotic Total Station	Tiltmeters, Jointmeter	Robotic Total Station, In-place-Inclinometer, Rod Extensometer	Tiltmeters	Robotic Total Station at key stages
Manual System	Inclinometers, Magnetic extensometers, Level surveys	Precise Levelling of Invert and Track, Tape extensometer	Precise Levelling of monitoring points, Inclinometer, Magnetic extensometers	Precise Levelling, Total Station surveys	Inclinometers, Level surveys
Transfer to Monitoring Office	Electronic – ½ hourly via radio modem Manual 12 hr intervals hand entered	Electronic hourly via modem and phone Manual 24 hr by CSV file	Manual 12 or 24 hr by CSV file Electronic hourly by radio modems	Electronic – ½ hourly via radio modems Manual 24 hr by CSV file	Electronic by at variable intervals by radio Modem Manual by hand entry and data files
Visualisation Software	I-Site Gtilt MS Excel	I-Site MS Excel	I-Site Gtilt MS Excel	I-Site MS Excel	I-Site Gtilt MS Excel
Remote Access	None	To I-Site via modem interrogation,	Web Access to permitted users	Web Access to permitted users	None
Alarm System	Visual, Automated text alert	Visual, Automated text alert	Visual	Visual and Audible, Relay to HEX Control Room	Visual, Automated text alert
Reporting Frequency	12 hr	24 hr	24 hr	8 hr	12 hr
Controls/ Contingencies	Stop excavation. Cast temporary concrete strut or replace excavated material (Observational Method)	Stop or replace excavated material Hold trains for manual inspections	Variation of TBM Operational Parameters Secondary Grouting regime	Variation of TBM Operational Parameters Secondary Grouting regime Suspension of Train Operation	Stop excavation. Cast temporary concrete strut or replace excavated material (Observational Method)
Benefits	Construction process, Health and Safety, Cost savings	3rd Party Infrastructure, Health and Safety	3rd Party Infrastructure, Airport Operations, TBM operating modes, Safety	3rd Party Rail Operations, Health and Safety	Construction process, Health and Safety, Cost savings

* Monitoring packages discussed in this paper

The MO maintained an independent computer network capable of receiving data from remote instrumentation and manually conducted surveys, analysing the received data quickly, advising on potential adverse trends and tracking deformations against previously agreed trigger levels. The MO communicated the monitoring information to the ART team and external parties as daily or shift reports depending on the particular phase of construction. A key part in the monitoring system was the appointment of a long-term supplier of monitoring systems and sensors. The appointment of ITM Ltd as specialist sub-consultant enabled a good working relationship to be developed.

The data processing was automated as far as possible using a custom-made data processing and graphical display package (I-Site®). The current I-Site displays were shown on a network of monitors in the site office so that more than one site duty engineer could view data at any one time (Figure 2).

To permit viewing of monitoring data via the Internet, computer algorithms, using a combination of HTML and ASP programming were developed that replicated the software's main functionality. Within every one-hour period, raw data would be collected and processed by the site software and held in a central database on the main server. The processed values, as well as the raw data for each sensor could then be selected by an authorised web user to chart any reading, instrument, set of readings or set of instruments. The software automatically updated the database to the web hosting company each hour, the intention being that the new data would be live on the Internet within a few minutes.

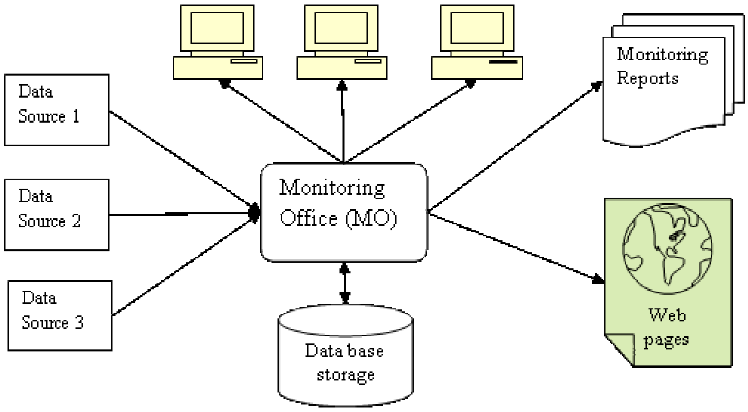

Figure 2. ART Monitoring flowchart

MONITORING WEST PORTAL CONSTRUCTION: AN OBSERVATIONAL METHOD APPROACH

Portal Construction

The West Portal consisted of four main sections, a TBM launch chamber, a length of cut & cover tunnel, an approach ramp and junction area both constructed in retained open cut. During construction the site was constrained due to its location within the airport complex, nearby aircraft operation and the LUL Piccadilly Line running under it (Figure 3(a)). For the purposes of this paper focus is given to the TBM launch chamber, which was a deep box structure measuring approximately 30m wide by 22m long by 17m deep.

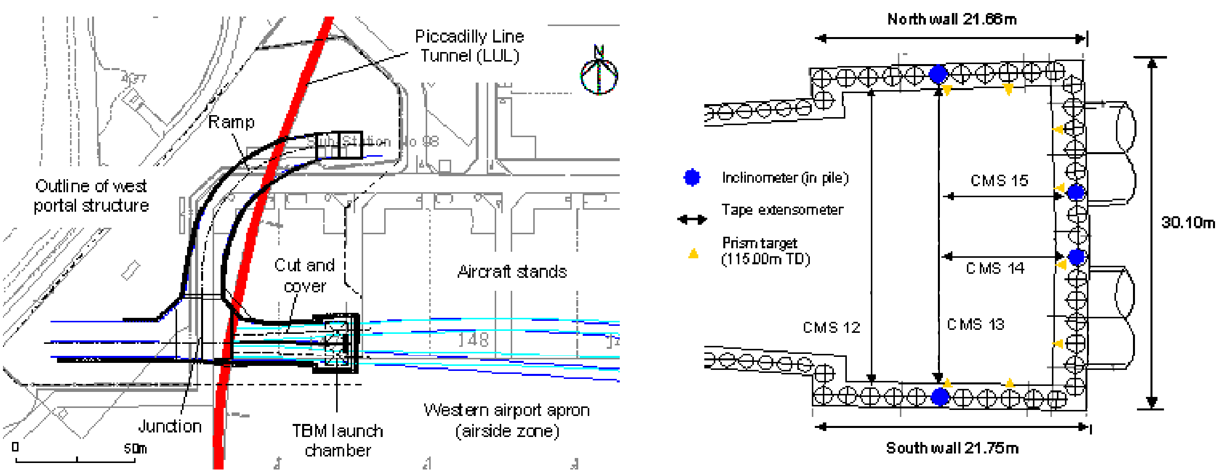

Figure 3. (a) West Portal location plan, (b) TBM launch chamber plan (CMS – convergence measurement section)

