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Assessment of London underground tube tunnels - investigation, monitoring and analysis

Peter Wright*

Tube Lines, 15 Westferry Circus, Canary Wharf, London E14 4HD, UK

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Abstract. Tube Lines has carried out a "knowledge and investigation programme" on the deep tube tunnels comprising the Jubilee, Northern and Piccadilly lines, as required by the PPP contract with London Underground. Many of the tunnels have been in use for over 100 years, so this assessment was considered essential to the future safe functioning of the system. This programme has involved a number of generic investigations which guide the assessment methodology and the analysis of some 5,000 individual structures. A significant amount of investigation has been carried out, including ultrasonic thickness measurement, detection of brickwork laminations using radar, stress measurement using magnetic techniques, determination of soil parameters using CPT, pressuremeter and laboratory testing, installation of piezometers, material and tunnel segment testing, and trialling of remote photographic techniques for inspection of large tunnels and shafts. Vibrating wire, potentiometer, electro level, optical and fibre-optic monitoring has been used, and laser measurement and laser scanning has been employed to measure tunnel circularity. It is considered that there is scope for considerable improvements in non-destructive testing technology for structural assessment in particular, and some ideas are offered as a "wish-list". Assessment reports have now been produced for all assets forming Tube Lines' deep tube tunnel network. For assets which are non-compliant with London Underground standards, the risk to the operating railway has to be maintained as low as reasonably practicable (ALARP) using enhanced inspection and monitoring, or repair where required. Monitoring techniques have developed greatly during recent years and further advances will continue to support the economic whole life asset management of infrastructure networks.

Keywords: London Underground; deep tube; tunnels; assessment; analysis; inspection; history; non-destructive testing; NDT; risk; cast iron; soil strength; pore water; circularity; monitoring.

1. Introduction

Tube Lines is responsible, under the terms of the Public Private Partnership (PPP) contract with London Underground (LU), for maintaining and upgrading the infrastructure of the Jubilee, Northern and Piccadilly lines (Transport for London 2002). As far as deep tube tunnels are concerned, the PPP contract is unique, in that it calls for an improvement in "knowledge and understanding" about the deep tubes, which previously were regarded as being in an uncertain, or "grey" condition. In practice this means that all deep tube tunnels and shafts, whether running tunnels, platform tunnels, cross passages, ventilation tunnels and shafts, or the warren of passenger or staff tunnels in stations, all have to be inspected, measured, analysed and reported on in accordance with LU and Tube Lines standards (London Underground 2007, Tube Lines 2006). In practice, over 5,000 individual structures have been assessed, but in a generic manner, facilitated by the use of Excel macros. Compliance with

*Corresponding Author, Principal Tunnel Engineer, E-mail: Peter.Wright@tubelines.com

Fig. 1 Cast iron and concrete segmental linings

standards can be defined in terms of a structural capacity ratio; if the capacity ratio is greater than 1.0 the tunnel structure is compliant with LU Standards, but if it falls below 1.0 the tunnel is non-compliant. In addition, if the structural condition or degree of non-compliance for any tunnel is identified as a concern, Tube Lines is responsible for maintaining the tunnel risk as low as is reasonably practicable (ALARP), which may involve more regular inspections or the installation of monitoring. In some cases a "real-time" monitoring system is justified and the risk is controlled through the operation of an Emergency Preparedness Plan (EPP), so that early warning can be given to prevent trains, customers or staff from venturing into a potentially unsafe area. Sometimes remedial work has to be carried out as a result.

This paper will outline the strategies and methods used in the tunnel assessment process, some of the monitoring and other remedial works deployed to keep the tunnel risk ALARP, and some of the idealised requirements for instrumentation and monitoring in the future.

While the majority of deep tube tunnels are lined with preformed segmental cast iron linings, many tunnels constructed after the 1970s have expanded or bolted concrete segmental linings. In addition there is a limited amount of sprayed concrete linings, constructed as part of the Jubilee Line Extension (JLE) in the 1990s, some deep station tunnels constructed of masonry around 1890, and even a small length of stainless steel lining, where an acid attack problem at Old Street had necessitated the rebuilding of a section of corrosion-resistant tunnel (Burgess *et al.* 2002). Typical tunnel linings are shown in Fig. 1.

2. Historical summary of deep tube tunnels

The first cast iron lined tube railway was constructed between King William Street in the City of London to Stockwell, four miles away to the south-west, where at that time, affluent city commuters lived. The 10ft 2in diameter tunnel was constructed in 4 years, using the newly-invented "Greathead Shield", and indeed the Resident Engineer for the works was J.H Greathead. Fig. 2 is a photograph of working conditions inside this device, which is basically a large metal cylinder, where manual excavation was carried out ahead of the bulkhead which had a rectangular opening. Once excavation of one ring width is complete, the hydraulic jacks shove the shield forward, and then the jacks are withdrawn to enable a ring of cast iron segments to be erected. Where poor ground conditions or excessive groundwater were encountered, the tunnel was pressurised with compressed air, retained

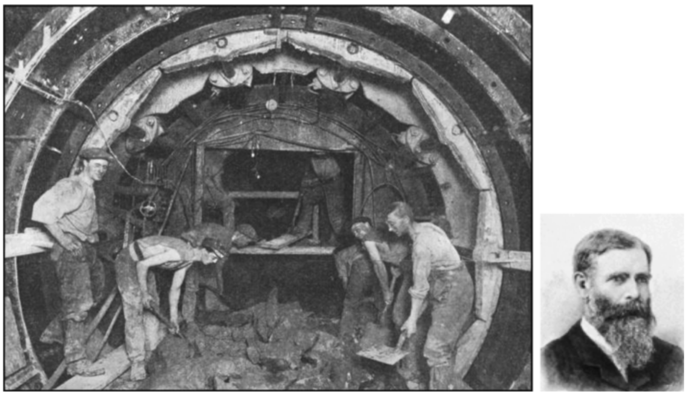

Fig. 2 The “Greathead Shield” and J.H. Greathead

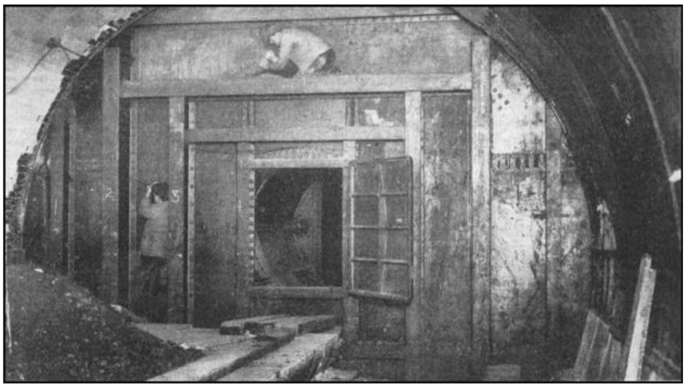

Fig. 3 A compressed airlock on the city and south London line

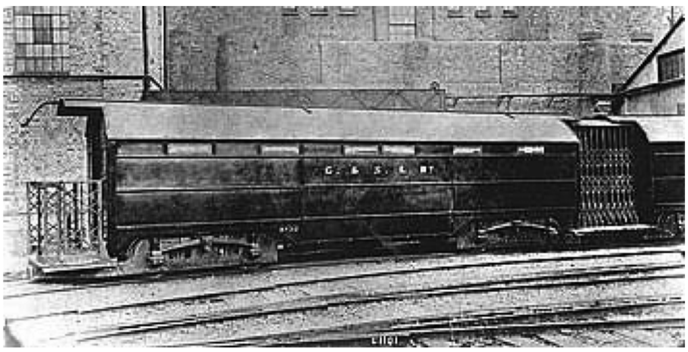

Fig. 4 “Padded Cells” for late 19th century passengers

by air locks such as that shown in Fig. 3. Not a single life was lost during the works, and this tunnel can be regarded as quite a landmark in the evolution of modern tunnelling. The original concept for the railway was to be cable-hauled, but the design was changed at the last minute to electric traction, although this meant that the passenger carriages were very cramped, and were nicknamed “Padded Cells” – see Fig. 4.

