Investigating the Effect of Tunnelling on Existing Tunnels

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ABSTRACT

A major research project investigating the effect of tunnelling on existing tunnels has been completed at Imperial College London. This subject is always of great concern during the planning and execution of underground tunnelling works in the urban environment. Many cities already have extensive existing tunnel networks and so it is necessary to construct new tunnels at a level beneath them. The associated deformations that take place during tunnelling have to be carefully assessed and their impact on the existing tunnels estimated. Of particular concern is the serviceability of tunnels used for underground trains where the kinematic envelope must not be impinged upon. The new Crossrail transport line under construction in London passes beneath numerous tunnels including a number of those forming part of the London Underground network.

The opportunity was taken to observe the response of the Central Line tunnels during the construction of the new Crossrail tunnels in central London. The research project focussed on grey cast iron segmental tunnel linings. Extensive instrumentation was installed within one of the tunnels and in the ground around it. In order to assess the influence of the existing tunnels on ground movements field monitoring was undertaken in Hyde Park to establish the greenfield conditions. The monitoring adopted comprised a combination of conventional techniques, such as precise levelling and taping and state-of-the-art instrumentation such as optical fibre and MEMs technology. In addition to the field work, advanced numerical analyses were performed to model the complex ground-structure interaction at Hyde Park using sophisticated constitutive models. Excellent agreement was achieved with the field data. Another component of the research project was to examine how the stresses develop within a cast iron segmental lining as it deforms. A half-scale cast iron model was tested in the structures laboratory, varying factors such as bolt force and the radial load applied to the extrados. A further theme of the research was to carry out a series of advanced soil tests on high quality samples taken during installation of the field instruments. Parameters obtained from these tests allow the input data for the numerical analyses to be refined. This paper summarises the main aspects of the research project and some of the primary findings.

1 INTRODUCTION

Currently there are many tunnels being constructed througout the world in the urban environment to cope with providing adequate infrastructure (e.g. transport sytems and services) within expanding cities and their associated increasing populations. Many cities already have comprehensive underground networks and so new tunnels have to be constructed in the close proximity of exisiting tunnels. Tunnel construction is inevitably associated with ground deformations, leading to concerns that these might adversely affect the existing tunnels. There are two issues: the stability of the tunnel and the allowable deformations to which it can be subjected. Stability would be affected only in extreme cases after significant deformations and so understanding the shape of existing tunnels in situ and how they develop as a consequence of nearby underground excavation is

of great interest. Most existing tunnels after their construction tend to 'squat', i.e. their horizontal diameter is greater than the vertical. Little is known about the state of stress and bending moments within the tunnel linings (e.g. how close they are to yielding) and how these might change if the tunnel is deformed further. An essential provision for running trains is that they have an adequate operational kinematic envelope, otherwise it may be necessary to impose speed restrictions or rolling stock might be damaged, both leading to major costs through repair and delays.

Crossrail is a major new railway transport system running east-west through central London. The new 7.1-m diameter tunnels, constructed mostly with earth pressure balance tunnel boring machines (EPB TBMs), pass beneath numerous existing tunnels. Clearly, serious consideration was given to how the new tunnels would affect them and whether mitigation measures should be implemented to help safeguard them. In the past quite different approaches have been adopted: in some cases bolts connecting segments being loosened or removed (e.g. Moss & Bowers 2006) and in others tightened (e.g. Kimmance et al. 1996). Loosening the bolts helps minimise additional bending moments but leads to tunnel lining displacements while tightening them helps inhibit displacements but at the cost of generating additional bending moments.

To address some of the numerous uncertainties and because of the very serious implications of disruptions to the railway operation, Imperial College London have undertaken a major research project to investigate the influence of tunnelling on exisiting tunnels. The research was primarily funded through the UK Engineering and Physical Science Research Council (EPSRC) with major contributions from Crossrail Ltd and Morgan Sindall and collaboration with London Underground Limited (LUL). There were five main aspects to the project:

i.   field instrumentation installation and monitoring within and around the existing Central Line tunnels and in the ground in Hyde Park to observe responses when the new Crossrail tunnels were constructed;
ii.   structural testing of specially manufactured half-scale lining segments;
iii.   numerical analysis of the field conditions and validation with the results from field monitoring;
iv.   numerical analysis of the cast iron segments and comparison with results from laboratory testing;
v.   advanced laboratory testing of high quality samples taken during installation of the field instrumentation.

This paper describes the scope of the study and reports some initial findings.

2 RESEARCH THEMES

2.1 Field instrumentation and monitoring

There were three components of field monitoring. The two main exercises involved monitoring (i) one of the existing Central Line tunnels where the new Crossrail tunnels were to pass beneath it (just east of Lancaster Gate station) and (ii) the ground around both the new and existing tunnels. Prior to these activities an opportunity arose to test some of the instruments and installation procedures in the Central Line tunnel at Tottenham Court Road station.