The TBM chamber was designed as a conventional top down structure comprising contiguous bored concrete piles (1.5m diameter), a 1.4m thick reinforced concrete roof slab and a single level of temporary intermediate propping at mid depth. Consisting of large tubular steel props, waling beams and hangers, the entire frame would have weighed over 60 tonnes; its installation was estimated at over 4 weeks and would have posed challenges to the contractor in terms of sequencing and ensuring adequate safety. The TBM chamber was constructed between March and July 2001.

Based on previous case histories of deep excavations in London Clay (Powderham 1994), the decision was taken to adopt the Observational Method (Peck 1969), and fully excavate the chamber without installing the base case temporary propping, thus creating substantial cost and programme savings (Hitchcock 2003).

In order to maintain an adequate level of safety during the main excavation phase, it was crucial to both monitor ground movements and have a suitable contingency scheme in place should the observed movement trends exceed the maximum threshold. Pre-defined trigger limits, using a red/amber/green 'traffic light' system were determined from the allowable wall deflections calculated in the original base case design. However, it was not possible to use the original steel props as a contingency due to the length of time required for their installation. Therefore an innovative approach was developed in which a contingency blinding strut (400mm thick un-reinforced concrete) would be cast across the entire area of the chamber in the event that a red trigger level was exceeded.

Excavation from roof slab level to 115mTD (depth at which the temporary propping would have been installed) started on 20 July 2001. Excavation to final formation then followed under Observational Method (OM) conditions on 15 August 2001, being completed within 114 hours. A concrete formation strut was then immediately cast to lock the walls, with the permanent base slab being constructed approximately one month later.

Monitoring Systems

A fundamental aspect of implementing OM is the need for a safety critical monitoring system. Three independent techniques were used to measure wall movements, and in order to establish instrumentation reliability; a number of convergence measurement sections (CMS) were set up within the TBM chamber. At these sections (Figure 3(b)), readings from all three instrument types could be directly compared.

Primary System

A manually read Ealey digital tape extensometer provided the primary monitoring of horizontal wall convergence. It was this method upon which the final decision to continue excavation was made. Readings were taken at four locations within the TBM chamber between opposing piles on the side walls and between the headwall and the soffit of the roof slab, at a frequency of 4 readings per 24 hours (i.e. over 2 shifts).

Secondary System

Automated surveying of optical prism targets was used as a secondary system and provided back-up to the primary tape readings. Horizontal pile deflections were measured by a Leica robotic TCA 1800 total station mounted on a custom made bracket fixed to the soffit of the roof slab (Figure 4). Once configured the total station was able to find and record X, Y & Z local co-ordinates for the prisms mounted on the piled retaining walls. Readings were taken at 30 minute intervals with the data being transmitted back to the monitoring computer in the site offices via a radio link.

Figure 4. Leica TCA 1800 total station mounted in the TBM chamber

Tertiary System

Four manually read inclinometers provided a means of monitoring pile deflection throughout the entire construction process, and were used as a check to the tape extensometers, assuming head fixity. The inclinometers were read twice during each 12 hour shift for the critical excavation period, after which the frequency was reduced.

Summary of Observations & Discussion

Trends of horizontal movement for both the north and south walls of the TBM chamber, measured at a level of 115mTD are presented in Figures 5 and 6. All three instrumentation systems show very close agreement over the main excavation period, with the walls moving inwards by approximately 8mm. Following the casting of a concrete formation strut, the rate of further wall movement is seen to very much reduce. The inclinometer profiles show maximum wall deflections of 17mm measured at mid depth several months after the excavation period. Since these were read in advance of the start of OM excavation, the values in Figures 5 and 6 have been rebased to the 15 August when the critical OM excavation started.

All observed wall movements were comfortably within the green trigger zone with no adverse trends detected, such that the contingency measures were not implemented. The time savings resulting from this phase alone were in excess of 4 weeks. As the robotic total station performed reliably with the data confirming the readings taken by the tape extensometer extremely well, it was selected as the primary method for later ART monitoring packages.

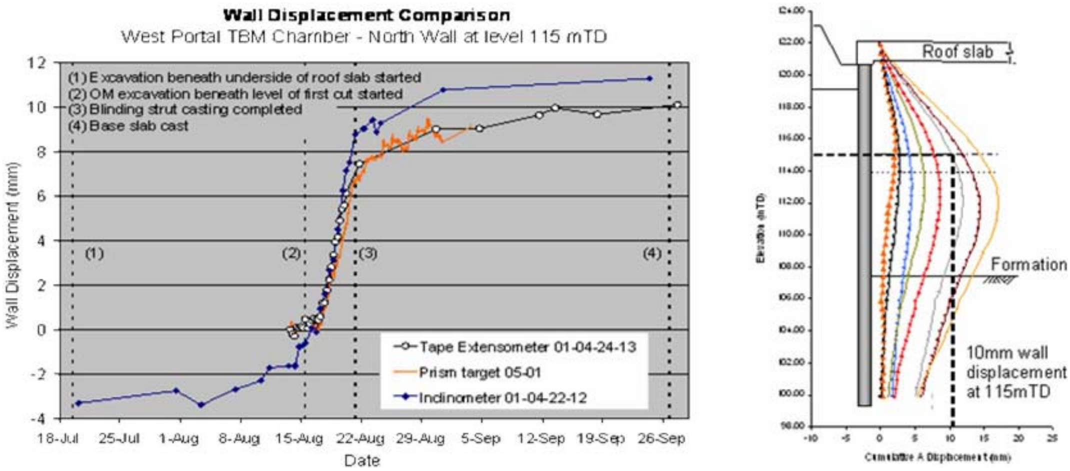

Figure 5. Comparison of TBM chamber monitoring data & inclinometer profile (north wall)