Most of the tube network in Central London was constructed in the following 20 years, and the

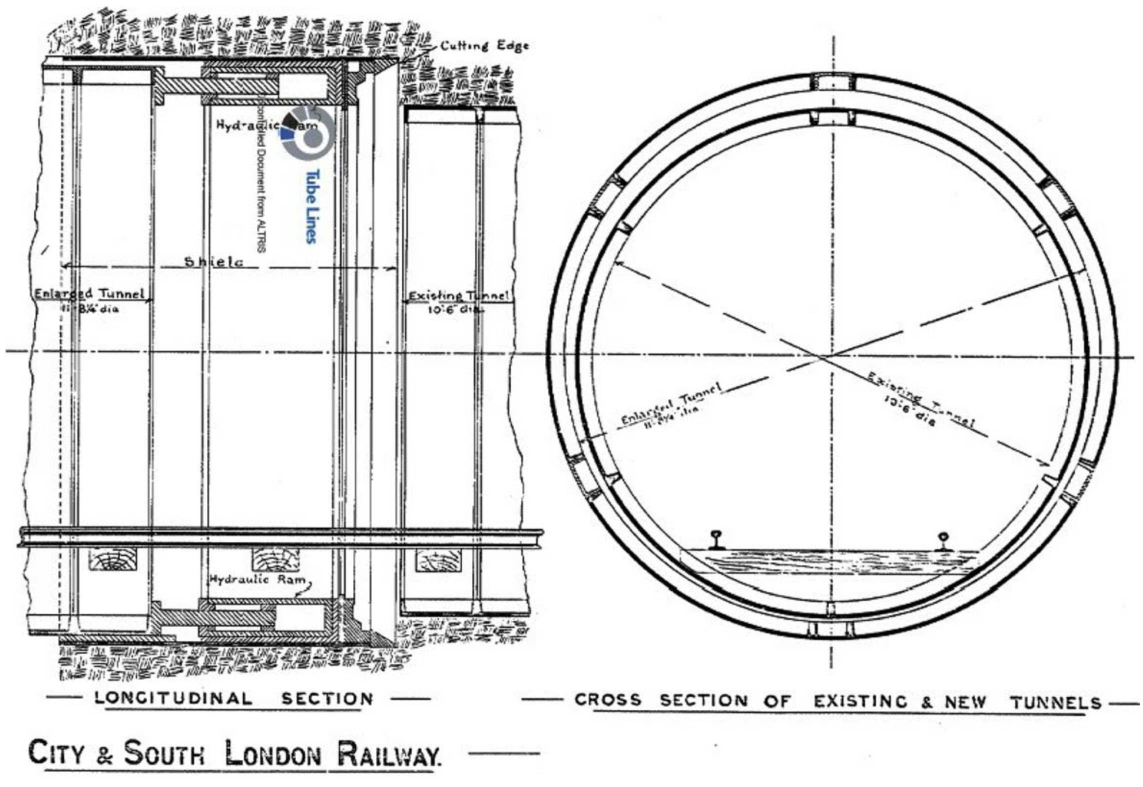

Fig. 5 Expansion of tunnels by insertion of key segments at radial joints

minimum diameter of running tunnels became 11ft 8¼in, necessitating the enlargement of the 10ft 2in and 10ft 6in tunnels in the 1920s by the insertion of short key segments at the radial joints (Fig. 5), a project that was carried out during the night-time when trains were not running, with trains running through the tunnel shield during the day. Unfortunately a ground collapse near the Elephant and Castle necessitated a tunnel closure, and the remainder of this tunnel expansion was carried out by continuous working.

During the 1920s and 30s the Piccadilly and Northern lines were extended to the outer suburbs and platform tunnels were also lengthened to accommodate longer trains (Follenfant 1974, Wolmar 2005, Day and Reed 2008).

In the 1960s the Victoria line was constructed and in the 1970s the Fleet line, later to be renamed the Jubilee line, was built as far as Charing Cross. In the 1970s and 1980s the Piccadilly line was extended to Heathrow Airport and the Terminal 4 Loop completed. In the 1990s the Jubilee Line Extension was built from Green Park out to Stratford in East London and the link to Heathrow Terminal 5 has been recently constructed and was opened in 2007.

A typical geological longitudinal section of a tunnel in Central London is shown in Fig. 6, which has been produced based on records from the British Geological Society, although most information is from boreholes commissioned by LU. Mostly the tunnels are constructed in London Clay, regarded as almost the perfect tunnelling medium, being stiff enough to support itself in the short term, relatively easy to dig and almost watertight. Short sections of tunnel in Central London are

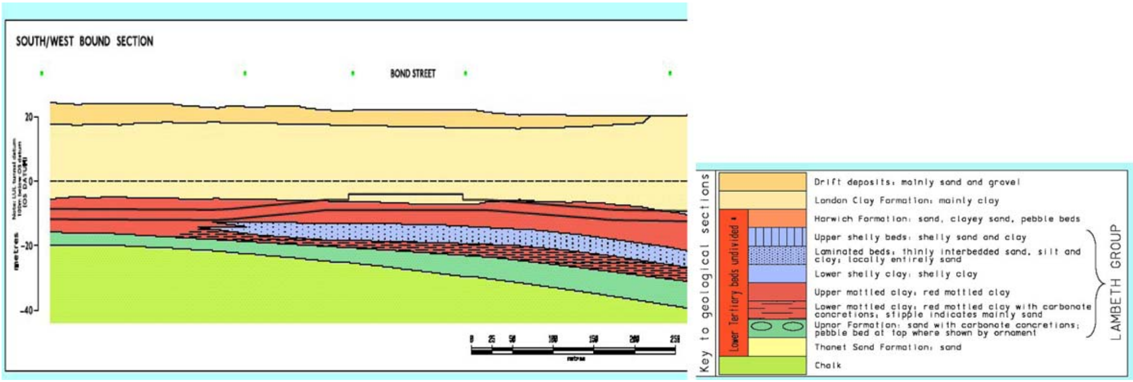

Fig. 6 Typical geological sequence

located in the more variable Lambeth Group, the water-bearing Thanet Sands and a very short section encounters the Chalk bedrock, near Russell Square.

3. Tunnel assessment

At first sight the business of tunnel assessment seems quite simple; LU running tunnels and platform tunnels are generally circular cast iron construction, and the ground conditions in which they were built are often very similar, suggesting the only significant variable is the depth. However, the tunnels could be subjected to a variety of pore water conditions, depending on whether there is underdrainage of water from underlying strata, or whether the tunnel itself acts as a drain. This in turn affects the magnitude of horizontal and vertical effective pressures exerted by the ground on the tunnel. The tunnel itself could be built out-of-shape at the time of construction, the tunnel linings may have been damaged at some stage and the quality of materials used could be (and indeed were) highly variable. Most of the old cast iron running tunnels and some platform tunnels were constructed very close together, and the digging of the second tunnel will have affected the forces and stresses acting on the first tunnel.

In addition, there are many ancillary structures that need to be analysed. For instance there are over 3,000 openings in the circular tunnel and shaft structures, which cause stress concentrations, that need to be analysed. Every time there is a change in tunnel diameter there is a headwall structure, which retains the earth; this too has to be analysed, as do the bases of shafts, which could be subjected to uplift forces. Many cross passages and passenger tunnels are rectangular boxes of various configurations and sizes, some with arched roofs and some reinforced flat roofs, and several thousand of these assets had to be analysed too.