2.1.1 Instrumentation and monitoring at Tottenham Court Road

One of the station tunnels at Tottenham Court Road was to be upgraded as part of the Crossrail works and so some of the instruments and methods to be used in the Central Line tunnel monitoring were tested at this time. Some of the segments were to be removed and so these were instrumented in various ways. It was established that the instruments worked well and there was good correlation between the different measuring systems. The magnitude of change in strain measured using electrical and mechanical strain gauges was found to be similar to that predicted assuming full overburden unloading with a segment modulus of 100 GPa. The work is described in detail by Yu (2014) and Yu et al. (2015).

2.1.2 Instrumentation and monitoring within the existing Central Line tunnels

A length of the eastbound Central Line tunnel running between Lancaster Gate and Marble Arch stations was monitored when the Crossrail tunnels were constructed beneath it. The new tunnels had a clearance of 4.2 m

and were at about 40 degrees skew. Various instruments and surveying techniques were implemented: electrical strain gauges, displacements gauges, eye bolts for tape extensometer measurements, state-of-the-art optical fibre sensors (installed and read by a research team from ETH Zurich, led by Prof Sasha Puzrin, working in collaboration with Imperial College) and a string of electrolevel beams along the tunnel length (results kindly provided by BAM Nuttall, Ferrovial Agroman and Kier Construction Joint Venture (BFK JV).

The main developments and findings from this exercise are as follows.

i. The deformed shape of the tunnel lining from the tape extensometer measurements corroborated well with the mode of bending in the lining segments captured by the strain gauge measurements.

ii. It was concluded that the effort involved in installing and reading the strain gauges was not justified given the level of information provided by them. The tape extensometer readings were comparatively quick and the eye-bolts cheap and easy to install and the readings gave a better overall idea of tunnel diameter/chord changes. This is considered to be an important finding in terms of time and economy.

iii. The magnitude of diametric changes as measured with the tape extensometer were less than ±0.1%, much smaller than the out-of-circularity generally measured in existing tunnels (~0.6%).

iv. Negligible movements across joints between rings were measured with the displacement transducers installed across them. This was corroborated by the measurements with the optical fibre sensors.

v. The optical fibre sensors were able to achieve a spatial resolution of about 1 cm with the distributed nature of the measurements using swept wavelength interferometry (i.e. it was possible to take measurements of strain every 1cm along the length of the fibre). This is considered a new development in the use of this style of monitoring within tunnels. The fibres were attached using a combined glue/magnet attachment system specifically developed for this situation.

vi. With the small spatial resolution achieved using the optical fibre sensors it was possible to monitor strains across joints. Results suggest that longitudinal deformation along the Central Line tunnel crown occurred within the segments rather than across the circumferential joints. This is important for understanding the overall response of the existing tunnel. The overall strain pattern observed is of a comparable form to that observed in the ground.

vii. Optical fibre sensors installed circumferentially within the tunnel were able to detect movement across the longitudinal joints as the Central Line tunnel deformed.

viii. Settlement profiles interpreted from the string of electrolevel beams were of similar form to those measured in the ground in Hyde Park. Comparing the magnitude and form of the two sets of measurements should allow relative bending stiffness values of the ground and the tunnel to be estimated.

The results from this aspect of the work will be published elsewhere.

2.1.3 Instrumentation and monitoring at Hyde Park

Extensive surface and subsurface instrumentation was installed above and around the existing Central Line tunnels and the new Crossrail tunnels. The scope of what could be installed close to the Central Line tunnels was limited as the tunnels run beneath the busy Bayswater Road. Three arrays of surface monitoring points were installed: one along Bayswater Road and two within Hyde Park. Additionally instruments were installed in a total of 38 boreholes to depths ranging from 20 m to 50 m to measure subsurface vertical and horizontal displacements and strains, pore water pressures and total stress changes. A plan view of the layout of instrumentation boreholes and surface points is shown in Figure 1. Some of the subsurface instrumentation was installed close to the Central Line tunnels (Section B-B) while most of them formed a main array in Hyde Park (Section A-A). A view across Section A-A showing the ground stratigraphy, arrangement of rod extensometers for measuring subsurface vertical displacements and the relative positions of the Central Line and Crossrail is given in Figure 2.