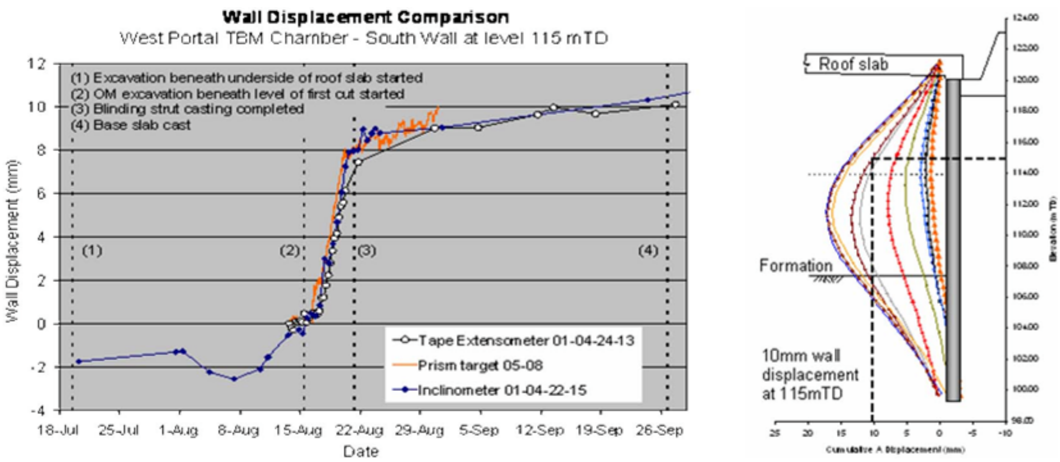

Figure 6. Comparison of TBM chamber monitoring data & inclinometer profile (south wall)

SURFACE MONITORING: INTERACTION WITH AIRFIELD INFRASTRUCTURE

General

The construction of a twin bore large diameter tunnel in shallow ground cover presented a considerable challenge with regard to the safeguarding of airport operation. The principal risk from tunnel construction was considered to be the potential for damage or disruption to aircraft stands, taxiways and underground services including 30 year old pressurised fuel mains.

Initial estimates of potential settlement were calculated assuming a tunnel design volume loss of 1% and a trough width factor of 0.45 (Sam, Rock & Audureau 2003). This approach suggested maximum settlements would be in the order of 40mm. To provide further assurance to the fuel main operator, the first 300m of the first drive was used to provide detailed observation of the ground movements caused by the TBM, from which back-analysis of data could be used to better calibrate predictive models.

Monitoring Systems

Primary System

Monitoring points were set out either in perpendicular arrays spaced at approximately 100m intervals, extending about 25m either side of the centreline or as points along the centreline spaced at intervals between 10 and 25m depending on the sensitivity of the locality to settlement. Due to the presence of extensive airfield pavement areas, much of the surface monitoring utilised 1.2m deep monitoring pins that penetrated through the pavement in a sheath allowing a comparison to be made between the pavement settlement and the movement of the underlying ground. As the tunnel route was entirely beneath the operational airfield, man-access for monitoring was limited.

Secondary System

To enable a more comprehensive study, the use of a robotic total station (Leica TCA 1800), an in-place electrolevel inclinometer and rod-extensometers augmented the precise levelling. The robotic total station was positioned on the roof of the nearby control building to monitor a series of mini prisms installed on the airfield. Monitoring of deeper ground movement was carried using automated arrays formed by a combination of in-place inclinometer sensors and multiple point rod extensometers between the two ART tunnel drives as shown in Figure 7.