Fig. 7 illustrates a typical section of running tunnel showing generic types of structures. In order to understand these generic structural types a variety of studies have been completed, some carried out internally by Tube Lines and some carried out by external consultants and contractors, some theoretical and some experimental/investigative (Tube Lines 2007a, b, 2008a, b, c, d). These studies form the parametric foundation on which the assessments have been carried out. An example is a study on geotechnical parameters, which summarises the existing state of knowledge, reports on site investigation work carried out from inside the tunnels, carries out some further

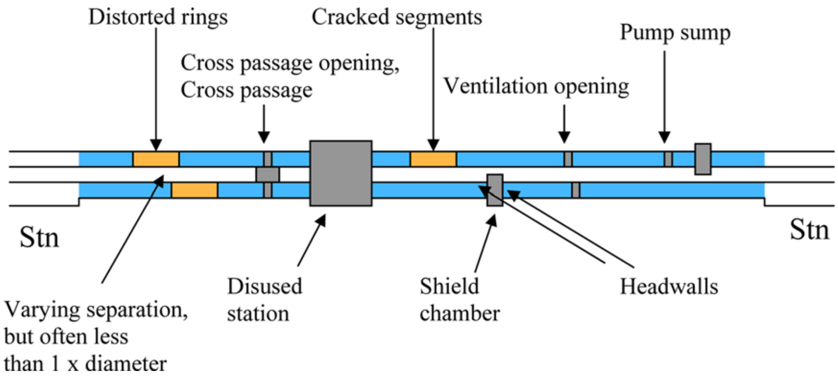

Fig. 7 Representation of running tunnel assets

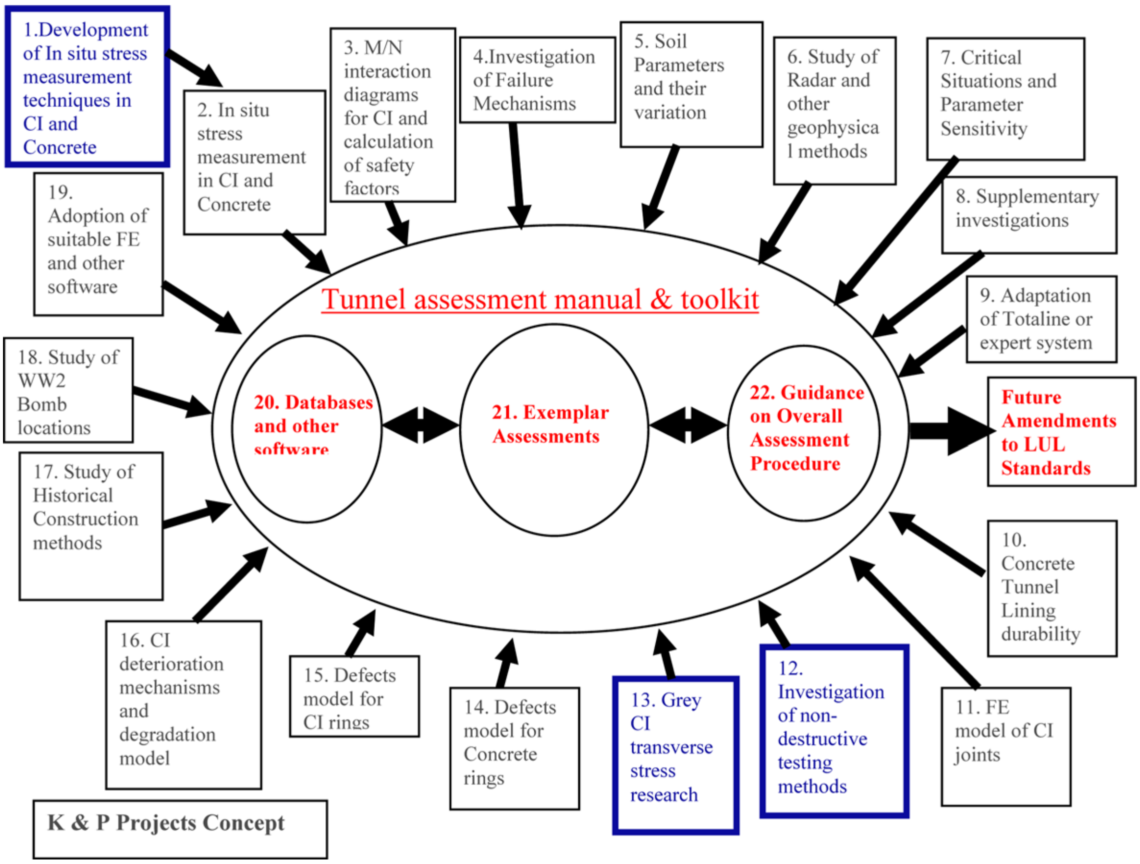

Fig. 8 Original assessment concept

analysis and proposes soil parameters to be used on a system-wide basis for assessment. Other studies summarise work carried out on the cast iron tunnel linings, including cast iron strength testing, in-situ stress measurements, tunnel lining circularity measurements and methods of 2D and 3D analysis. Fig. 8 is a slide from 2001 showing the intended strands of generic work; indeed most of this work has been carried out in some form or other.

The development of the tunnel assessment work has also been driven by risk factors. Put crudely the risk, however unlikely it may seem, is that the tunnel may fail, with consequential loss of life. Figs. 9 and 10 show how, working back from this consequence, the engineering factors influencing failure can be identified and what investigation tools can best be deployed to mitigate these engineering factors (Manex UK 2004). For instance the existence of voids outside the tunnel was seen as a significant collapse risk, which was seen at first as being detectable by radar and ultrasonics, as shown in Fig. 10. However, it was subsequently decided that the best approach was to carry out quite comprehensive circularity surveys, as an out-of-circular tunnel could more economically signal the existence of a void than could radar or ultrasonics. In fact, radar was used only to detect