The main developments and findings are as follows (see also Wan 2014).

i. Numerous lessons were learnt during the extensive subsurface instrumentation installation period. The main points have been written up by Wan and Standing (2014a). It is anticipated that the detailed consideration of the mix proportions to be adopted for the different grouts used to install instruments will be of considerable interest to the geotechnical community involved with ground monitoring (different mixes were used for backfilling extensometer, inclinometer and piezometer borehole installations).

    ii.   The relatively new technique of installing multiple piezometers in a grouted borehole was adopted as part of the monitoring scheme. The piezometers were generally found to work well and independently. Details are given by Wan and Standing (2014b). This paper also gives details about the number of London Clay claystones encountered during the drilling of all the boreholes. Such detailed information is not often reported.
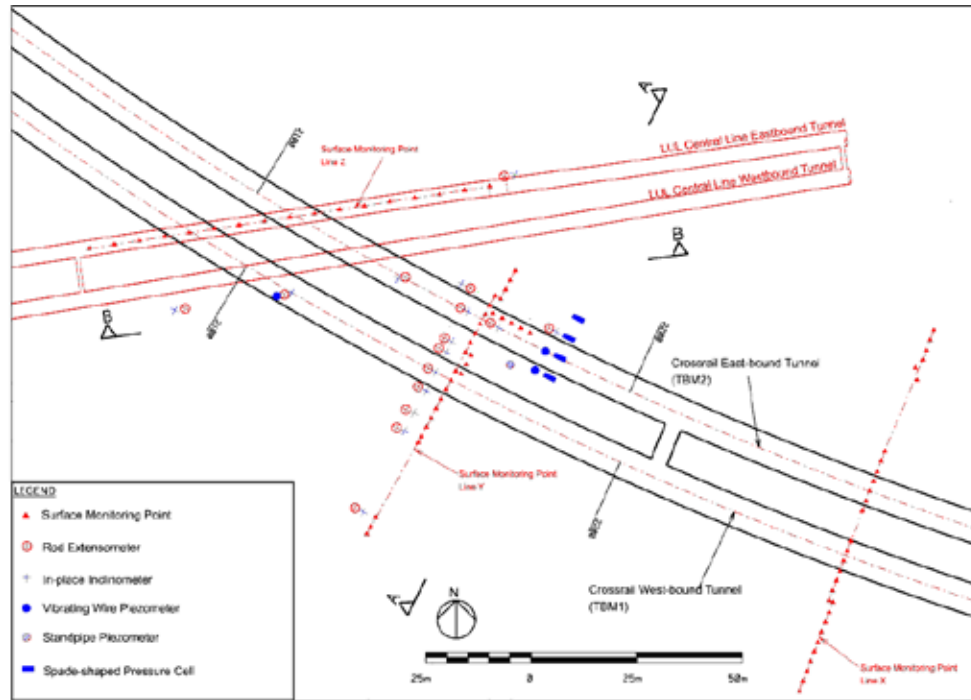

Figure 1: Plan view of existing Central Line and new Crossrail tunnels and layout of instrumentation in Hyde Park
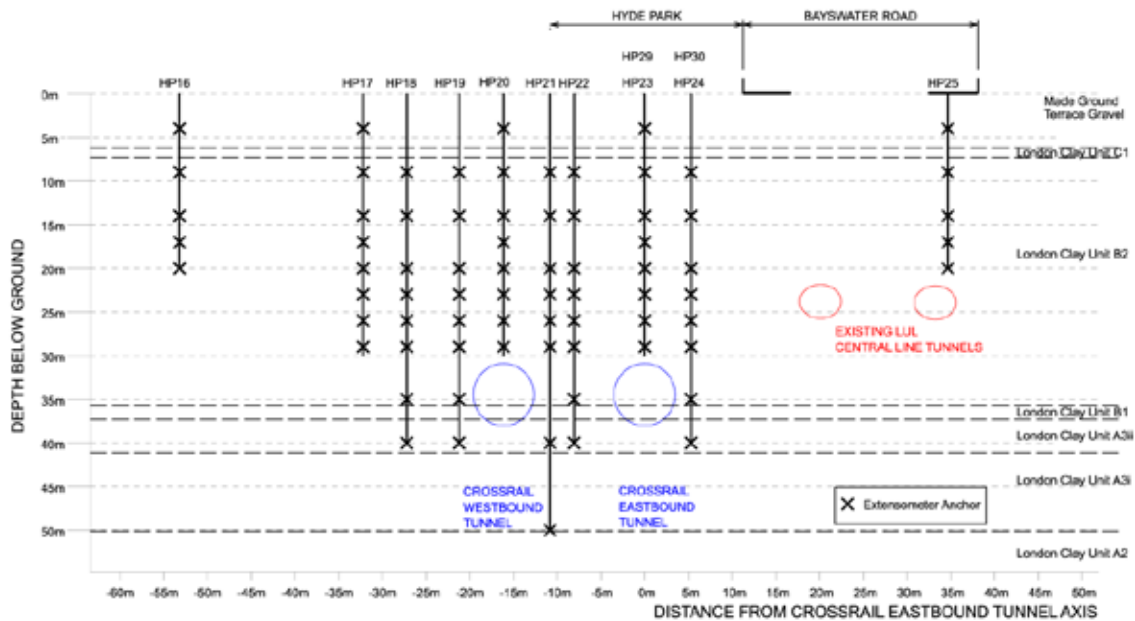