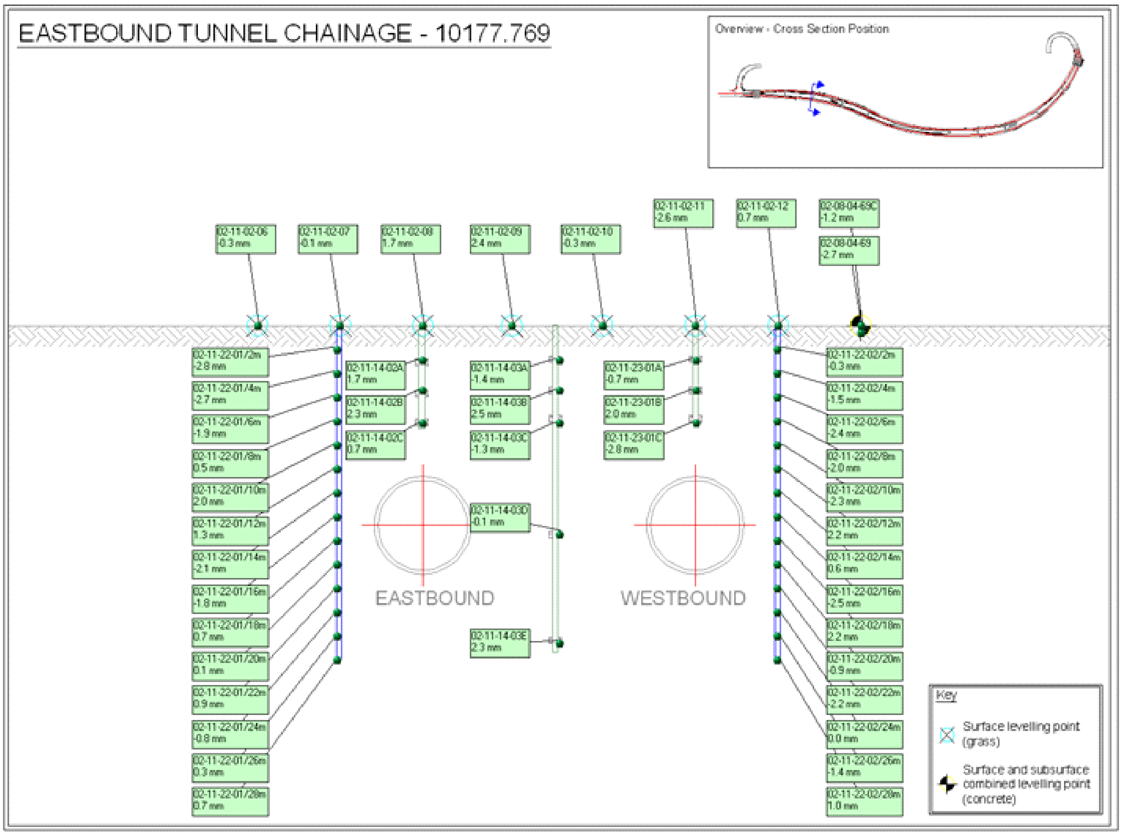

Figure 7. Automated deep section monitoring array (ART Chainage 10177)

All instruments other than prisms were installed below ground within airport approved lockable covers capable of withstanding the maximum wheel load of any aircraft allowed to use the airport. The data acquisition system was installed in a special, low profile stainless steel enclosure to the specification of BAA.

Summary of observations & discussion

Unsurprisingly the ground movement observed varied with depth of cover available to the TBM. At the position of the deep monitoring section (Chainage 10177) the depth of cover was approximately 11m, and surface movements were recorded as shown in Figure 8(a). Initial ground heave commenced on the 11 Sep 02, when the TBM was at the section line, thereafter the surface gradually heaved reaching a maximum of about +22mm approximately 8m behind the tunnel face. Then the direction of movement reversed and the heave reduced reaching about +10mm some 20m behind the face.

Where the depth of cover was about 2m greater, Ch 10252, Figure 8(b), the heave-settlement profile observed was less acute, with a maximum heave of about 7mm and settlement of less than 5mm. Other manually surveyed surface settlement pins located above and to the side of the tunnel showed a similar pattern with the maximum on-line surface heave of between 15 and 20mm. Points to the side of the tunnel alignment showed a comparatively smaller initial heave and final settlement. Those points that showed the largest initial heave generally retained a small net heave after the TBM had passed.

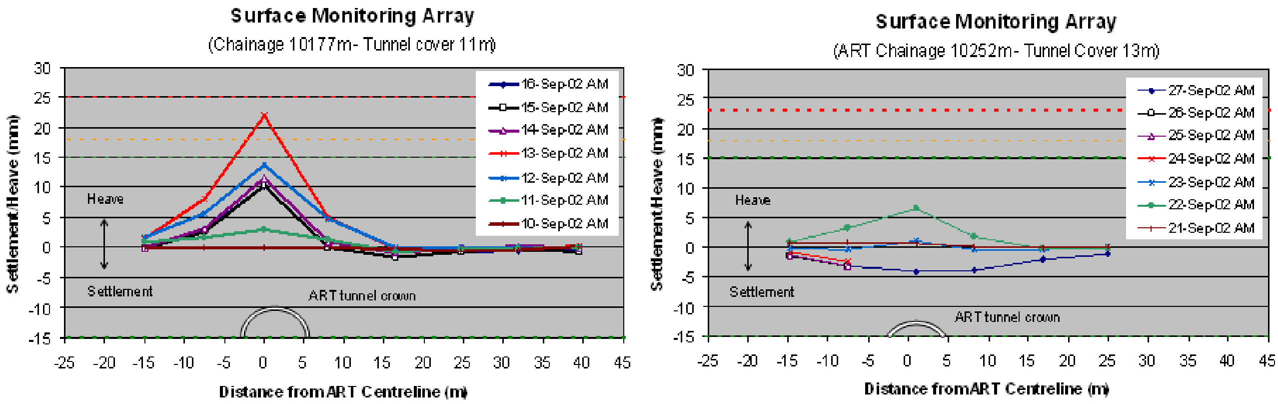

Figure 8. Tunnel induced ground surface movement at (a) ART Chainage 10177, and (b) ART Chainage 10252

Where the manual precise levelling was augmented with data from the automated total station, near continuous readings were obtained for ground movement in both horizontal and vertical directions. Generally the agreement between the vertical automated data and the manually observed data was exceptionally high, however, the automated data does indicate a strong diurnal pattern that was considered to be the result of structural movement of the building on which the theodolite was located rather than any particular surface movement. Despite this scatter, the main trends and significant variation are clearly discernable as shown in Figure 9.

The data from the mini prisms gave a near real-time trace of the ground movement and identified the peak movements, which may only be collected randomly by the wider interval of the manual monitoring. Additionally, the mini prisms have provided data on the horizontal movement of the ground in response to the tunnel construction, although this data is subject to some ‘environmental noise’. Following the main ground heave event, data is consistent with expectation in that the point located off the tunnel centreline is displaced by some 3mm in the y-direction (approximately perpendicular to the tunnel axis at this position) while the point on the centreline is displaced some 3mm in a direction approximately parallel to the tunnel axis.

While the vertical data agreed well, it should be noted that for the data presented, the mini prism observations were made on the 1.2m long pins that penetrated through the concrete pavement and the manual data is collected from points affixed to the surface of the pavement slab, thus it is not surprising that a small discrepancy in final level is seen.