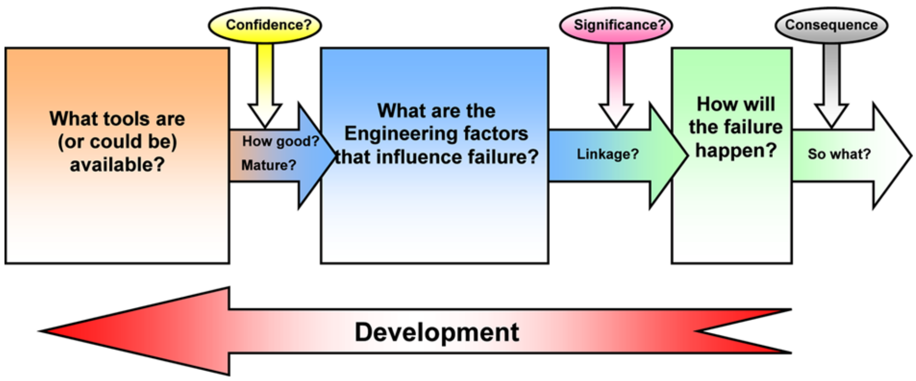

Fig. 9 Risk-based approach to tunnel assessment

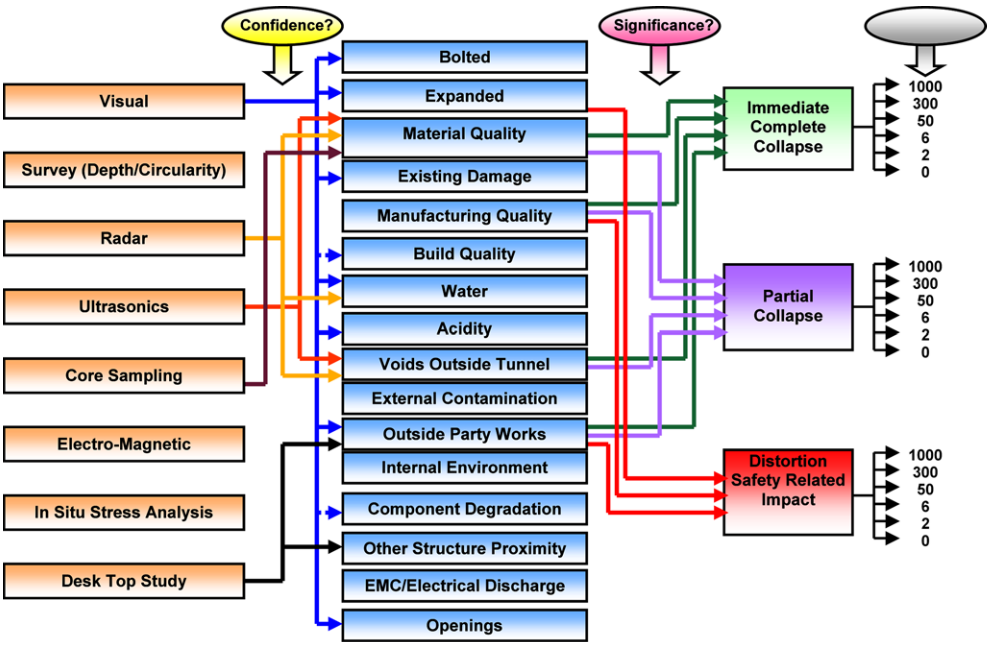

Fig. 10 Risk-based approach to tunnel assessment

Fig. 11 ground penetrating radar to detect brickwork laminations

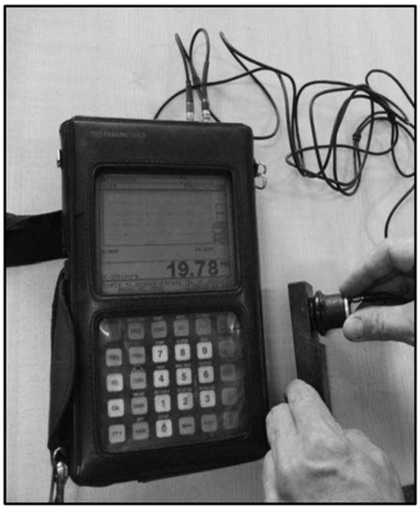

Fig. 12 Ultrasonic testing kit

lamination in tunnel brickwork at some locations (Fig. 11). However an ultrasonic tool was procured and used to measure thicknesses of cast iron to try to detect reductions in thickness through corrosion or graphitisation (Fig. 12).

The first year of the Deep Tube Tunnel Knowledge and Inspection Programme, Annual Works Plan 1 (AWP1) was mostly concerned with basic inventory and consideration of methodologies. Having set down the anticipated generic investigations (Fig. 8) and attempted to determine which methods of investigation would deliver the most economic and effective results (Fig. 10), Tube Lines embarked on a series of pilot studies. In the second year of assessment, termed AWP2, Tube Lines picked a subset of tunnels of various different types, materials and construction, at different depths and constructed in different subsoils, and carried out investigations on each. Typically the tunnel lining materials were tested, the soils in which the tunnels were constructed were also tested, loadings were assessed and analyses were completed. This work generally teased out most of the issues of concern and guided where work should be focussed in subsequent years (AWP3 to

AWP6). Most of these latter years involved the development and implementation of methods of "Inspection for Assessment", spreadsheet-based calculation methods for thousands of assets and consistent and comprehensive reporting.

4. Tunnel analysis for assessment

Historically tunnels have been analysed/designed using an elastic continuum formulation, which has been developed by a number of workers in the field (Fig. 13). The approaches proposed by Muir Wood (1975) and Curtis (1976) have been used extensively in the UK, although other approaches have been used in the US and parts of mainland Europe. This work has been summarised by Duddeck and Erdmann (1985). In a soft elastic continuum (soil) the tunnel lining in compression carries nearly all the overburden load, ie., the column of earth vertically above the tunnel, but a bending moment will also be present if there is a difference between horizontal and vertical earth pressures. Unfortunately however, the ground is rarely elastic or homogeneous, pore water may exert pressures on tunnels or may not, if the tunnel acts as a drain, and the construction process is not taken account of at all; the elastic continuum methods are often referred to derogatively as "wished-in-place" approaches.

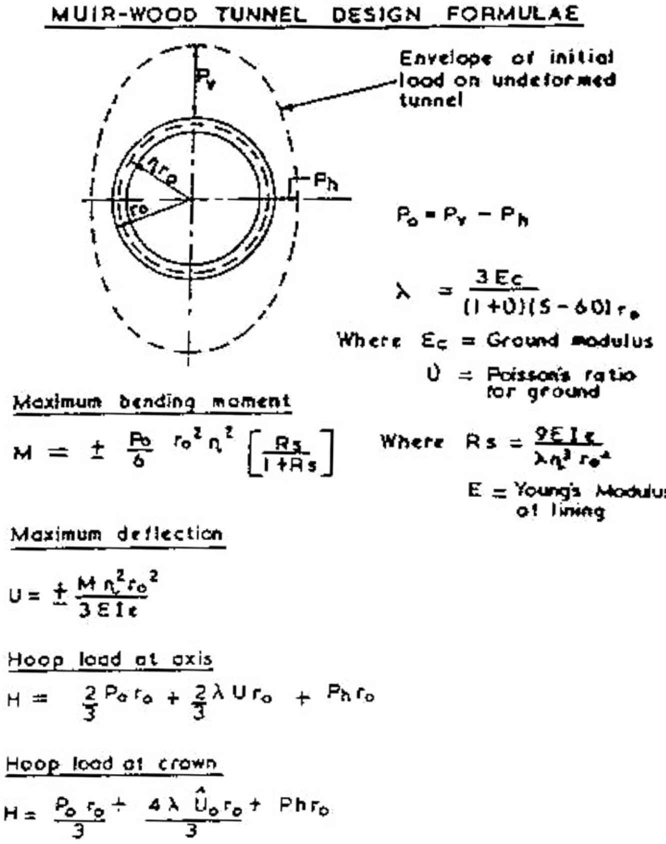

Fig. 13 Muir-wood tunnel design formula

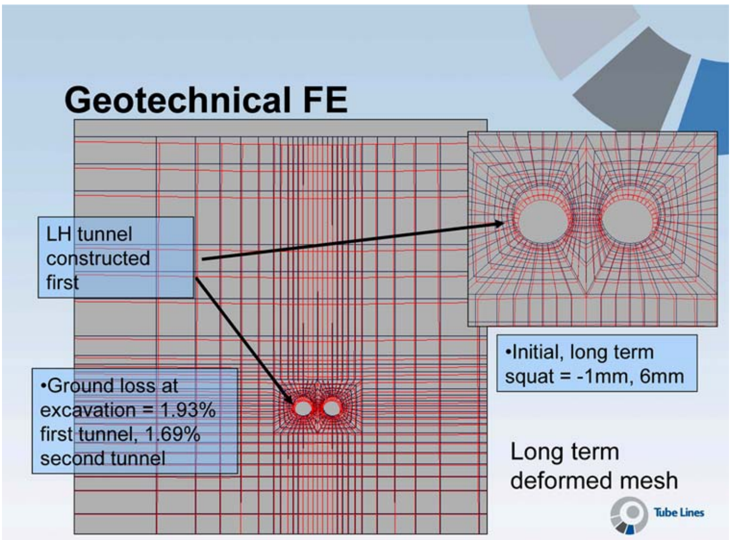

Fig. 14 Typical twin tunnels analysis by the finite element model

The use of geotechnical finite element (FE) analysis enables many of these problems to be overcome and the computing power now required for a 2D FE run is becoming trivial (Fig. 14). Such analysis also enables the modelling of twin tunnels, one constructed before the other, as the first tunnel constructed tends to pick up additional stresses as the second tunnel is built. However, 2D FE still suffers from the drawback that the tunnel building process, which is three-dimensional, plus time, is modelled using a “virtual support” to the ground, a certain percentage of the overburden load, designed to take account of the longitudinal ground support, between the tunnel face and the