Figure 2: Section A-A showing the ground stratigraphy, arrangement of rod extensometers and relative position of Central Line and Crossrail tunnels

iii.   Pore pressures in the near vicinity of the existing Central Line tunnels were found to be slightly lower than hydrostatic, indicating that some drainage takes place into the existing bolted grey cast iron segmentally lined tunnels.

iv.   The field monitoring allowed differences in the ground response to tunnelling to be observed in a greenfield condition compared with the ground close to and affected by construction of the existing tunnels and the subsequent consolidation that took place. Generally wider settlement troughs were observed where the existing tunnels were located. However, in observing the ground response to the second Crossrail tunnel, it was seen that the recently constructed first Crossrail tunnel had a much greater influence on the ground response than the Central Line tunnels.

v.   Observed ground responses were linked with the various earth pressure balance tunnelling machine 'parameters'. Subsurface measurements indicated that the ground responded as an inward (contracting) displacement field. This was closely linked to parameters such as the face pressure and also is strongly controlled by the depth of the tunnel and overburden. This is considered an important finding as it means that conventional empirical prediction methods can be applied in such cases. A recent publication concerning the same type of tunnelling in London Clay as part of the Channel Tunnel Rail Link project showed an outward (expanding) displacement field that would be much more difficult to predict (Standing and Selemetas 2013).

vi.   Although mostly conventional instrumentation and precise surveying techniques were used, e.g. rod extensometers, in-place inclinometers (MEMS tilt sensors), and vibrating wire piezometers, ETH Zurich also installed optical fibre sensors in two rod extensometer boreholes and two shallow trenches (transverse and longitudinal to the westbound Crossrail tunnel). The borehole installations provide hitherto unseen detailed continuous strain profiles. When integrated, these profiles matched the discrete displacements measured at the locations of the rod extensometer anchors. They also allowed cracking in the backfilled grout column to be observed.

vii.   The quality of the data from the optical fibre sensors installed in the near surface trench far exceeded those from the manual micrometer stick measurements. Various types of optical fibre were tested within the installation (detailed in Dominik Hauswirth's ETH Zurich PhD thesis 2014). The quality of the measurements was so good that it has been possible to propose a new method of predicting vertical as well as horizontal displacements in advance of the tunnelling machine reaching the point of measurement (written up by Hauswirth et al. 2014).

2.2 Structural testing of specially manufactured half-scale lining segments

Twelve grey cast iron (GCI) half-scale segments were specially cast using ingredients and mix proportions similar to those used a century ago as determined from London Underground archives and exactly replicating geometric details of the original segments. The scale was dictated by the limitation of casting the thinnest part of the segments (the web/skin). At the same time 'coupon' samples were cast for testing. Two suites of tests were undertaken within the structures laboratory at Imperial College. The first involved performing two-segment tests similar to those of Thomas in the 1970s on full-scale segments. The second set of tests used a full ring (comprising six segments bolted together) which was loaded to simulate ground stresses acting on the lining from the ground around them as in situ and then deforming the ring into elliptical shapes of similar form and magnitude observed in existing tunnels. In both cases the segments and joints between them were comprehensively instrumented and monitored to investigate factors such as how stresses developed in the segments and the influence of bolt forces and joint stiffness.

2.2.1 Coupon testing

The coupon samples cast at the same time as the segments were machined into 'dog-bone' shapes and tested in tension using a rig as shown in Figure 3. The main developments and findings are as follows.

i.   Initially several trial tests were performed on dummy samples to optimise the way in which the tests were to be performed e.g. the best way of gripping the ends of the samples and the method of measuring strain/displacement.

ii.   The yield stress and ultimate strength of a number of coupons were established and found to be comparable to those available in the literature. Of particular importance was the yield stress as in

testing the segments the intention for most of the tests (especially the initial tests) was to keep the stress level within the GCI within the elastic range. This was to facilitate interpretation of the strain gauge data.

iii.   Multiple tests involving load-unload loops confirmed that the stiffness of the GCI reduced as it was loaded to higher levels and then unloaded. Mapping this behaviour was essential in understanding the overall GCI material characteristics and also for the interpretation of strain gauges when the segments were loaded beyond the elastic range (and subsequently unloaded).