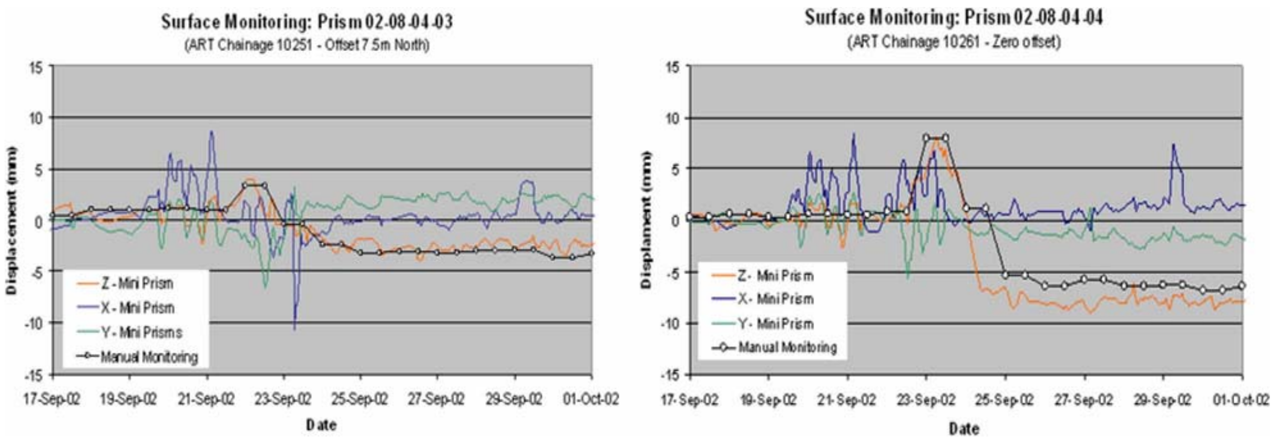

Figure 9. Comparison of manual precise levelling and data from automated mini prism survey

The maximum horizontal movement of an inclinometer located at the deep section (chainage 10177) 6m from the tunnel centre-line or approximately 1.5m from the tunnel sidewall is shown in Figure 10. Positive values indicate movement away from the tunnel. The inclinometer shows very little movement ahead of the TBM, but as the TBM passes, the ground moves away from the tunnel by about 7mm and then after the shield has passed the ground moves back towards the tunnel resulting in a net inward movement of 2.5mm. The point of maximum lateral movement occurred approximately at the tunnel axis.

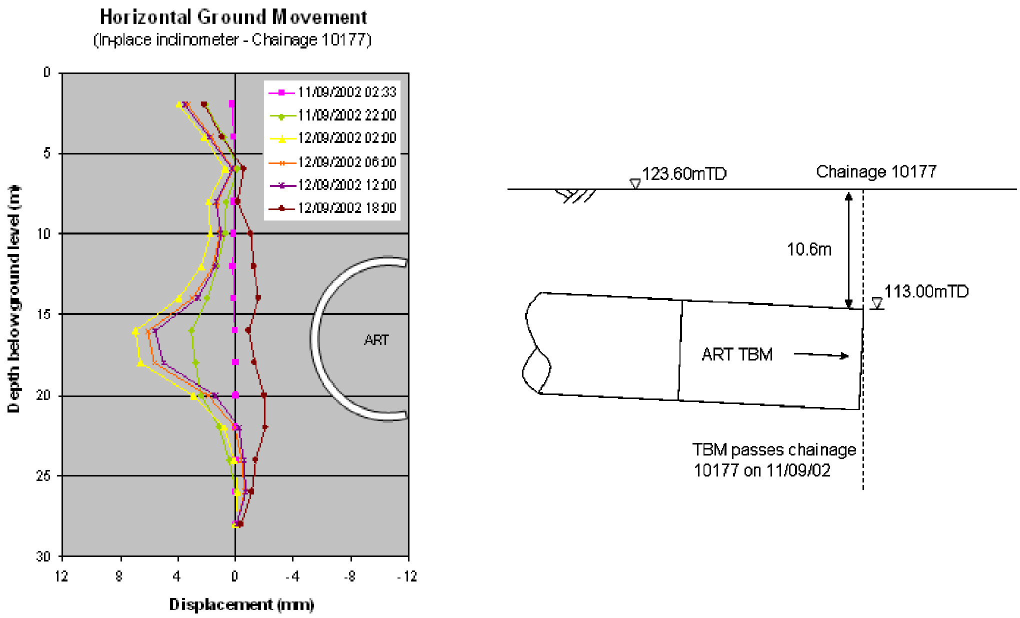

Figure 10. Horizontal ground movement from in-place inclinometers at chainage 10177 (TBM pass on 11 Sep 2002)

The movements recorded in these instruments suggested that the thrust against the tunnel face approximately balanced the ground stresses so that very little ground movement ahead of the face occurred. The heave and horizontal movement away from the tunnel suggested that the bentonite pressure around the tunnel exceeded the vertical and horizontal ground stresses. The net settlement above the tunnel and the inward movement observed in the inclinometer after the shield had passed suggested that the grouting allowed some ground relaxation around the segmental lining.

MONITORING THE HEX CROSSING: INTERACTION WITH THIRD PARTY TUNNELS

Tunnel Construction

Optimisation of the tunnel alignment during the design period meant that the final design axis level of the ART at the point where it crossed the HEX was 12m below ground level resulting in a theoretical clearance of 3.5m between the HEX tunnel crown and the ART tunnel invert (Figure 11). The machine was generally operated with air pressure applied at the face and with bentonite injected around the shield. Within the zone of influence of the HEX tunnel, defined as an area 40m either side of the HEX tunnel centre-line the average rate of progress was 18.9m/day. The TBM crossed the HEX tunnel on the 18 October 2002.