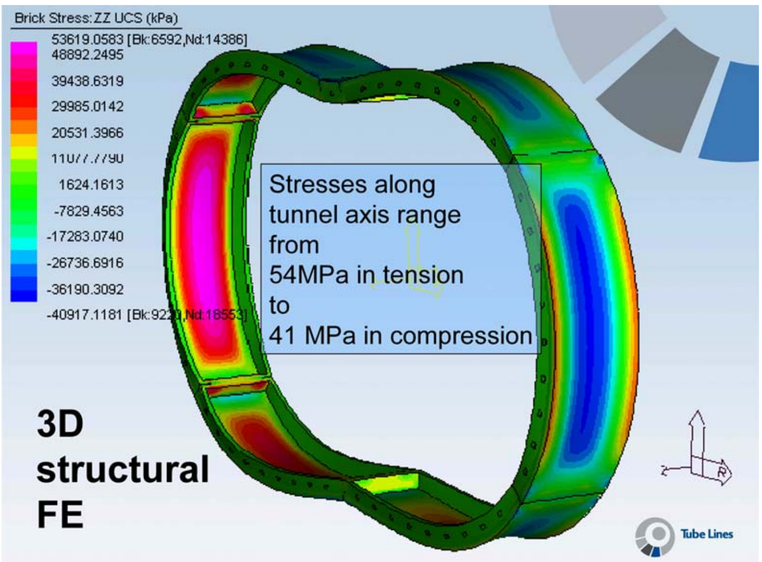

Fig. 15 3D structural modelling of segmental tunnel - longitudinal stress

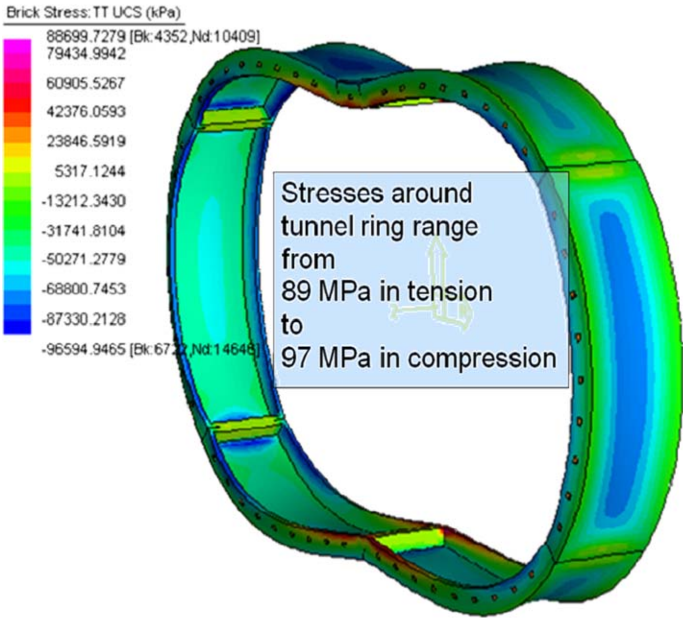

Fig. 16 3D structural modelling of segmental tunnel - tangential stress

completed tunnel behind. This percentage overburden load is then transferred to the lining as the tunnel advances. In addition the settlement at the surface due to tunnel construction is generally poorly modelled by the usual soil formulations in FE, giving a trough which is too wide and too shallow compared with what is the case in practice and therefore may give unconservative predictions of building damage at the ground surface. Mair (1999) gives a good summary of the state of the art.

Modelling of tunnel linings in 3D can give surprising results and Figs. 15, 16 and 17 show how the deflection and stresses in a ring of cast iron running tunnel lining could be quite complex. Fig. 15 shows the exaggerated deflection and the stresses in the direction along the tunnel. It can be seen how the segments “dish” between the flanges under the influence of the soil loading and there is a tendency for the circumferential flanges to splay outwards. This is possibly due to the presence of a caulking groove which extends for the full depth of the flange and allows this deformation to occur. Stresses tend to be tensile (+ve) on the inside and compressive (-ve) on the outside, as would be expected. Fig. 16 shows the tangential stresses in the lining, which, incidentally, are higher than what might be expected from a 2D elastic continuum analysis for this loading and deformation.

This particular model shows that the joints, particularly at the invert, are discontinuous, showing that the joint is actually opening a little. This FE model is a non-linear one with a no-tension material between the joints. However, despite the joints opening, as shown at the circumferential flanges, the radial flanges, due to the deformed shape of the segment, are still touching and there are still compressive stresses at the contact between the radial joints (Fig. 17). This illustrates that any bolts fastening the radial flanges together may not have any effect until the joint opening becomes more pronounced.

Complete geotechnical/structural modelling of tunnel construction in 3D is still not quite economic with today’s computing power, but will undoubtedly become so with time, as computing power continues to improve.

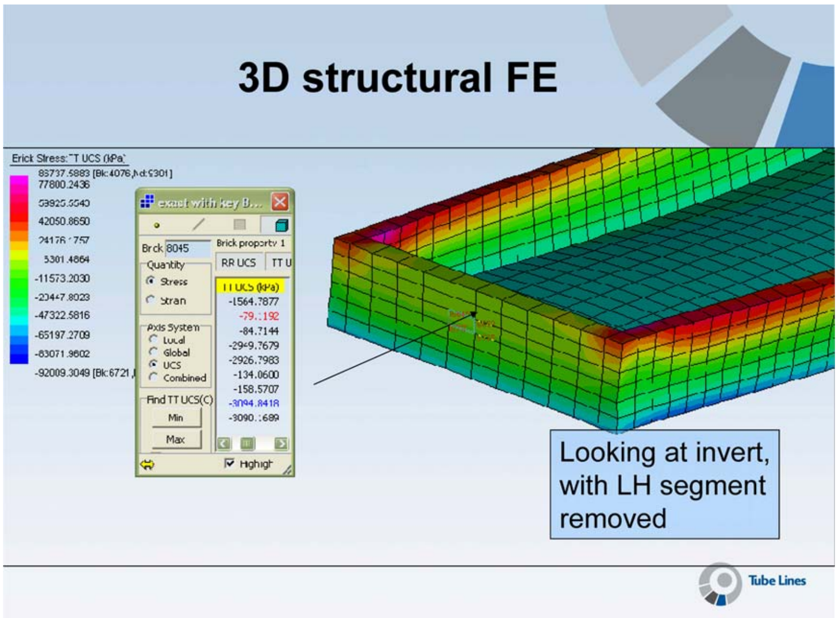

Fig. 17 Compressive stress at bolting position

5. Inspection and measurement

All tunnel and shafts are required to have a close inspection as part of the tunnel assessment. Pilot studies have been carried out in shafts using a camera suspended on a remotely controlled but tethered helium balloon (Fig. 18) or a camera mounted on a telescopic pole, rather than building an access scaffold in the shaft or using roped access. In practice, however, roped access has been generally used, as LU Standards demand a "touch-distance" inspection of assets.