iv.   In addition to the coupon tests, tensile tests were performed on wrought iron bolts recovered from the Waterloo and City Line. The results were compared to the known behaviour for mild steel to confirm that it was appropriate to use mild steel bolts in the laboratory investigations for this research.
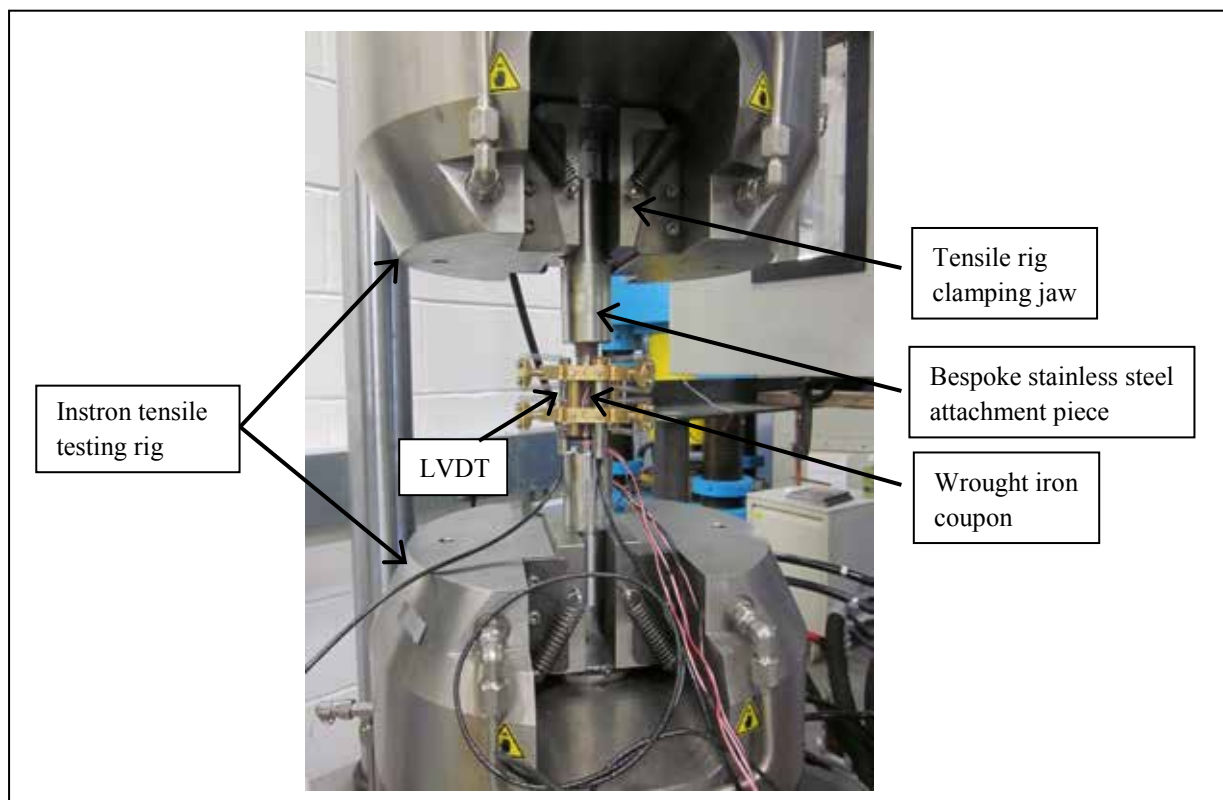

Figure 3: Setup for tensile testing wrought iron coupons

2.2.2 Two-segment tests

Prior to testing, the segments were comprehensively instrumented with strain gauges (Figure 4). Optimal positions were selected based on numerical analyses carried out to model the two-segment test set-up (covered in Section 2.4). Additionally special clamps were designed and made to hold displacement transducers in the vicinity of the bolted joint and instrumented bolts were also specifically purpose made.

   The main developments and findings are as follows.

i.   An experimental rig was developed to test two segments bolted together in a similar fashion to the tests performed by Thomas in the 1970s (e.g. Thomas, 1977). The bolted pair of segments, curving downwards, with one end hinged and the other on a roller, was deformed in small steps using a line load applied parallel to and close to the joint (at the uppermost part of the pair). The level of control and instrumentation on the segments was much greater than those available in the original tests by Thomas.

ii.   The data from Thomas' tests were reviewed to provide an initial estimate of the joint bending moment capacity. A series of two-segment tests with varying bolt preloads was then conducted and the results

interpreted under the assumption of elasticity. As the conditions of the two segment test were statically determinate, the interpretation of the instrumentation and estimation of the bending moment could be compared against analytical equations. There was good agreement between Thomas' tests with the full-scale segments and those in this research at half-scale.

iii.   The two-segment tests proved valuable in that it gave confidence that the methods used to interpret the instrumentation, especially the strain gauge readings, were appropriate. The same methods of interpretation were used in the full-ring tests.

iv.   A number of other observations were correlated with the results from the numerical analysis described in Section 2.4. For instance, it was found that the load in the middle bolt (the segments were connected together by three bolts) changed negligibly as the load was applied, compared with the two outer bolts.

v.   The stiffness of the bolted connection was found to reduce as the joint started to open.