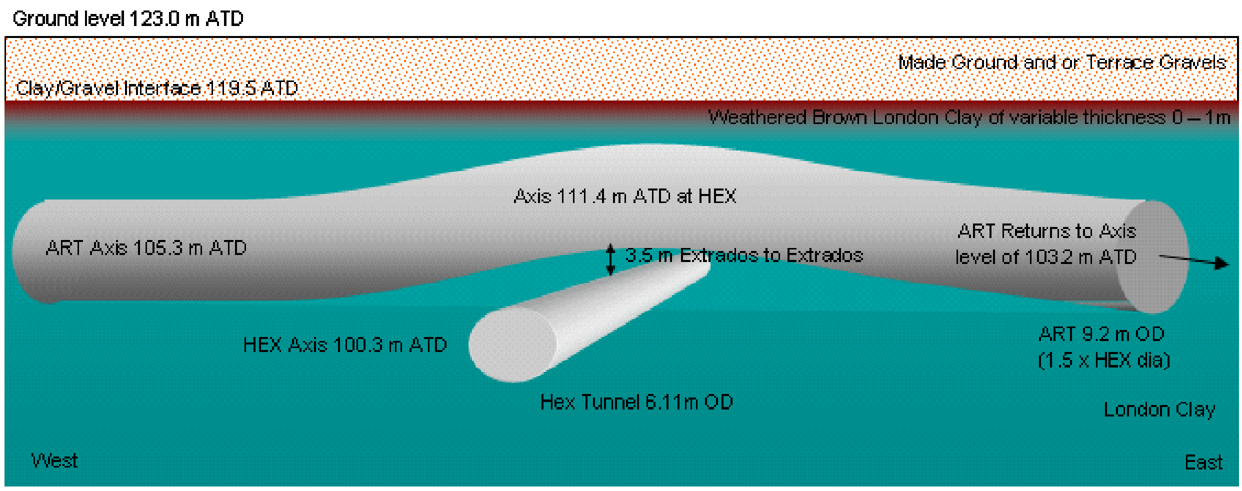

Figure 11. Schematic drawing of ART crossing existing HEX tunnel (not to scale)

Monitoring systems

Mott MacDonald, as the ART Designers, had previously undertaken numerical modelling of the HEX crossing and had provided an estimation of the deformations (Pound, Hsu & Walker 2003). The magnitude of the expected movement was small, between 2 and 20mm (depending on mode of TBM operation) and therefore the monitoring system had to be capable of measuring to an accuracy of at least ±1mm over the whole monitoring zone and to resolve the readings to a sub-millimetre level with good repeatability.

At an early stage in the monitoring scheme design process, an inspection of the HEX tunnel was carried out to identify physical constraints to monitoring implementation within the tunnel. However, due to the HEX tunnel being of modern design, significantly more space was available for instrumentation. However, the presence of overhead electrical catenary restricted access and the types of instrument employed to monitor crown movement. A diagrammatic representation of the instrumentation and constraints around the HEX tunnel at a typical monitored section is shown in Figure 12.

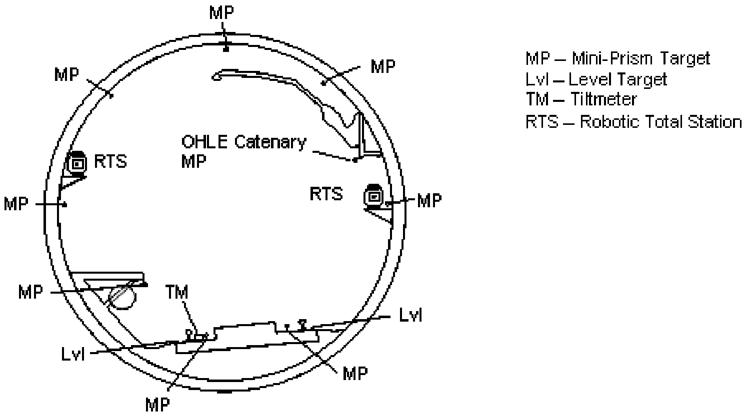

Figure 12. HEX tunnel instrumentation

To provide the robustness necessary for a safety critical system, primary and secondary real time methods were used. The remote data was confirmed by manual observations taken during Engineering Hours (hours during which the trains were not operating), which provided a tertiary monitoring system.

Primary system

The primary monitoring system comprised an optical technique using two high specification robotic total station instruments (Leica TCA2002), which intersected arrays of mini-prism targets (112 in total) installed around the tunnel lining and in the cess. The instruments were capable of automatically resolving prism positions to better than 0.5 arc seconds and 0.1mm (+1ppm). Two instruments were required due to the curvature of the HEX tunnel through the ART crossing zone. The total stations were installed on brackets attached to the tunnel lining and the prism arrays were spaced nominally at between 3m and 5m intervals along the HEX tunnel (Figure 13). The I-Site software interface used to identify the locations and current status of each mini prism is shown in Figure 14.

Figure 13. Automated total station located within HEX tunnel

Secondary system

To confirm and backup the data recorded with the robotic total stations, a secondary real-time system was designed using discretely placed electrolevel tiltmeters. As the track had been identified as being the most sensitive part of the HEX tunnel 21 tiltmeters were arranged either transversely or longitudinally along the track bed in an alternating pattern. This allowed remote assessment to be made of changes of track cant and track gradient and thus can be used to confirm the movements observed using the primary system. A Campbell Scientific CRX10 data logger captured data with the information being fed back to the main monitoring PC. The main advantage of the secondary tiltmeter system is that they have been used successfully for many years within the industry and as such there is reasonable confidence in their reliability. Based on the experience from the ART monitoring, tiltmeters offer a high sensitivity to movement, whilst maintaining high individual accuracy when used as discreet instruments.

Tertiary system

Manual observation of tunnel deformation formed the tertiary monitoring system and was carried out by, precise levelling on 40 levelling studs, gauge and cant surveys using a standard track gauge, and alignment and versine surveys carried out using standard total station techniques. The manual data concentrated on the track-bed as the size of the HEX tunnel and the presence of the overhead line electrification significantly increased the risk of using conventional steel tape extensometers or inverted crown levelling. Again the manual surveys were used to confirm the data recorded by the robotic total station instruments, but was also the preferred method for assessing changes in rail cant and gauge as it was not considered possible to affix a target prism directly to the rails themselves.