Fig. 18 Shaft inspection using helium balloon

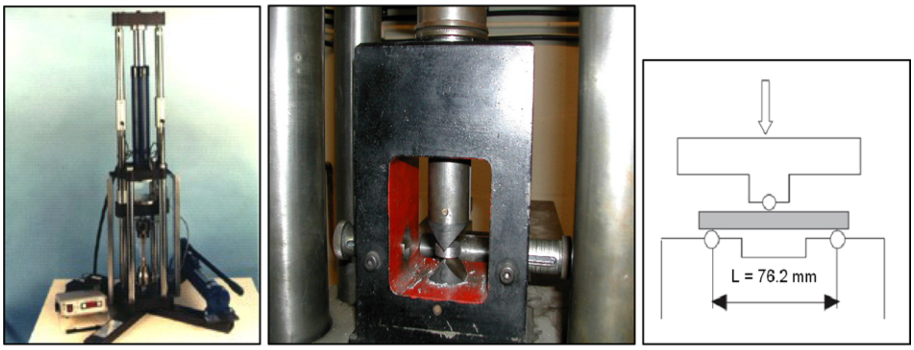

Fig. 19 Tensile, wedge penetration and bending tests for cast iron

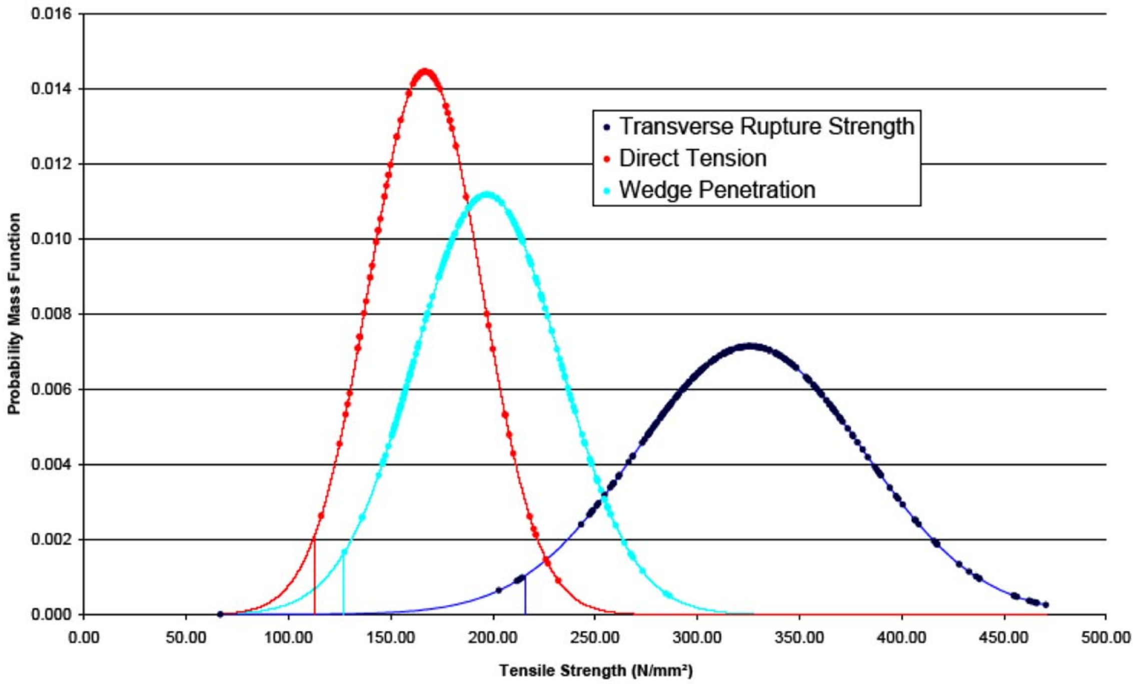

Fig. 20 Results of tests on cast iron samples

Cast iron lining thickness and degradation has been determined partly by core-drilling (150 or so cores) and partly by ultrasonic measurement (approx. 3,000 measurements) (Castings Technology International 2003). In fact the main result has been that in general there has been little or no detectable loss of section on the tunnel or shaft extrados over the 100 years or so that these deep tubes have been in operation. Samples have been extracted from the cast iron cores from which strength testing has been carried out (Figs. 19 and 20). Fig. 20 illustrates the normal distribution plots for direct tension, wedge penetration and transverse rupture strength (bending) and it can be seen that the characteristic tensile strength of the cast iron (ie., the strength below which not more than 10% of samples will fall) is actually lower than the 150 N/mm^2 for this grade of iron in the LU Standard. However, the apparent tensile strength in bending is much higher; and while part of this is

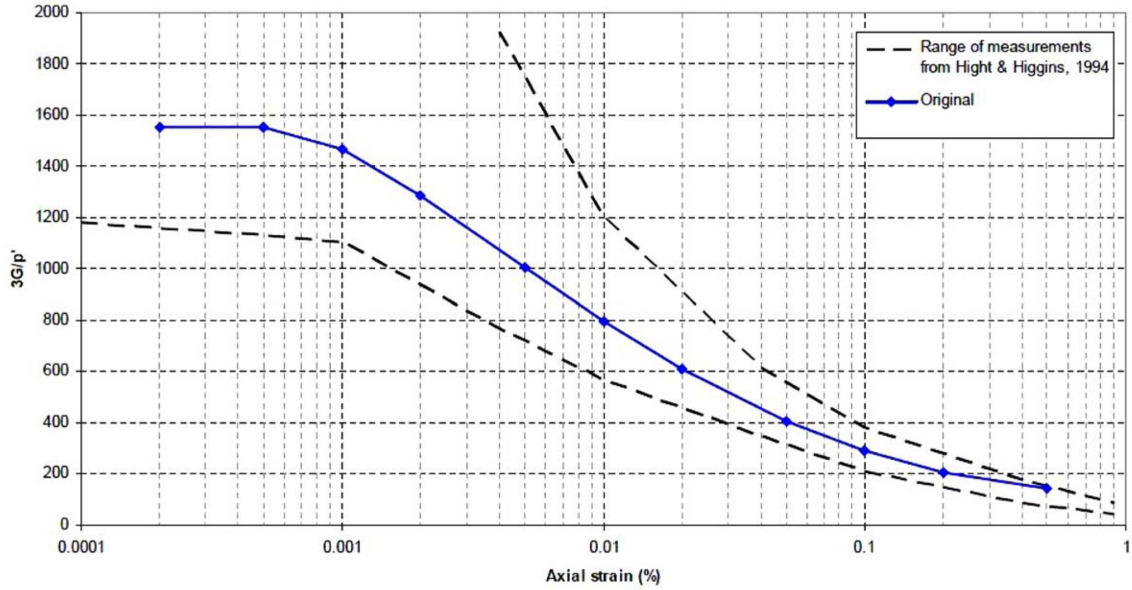

Fig. 21 Typical relationship between shear modulus and strain

Fig. 22 Soil testing using CPT test apparatus and laboratory

due to frictional effects in the testing apparatus, part of it does represent a valid tensile strength in bending, due to non-linear stresses.

The properties of London soils and the London Clay in particular, are well known, as so much academic work has focussed on them (Hight *et al.* 2003, 2007). The typical variation of shear stiffness with strain, as illustrated in Fig. 21, is well known, and it is understood that high strains and consequently low stiffnesses are associated with tunnel construction. A key question that the tunnel team asked early in the assessment programme concerned the properties of the soils adjacent to the tunnels after 100 years of drainage, warming and consolidation. Would the soil have reverted to the higher strength and stiffness that would be expected in virgin soil before tunnel construction, or was there a lower stiffness associated with the original construction? Another question concerned the water table within the clay soil; had the tunnel acted as a drain and drawn down the water table in the clay during the 100 years after construction? To answer these questions a programme of Cone

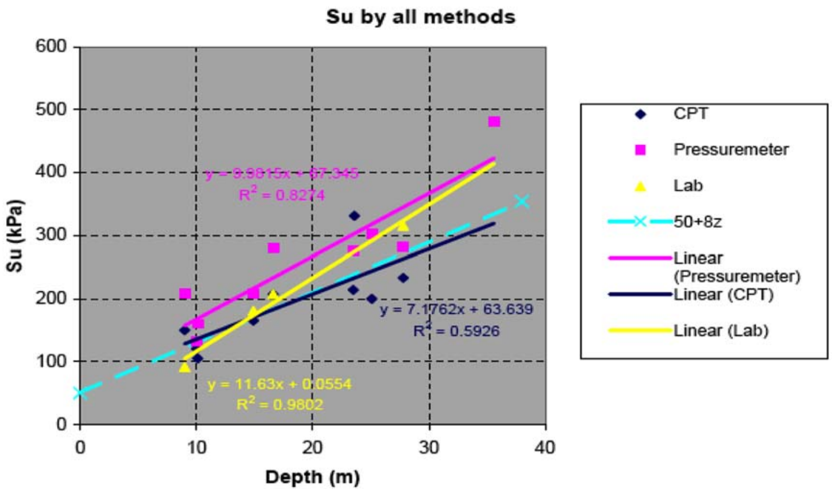

Fig. 23 Undrained strength test results

Penetration Testing (CPT) was carried out through the side of the tunnels at axis, using a CPT rig adapted to be bolted to the tunnel lining (Fig. 22) (Lankelma *et al.* 2005, 2006). In addition, samples were extracted for high quality testing, CPT pressuremeter tests were carried out, and piezometers were installed, generally at 1, 3 and 5 metres horizontally from the tunnel. Fig. 23 shows undrained strengths measured by three different methods, which compares well with a strength profile of 50 + 8z kPa with depth (z) in metres at depths up to 40 metres. However, at greater depths up to 80 m under Hampstead Heath, the measured strength and stiffness is significantly less than would be expected from the 50+8z profile. This is thought to be due to the fact that under Hampstead Heath the London Clay is less overconsolidated, due to reduced glacial erosion, compared with what might be the strength at a similar depth in central London. Fig. 24 shows the piezometer readings at 1, 3 and 5 m from the tunnel extrados, after several months have been allowed for readings to stabilise. This clearly shows that, in general, pore water seems to be slowly draining into the tunnel, even where there is no visible evidence of seepage.