Figure 4: Two-segment test set-up and details of instrumentation across joint and on bolts

2.2.3 Full-ring tests

The purpose of performing these tests was to deform the ring to similar shapes observed *in situ* both prior to and after nearby underground excavation and observe changes in quantities such as stresses within the segments, bolt forces and joint openings. In this way the effect of predicted ground movements from tunnelling could be assessed to gauge the level of distress they might inflict on the existing tunnel lining. In order to achieve this a highly sophisticated novel testing rig was designed, manufactured and tested over several months (Figure 5). This was a major development (summary details given below). Two series of tests were then performed: a major set of tests with stresses kept within the eastic range and a final pair of tests where the ring was taken to failure.

The main developments and findings are now given.

i.   The development of the test set-up was a staged process, especially in the development of the control system for applying loads and displacements to the ring. The ring was loaded by 18 actuators positioned at equal distances around a reaction ring that surrounded the test ring. There were therefore

three actuators per segment. This allowed much greater control of displacements and loads than could be achieved with soil. The ring was loaded while in a horizontal plane on a structural floor. Each actuator bore onto a spreader pad via a load cell to help distribute the load. The ring was deformed using a combination of computer-activated load and displacement control. Initially a uniform radial stress was applied to the ring via all actuators and then some were held at constant load while others were displaced to produce essentially elliptical forms. Multiple tests were performed to assess the effects of differing initial radial stresses, representing four typical tunnel depths (to about 25 m maximum) and various bolt forces (5, 7.5 and 10 kN). The influence of installing tar-infused hemp grommets within the bolt holes was also investigated (grommets can be seen in the upper right-hand photgraph of Figure 4).

ii.   The extensive instrumentation installed on the ring allowed both global and local joint responses of the bolted segmental cast iron lining to be studied experimentally and the internal actions relating to a particular deformed shape could be measured. The design and development of the bespoke loading facilities from scratch is a major contribution of this research into the behaviour of bolted segmental linings. This work is written up in detail by Yu (2014).

iii.   It was found that at high hoop force stress levels, relevant to deeper tunnels, the bolted segmental ring behaved as a continuous ring while at low levels joint stiffness values started to reduce allowing greater articulation.

iv.   For the small distortions imposed during the first main series of tests, the presence of high compressive hoop force was found to render the magnitude of bolt preload insignificant in terms of influencing bolted segmental lining behaviour. This suggests that in such circumstances there may not be much benefit in either tightening or loosening bolts as mitigating measures to excavation-induced ground movements.

v.   Tests performed using grommets (inserted beneath bolt heads and nuts to make the holes more waterproof) showed that the bolt forces decreased after tightening them to a fixed load. It was necessary to retighten them several times before the forces held. This implies that bolts installed in situ with grommets are likely to be at lower forces than those without.

Figure 5: Aerial view of half-scale full-ring test set-up (red outer ring provides load reaction for actuators)

iv.   At an overburden load corresponding to about 24m below ground level, the onset of joint opening was found to start once the inner radius had increased by about 0.20% by *unloading* at the spring line, contributing to the reduction in the overall stiffness of the ring. At this level of deformation, the extreme fibre stress in the ring was 22% of the ultimate tensile strength, i.e. within the elastic limit of grey cast iron, which in practice is usually taken as 25% of the ultimate tensile strength. At the same level of overburden, the joints started to open once the inner radius reduced by 0.58% from *increasing* the load at the spring line. In this case, the extreme fibre stress in the ring was 94% of the ultimate tensile strength, i.e. the ring segments would deform inelastically before the joint would play a part in the distortion of the ring.

v.   For tests performed keeping within the elastic range of the GCI, the experimental measurements indicate that using Morgan's equation (1961) to calculate the maximum bending moment for a tunnel ring assuming elliptical distortion based on a maximum magnitude of radial displacement under-predicts the maximum bending moment in the ring, even before the application of any reduction factor (as suggested by Muir Wood 1975). The results from the two tests taken to higher strain levels (and ultimately failed) are still being processed in detail. It should also be noted that in the experimental work (and the FE simulations) the tunnel was assumed to be perfectly circular and any deformations were the result of external loading.

vi.   As noted above, regarding results from the two tests taken to high strains, performed by Dr Sheida Afshan, only preliminary analyses have been performed so far.

2.3 Numerical analysis of the field conditions

There were three main sets of analyses performed during the course of the study. All analyses were performed using the bespoke Imperial College Finite Element Program (ICFEP), described in detail by Potts and Zdravković (1999). Initially a sophisticated two-surface kinematic hardening constitutive model was calibrated using advanced laboratory soil data from extensive testing of London Clay samples. At the time of this aspect of the study, the tests from Hyde Park (see Section 2.5 below) had not yet started so other well-documented data were used. This constitutive model and the parameters adopted were then used to model the well-documented St James's Park Jubilee Line Extension case study, accounting for different London Clay units. Excellent agreement with the field monitoring data was achieved for both short- and long-term responses.