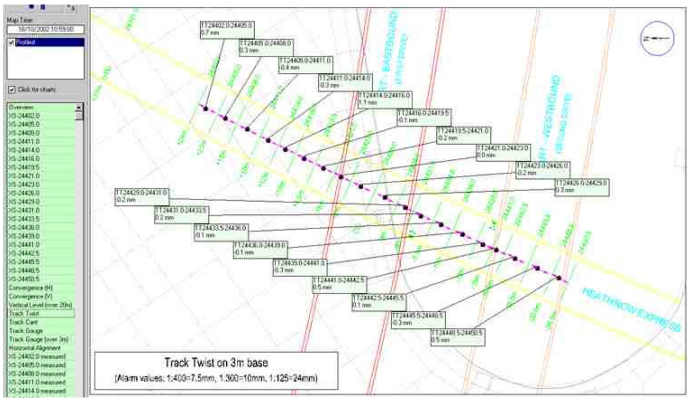

Figure 14. Data interface from I-Site® software showing locations of monitoring arrays within the HEX tunnel

Summary of observations and discussion

The actual displacements experienced by the HEX tunnel, during the passage of the ART TBM over the tunnel were small and, for the most part, were below the levels predicted by numerical modelling. The first signs of movement of the tunnel lining resulting from the advance of the TBM were indicated by changes in the horizontal and vertical convergence as monitored by the total station theodolites.

Instrumentation comparison

In order to compare the manual and automated monitoring systems, movement of the HEX track-bed has been considered since only the track contained elements for all three systems. Vertical movements recorded at two sections (or arrays) along the HEX tunnel at 3m and 7.5m from the ART centreline are presented in Figure 15. It should be noted that data collected from the longitudinal tiltmeters has been corrected for instrument 'knocks' and summed assuming 'virtual' electrolevel beams of a length equal to the distance between the sensors. The 'reduced' data was then end-corrected assuming fixity at both ends and compared to the total station and precise levelling data. The sign convention used shows heave as positive vertical movements and settlement as negative.

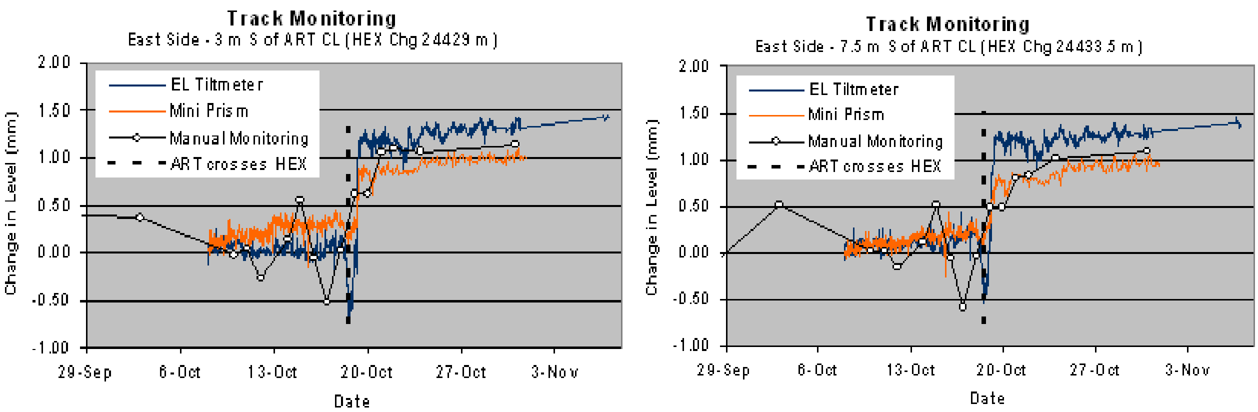

Figure 15. Comparison of HEX vertical track movement at (a) 3m south, (b) 7.5m south of ART centreline

As can be seen, the data collected from the various track surveys was of a very good standard and was very comparable. The amount of vertical movement experienced by the track-bed was small being less than 1.5mm as the TBM passed overhead. In each comparison, the data rarely deviates by more than 0.5mm and in all cases the movement trends were reproduced extremely well. The manual survey and the mini-prism survey were in good agreement throughout the monitored length of HEX tunnel. The electrolevels however showed better agreement at the beginning of the string (north of the ART crossing chainage) with progressively poorer correlation observed to the south of the ART crossing. Toward the end of the string the tiltmeters were heavily corrected to achieve a null value.

Vertical tunnel movement

The main response of the HEX crown lining (Figure 16) was significantly greater than that of the track-bed, but appeared to occur slightly later when the TBM was 2m past the HEX centreline. This correlates with the inclinometer data shown in Figure 10, when the maximum horizontal ground movement occurred after the TBM had reached the monitored section. However, slight initial upward movement of the crown did occur when the TBM was just 3m away from the HEX centreline. The crown deflection indicated that movements of between 3 and 5mm were experienced by prisms up to 3m from the ART centreline along the HEX tunnel, but beyond 15m the passing TBM had a negligible effect. Movement of the crown immediately post crossing indicated a second phase of crown depression of up to 0.7mm; which may be related to plant loading within the ART. Following the TBM crossing, a long-term rise in crown level occurred with a maximum rate of creep estimated at 0.05mm/day. This was observed for 2 weeks up until the prism monitoring was stopped.

Horizontal tunnel movement

Horizontal displacement of the HEX crown also occurred during the crossing. The data collected from the total station monitoring system is summarised in Figure 17. In order to permit a meaningful comparison between the profiles, the data has been end-fixed to zero values 25m north and south of the ART crossing. An initial profile for the 10th October is shown as a hashed line, curved along the tunnel wall. Profiles are shown after this time as ART face distances to or from the HEX centreline.

First movements were discernible when the ART face was about 1m from the HEX centreline position and rapidly developed to a maximum value of 1.6mm in the direction of tunnelling when the TBM had passed the centreline by 2.3m. Thereafter, the displacement reversed and, at 9m past the centreline position, a minimum value of 1mm to the west (opposite direction) had occurred. As the TBM progressed beyond the influence zone, the crown prisms recovered slowly and returned to within 0.2mm of their original positions.