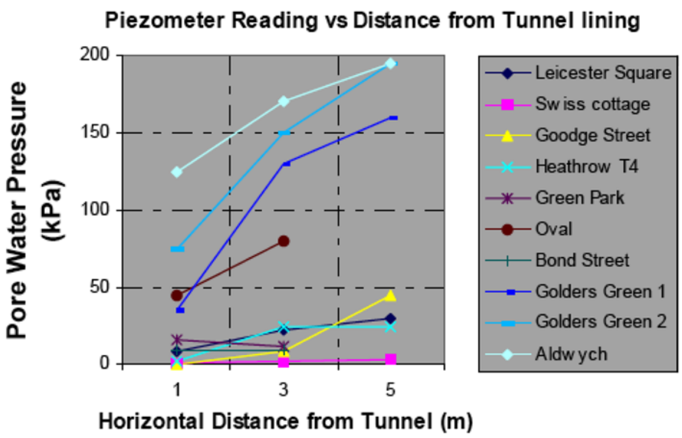

Fig. 24 Stabilised piezometer test results

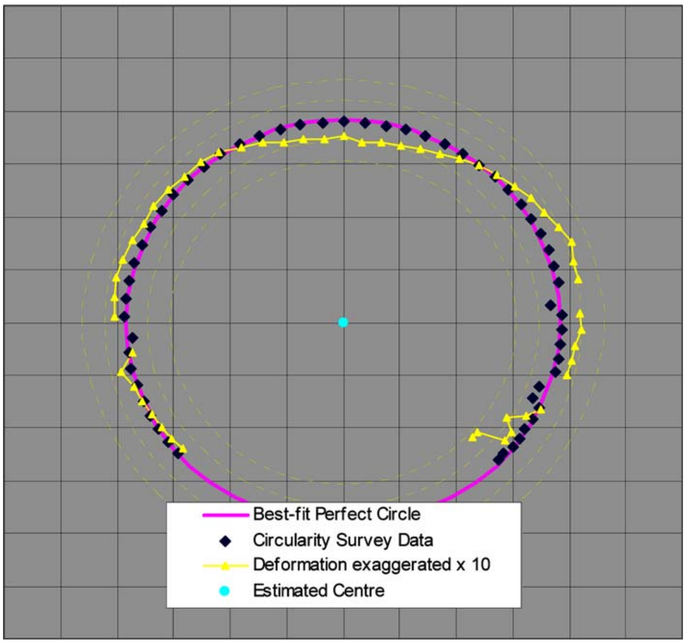

Fig. 25 Typical circularity measurement from laser scan

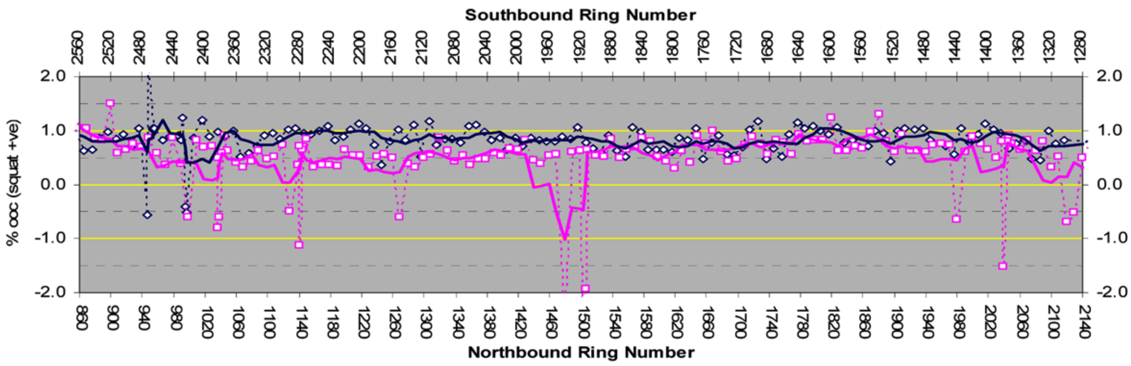

Fig. 26 Typical longitudinal plot of tunnel distortion

Figs. 25 and 26 show typical circularity measurements carried out in the tunnels using a laser trolley-mounted device. Fig. 25 shows the crown of the tunnel has distorted downwards (“squatted”) by approximately 1% of radius in this instance, and the longitudinal plot in Fig. 26 seems to show that the Northbound tunnel, shown in blue seems to have squatted more than the southbound tunnel, in pink. This could indicate that the northbound tunnel was the first to be built, and squatted further while the southbound tunnel was being constructed. Typically, circularity measurements on the cast iron tunnels indicate average squatting distortions of 0.5-1.0%.

The assessment team was keen to try to obtain in-situ stress measurement in the tunnels, to validate the analysis calculations. Unfortunately, as tunnels generally do not move much, it was difficult to get any changes in stress which could be measured. In cast iron tunnels an overcore approach was used, where the cast iron is cored around a strain gauge and the change to zero stress

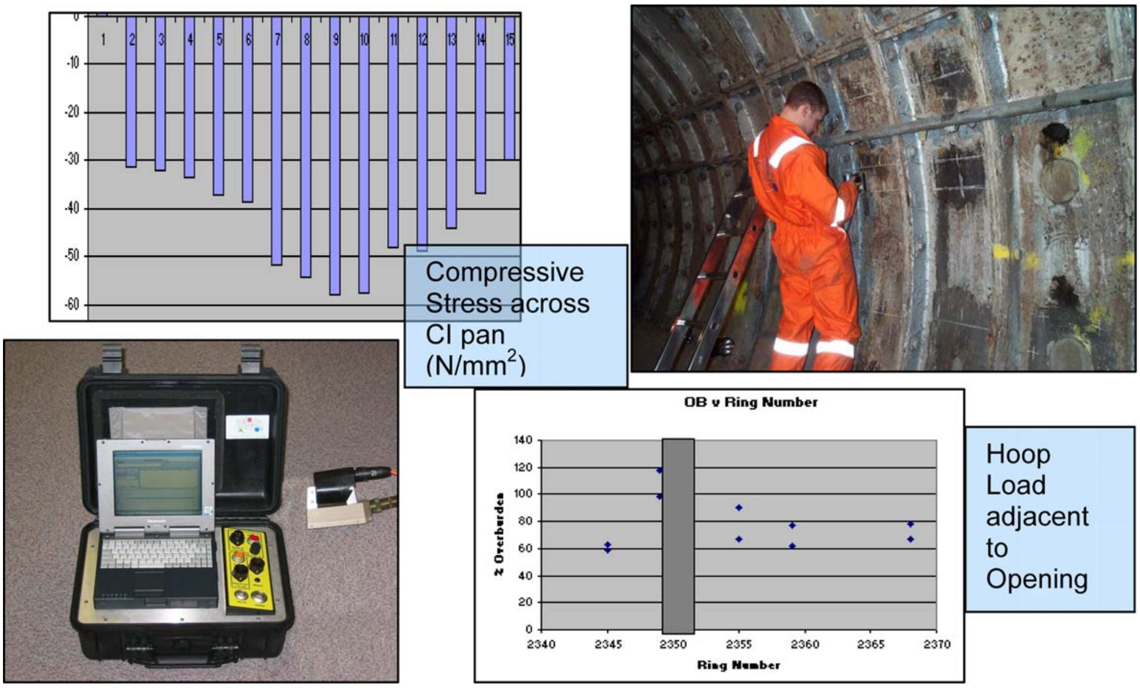

Fig. 27 Stressprobe testing device

after the overcoring is measured, but the variability of the results was such that this work did not have a significant value. Better results were obtained using a probe which can measure changes in the material's magnetic domain behaviour caused by stress. Stressprobe was widely used to determine stresses in plain tunnel and adjacent to tunnel openings, and although some useful results were obtained, a significant amount of further work needs to be carried out to improve this method, particularly where a biaxial stress field exists, in the segment pan, for instance (TSC Inspection Systems 2004). Fig. 27 shows how the stress increases in the centre of the segment pan, as anticipated in the 3D structural analysis, and the figure also shows how the stresses increase in the tunnel adjacent to an opening, shown as a grey area. It is planned to carry out further stress measurement work in the Northern line tunnel under the River Thames, where tidal effects should cause the stress to vary with time, which should help to validate the method.