The same model was used to simulate the new Crossrail tunnel construction at Hyde Park accounting for the previous stress history of the site. Again excellent agreement with the field data (Wan, 2014) was obtained even though the Crossrail tunnels are larger and constructed with a different tunnelling method (EPB vs. open-face shield at St James's Park), indicating the capability of the soil model to predict realistic soil movements from tunnelling in general.

The final stage of analysis was to model the situation at Hyde Park in 3-D (Figure 6). Because of the number of elements and the computing power required it was not practicable to use the sophisticated constitutive model used previously. Therefore a pre-yield non-linear elastic small-strain stiffness model coupled with a Mohr-Coulomb plastic model was adopted. Other simplications made were to assume that the Crossrail tunnels were perpendicular to the Central Line (i.e. ignoring any skew) and to model the pair of tunnels as a single tunnel. Parametric analyses were run varying factors such as EPB TBM face pressure and the longitudinal stiffness of the existing tunnel. This exercise resulted in excellent qualitative agreement with the way in which the existing tunnels distorted as the new tunnels approached and passed them. Insight was also gained for the same stages into how bending moments and lining stresses developed. Another important finding from this work was the effect of shear stresses acting on the extrados of the exisiting tunnel(s) on the bending moment distribution within the lining.

The main developments and findings are as follows (for further details see Avgerinos 2014).

i.   Two detailed case studies have been formulated (St James's Park and Hyde Park) using a sophisticated two-surface kinematic hardening constitutive model. These cases provide great insight into mechanisms of ground response to tunnelling and illustrate that the analyses can cater for different tunnelling methods.

ii.   Excellent agreement was achieved with the analyses performed for the St James's Park case study for both the short- and long-term ground response to tunnelling. An important component of the analyses is that parameters from intact rather than reconstituted samples were used.

iii.   Implementing realistic anisotropic permeability values for the different London Clay units led to closer agreement with the monitoring data.

iv.   The 2D FE simulations of the Central Line using an initial earth pressure at rest coefficient, $K_0 = 1.3$ to 1.4 showed that after allowing 100 years of consolidation, the maximum distortion in the existing tunnel was 0.2% squat. This implied that although the measured distortion is generally greater than 0.2% in the LU tunnels, it may be due to imperfect construction and self-weight distortion rather than ground loading. A field exercise conducted as part of the research at the LU Acton Depot certainly showed that tunnel rings constructed above ground could display greater than 1% of ovalisation from self-weight and initial out-of-built assembly of the segments.

v.   The influence of the tunnel lining permeability is significant. It affects factors such as the shape of the tunnel after construction (squatting or egging) and also the load distribution with greater hoop stresses being developed in the long term for the impermeable case.

vi.   It was observed that the tunnels deform as a consequence of both the normal and the shear stresses acting on the back of the lining. This was important with respect to the half-scale ring where only normal stresses were applied on the ring extrados.

vii.   The excavation of the Crossrail tunnel below the Central Line tunnel axis was found to impose changes on the internal forces in the Central Line tunnel lining. The most crucial combination of the circumferential hoop force and bending moment distributions in the Central Line tunnel lining occurred when the Crossrail tunnel excavation face is directly below the Central Line tunnel axis.

viii.   The face pressure applied to the ground affects the predicted soil movements. An increase of the face pressure (but not exceeding the overburden) decreases the ground surface settlements and the rate at which they develop.