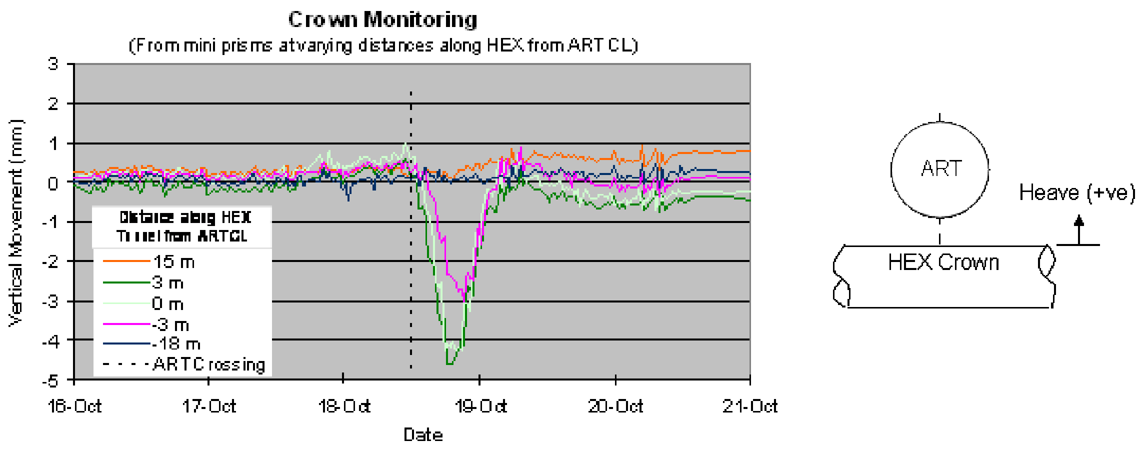

Figure 16. Vertical movement of the HEX crown at various distances along the tunnel from the ART centreline

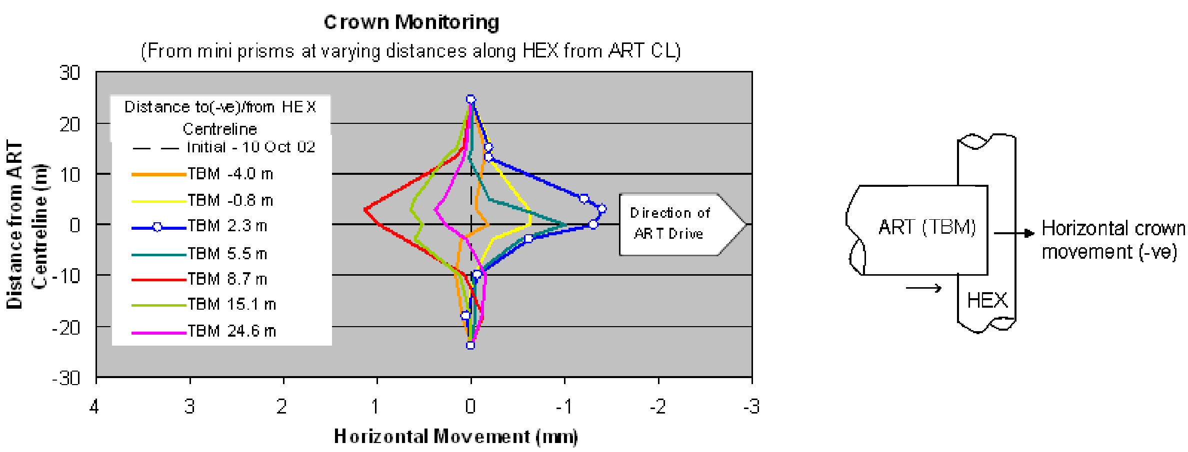

Figure 17. Horizontal movement of the HEX crown at various distances along the tunnel from the ART centreline

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations are made:

- Early interfacing with relevant stakeholders enabled comprehensive risk assessments to be made. Monitoring requirements were agreed and it is recommended for future projects that sufficient time be allocated to ensure that all parties buy-in to the construction and monitoring processes.
- Specification of a fully integrated monitoring scheme, installed concurrently in several structures under centralised as opposed to multiple control, allowed for prompt assessment of excavation and tunnelling impact; this provided the contractor with feedback on the operating process, enabling maximised production with the confidence that no damage or disruption to airport or third party infrastructure occurred.
- The adoption of 'primary' and 'secondary' monitoring systems gave both a high degree of confidence that data were correct as well as providing a back up should one system fail. The direct comparison that was possible between different instrumentation systems has also shown that automated monitoring in safety critical areas can produce high quality real-time data, and capture movement trends with sub-millimetre accuracy allowing an early identification of potentially adverse trends.
- The decision to run a single, large database replicated to the internet ensured that data could be easily managed and information distributed to interested and critical users in a timely and very convenient manner. The utilisation of 24 hour engineering cover also ensured that the most critical aspects of the works were conducted such that the tight job specifications were met with a high degree of confidence.
- The interfacing with various stakeholders in the early stages of setting up the comprehensive monitoring regime was found to be very important and it is recommended for future projects that sufficient time must be allocated to ensure that all parties are involved with, and are in agreement with, any proposed monitoring system.

Acknowledgements: The authors wish to thank BAA plc for permission to publish this paper and colleagues at Mott MacDonald and ITM Ltd for their support in writing this paper.

Corresponding author: Mr Gary Walker, Mott MacDonald, 20-26 Wellesley Road, Croydon, Surrey, CR9 2UL, United Kingdom. Tel: +44 208 774 2540. Email: Gary.Walker@mottmac.com.

REFERENCES

HITCHCOCK, A.R. 2003. Elimination of Temporary Propping using the Observational Method on the Heathrow Airside Road Tunnel (ART) Project. *Ground Engineering,* **36**(5), 30-33.

PECK, R.B. 1969. Advantages and limitations of the observational method in applied soil mechanics. *Geotechnique,* **19**(2), 171-187.

POUND, C., HSU, Y.S. & WALKER, G.R. 2003. Predicted and Observed Ground Movements around a Tunnel Boring Machine at Heathrow Airport. *International Conference on Underground Construction*, London, 549-562.

POWDERHAM, A.J. 1994. An overview of the observational method: development in cut and cover and bored tunnelling projects. *Geotechnique,* **44**(4), 619-636.

SAM, H., ROCK, T.A. & AUDUREAU, J.L. 2003. Heathrow's Airside Road Tunnel – Major Challenges. *International Conference on Underground Construction*, London, 407-418.

WILLIAMS, I. 2005. Managing Risk at T5. *Tunnels and Tunnelling International*. London. April 2005.