ix.   Using the 3-D numerical analysis it was possible to assess the influence of the longitudinal stiffness of the Central Line tunnel. The agreement with the field measurements of the longitudinal strains along the Central Line crown (using the fibre optic sensors) became worse as the longitudinal stiffness of the Central Line lining was decreased in the numerical analysis. This indicates that the Central Line tunnel lining has a significant longitudinal stiffness.
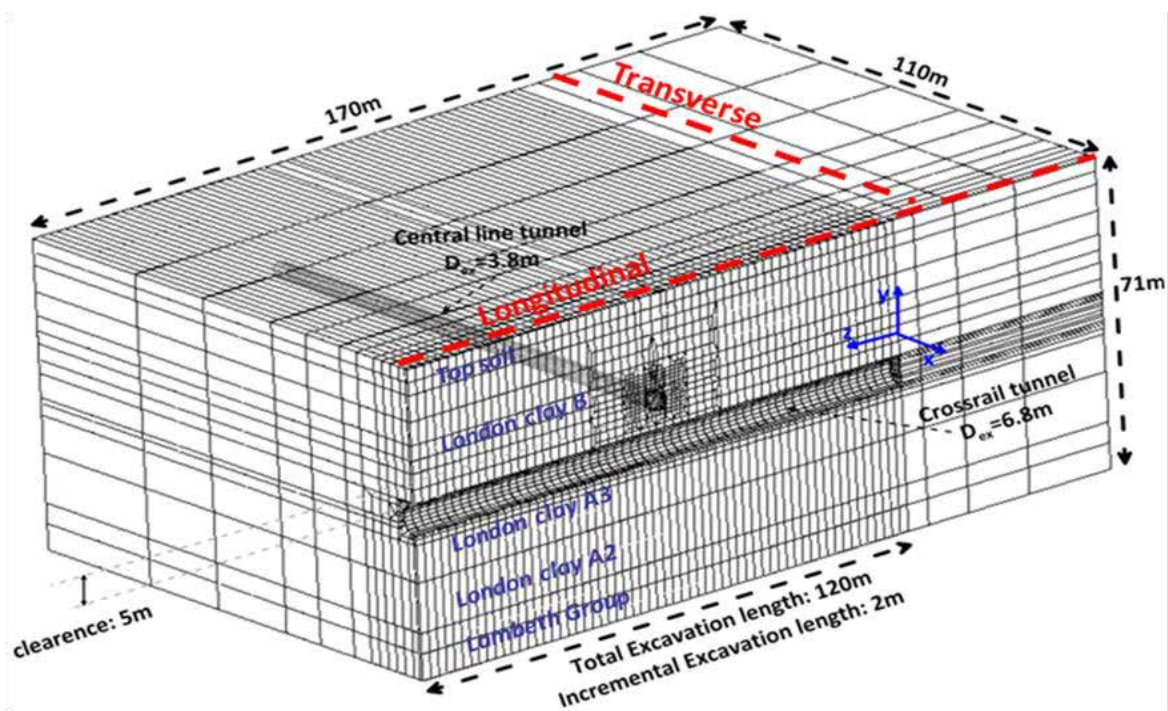

Figure 6: Mesh used for simplified 3-D ICFEP analysis of construction of Crossrail tunnel beneath Central Line

2.4 Numerical analysis of the cast iron segments

A 3-D finite element model using ICFEP was developed by Dr Katerina Tsiampousi in conjunction with the two-segment test laboratory experiment. A linear elastic model was implemented for the iron, while joint opening was allowed in modelling the connections. Results from the test indicated regions where greater element refinement was necessary in the FE mesh, as well as the level of detail required, e.g. caulking groove.
    The main developments and findings are given below.

i.   The main series of tests showed that the stiffness of the bolting system assumed in the FE model was too high. The actual bolting system of bolts, nuts, washers, and the contact between them rendered the stiffness of the system several times lower than the stiffness of the mild steel bolt. Since the stiffness of the bolting system affected how the FE model predicted the deflection of the longitudinal flange, this was a valuable finding for future FE modelling of segmental ring behaviour.

ii.   In general the FE predictions compared well with the laboratory measurements (Yu 2014). The FE model proved helpful in providing a guide to the behaviour of the two segment arch beyond the loading conditions tested in the laboratory. An important prediction was that when the joint was subjected to negative bending in the FE model, all three bolts had similar increases in bolt load and the joint opened uniformly along the extrados, i.e. the displacement at the outer edge was predicted to be similar to the displacement at the middle of the segment. This led to a revision of the joint moment capacity estimation for the full-ring test where joints were subjected to both positive and negative bending.

iii. Additionally, the FE analyses allowed an interrogation of the principal tensile and compressive stresses in the longitudinal flange. Since the analyses were linear elastic the results could only provide a guide to the capacity of the joint. Nonetheless by limiting the tensile stresses in the longitudinal flange as predicted by the FE simulations to below the ultimate tensile capacity of cast iron, it was shown that the initial estimate of joint moment capacity was reasonable. Non-linear analyses would be necessary to determine the true joint capacity.

2.5 Advanced laboratory testing of London Clay samples

High quality rotary samples were obtained from three of the boreholes made for installation of field instrumentation. These were positioned at increasing distances from the Central Line tunnels to investigate the effect of its construction on ground properties. 19 advanced triaxial tests have been performed with state-of-the art instrumentation for measuring small strains (three axial and radial locations) and cross anisotropic moduli (using bender elements). Samples were consolidated anisotropically back to their *in-situ* stresses prior to undrained shearing in compression. Because of the stringent creep periods held at the end of each stage of the tests each tests generally takes 2-3 months. This aspect of the research project has been completed by Dr Ramtin Hosseini Kamal and Dr Khalid Al Haj. As with the numerical analysis of the two-segment test publications presenting and discussing the results are currently being written up.

3 CONCLUSIONS

The work performed for this research project has provided considerable insight into the complex soil-structure interaction boundary value problem involving the effect of tunnelling on existing tunnels, with a particular emphasis on those constructed with grey cast iron segmental linings. Numerous initial findings from the five individual but interlinked themes of the research project are presented in this paper. Some publications giving more details have been written and are referenced here. Many other papers are currently being prepared.

ACKNOWLEDGEMENTS

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