6. Remediation

Although most tunnels have an assessed capacity ratio greater than 1.0, and are therefore compliant with LU standards, some structures have a capacity ratio less than 1.0, and in these cases the risks to operatives and customers need to be evaluated. Under UK safety law there is a requirement to reduce risk to a level which is as low as reasonably practicable. This has been interpreted in law to mean that safety measures should be undertaken unless the cost in terms of money, time and trouble is grossly disproportionate to the safety benefit which is expressed in terms of the value of the risk averted by the safety measure (London Underground Standard 1-521 Safety

Decision Making 2008).

Clearly if structural capacity ratios are significantly less than 1.0, this represents an increased risk, for which an evaluation of the increased risk can be made, based on the anticipated likelihood and consequences. In some cases, there is visible damage too and this inevitably increases the urgency with which the work needs to be carried out. Almost always some kind of monitoring and emergency control process will be used as mitigation, to ensure that, should the monitoring indicate worsening conditions, trains, customers or employees do not enter the area. Often some form of strengthening may also be economically deployed.

There are over 1,000 openings in tube tunnels on the Tube Lines network, of which a significant proportion have low capacity ratios, seemingly due to the absence of any real design when these were built. While most have not exhibited any physical damage, a small number have. For example, in 2004, the web of a lintel over an opening on the Piccadilly line was found to have buckled and cracked, there was evidence that significant shear distortion of the lintel had occurred and the tunnel linings above the lintel had moved some 30 mm into the tunnel; bright metal indicated that this was a recent failure (Fig. 28). Monitoring, in the form of electrolevel gauges and crack potentiometers was installed, an Emergency Preparedness Plan was put in place to respond directly to mobile phone messages from the monitoring system, and the design of remediation was started. Ultimately propping was installed in the opening, the lintel was stiffened and the cross passage filled with concrete. A similar potential failure on the Northern line has been instrumented in the same way, but as the instruments seem fairly stable over a period of three years or so, although a support structure has been designed, the actual strengthening remediation has not yet been installed.

In fact, although corrosion of cast iron tunnels is generally not a problem it is not unknown for significant corrosion of the extrados of a cast iron tunnel to occur. Near Old Street station the cast iron lining had been attacked by an external acid over the years and by the 1990s the tunnel was severely cracked. A short section of tunnel had to be rebuilt around the existing tunnel in expensive stainless steel.

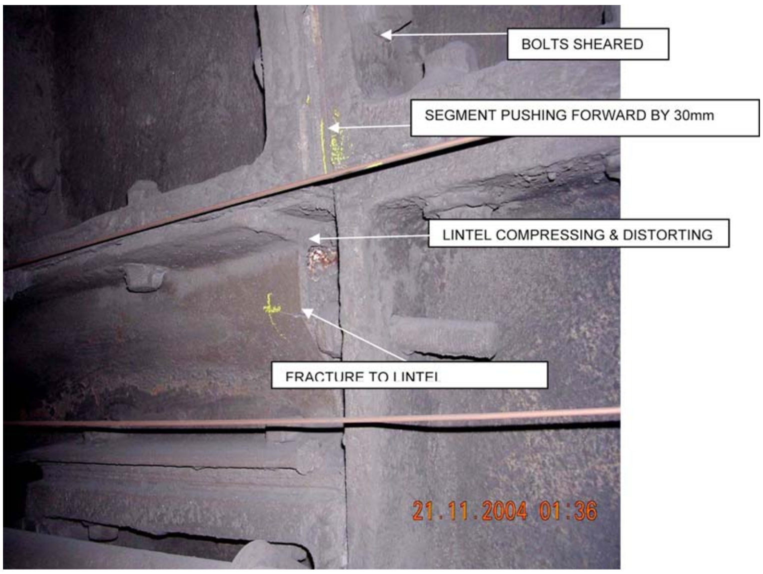

Fig. 28 Lintel partial failure

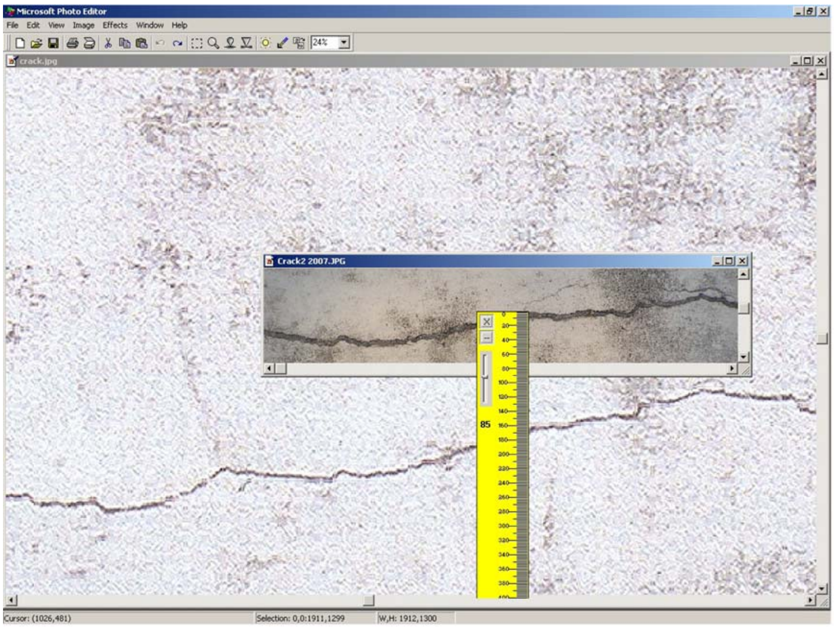

Fig. 29 Crack in crown of sprayed concrete lining 1999 and 2007 (inset)

Fig. 30 Outside party developments over existing tunnels

More recently constructed tunnels can exhibit problems too. In 2007 a section of sprayed concrete tunnel on the JLE was found to have an open crack along the crown. From a comparison of photographs it appeared that this crack had opened over the past four years (Fig. 29). In this case "Cyclops" type optical monitoring was installed to check whether movement was actually occurring; in addition a core was drilled around the crack to determine how deep the crack extended. The investigation concluded that the crack did not indicate any immediate structural instability, despite ongoing limited further opening of the crack, but could be a concern if further surcharge loading was applied to the ground surface in the future. This situation will continue to be monitored.

It is the construction of outside party developments however, that have the greatest impact on existing tube tunnels (Fig. 30), through piling close to tunnels, or the construction of deep basements over or around tube tunnels. In these cases the LU safety case can only be maintained through the installation of a real-time monitoring system during construction of the outside party development. A variety of monitoring types have been used, such as vibrating wire, electrolevels and potentiometers, but the method of choice at present is “Cyclops” type optical monitoring, as it will give direct displacements and distortions in the horizontal and vertical directions.

An area of close scrutiny for Tube Lines is along a 200 metre section of expanded concrete tunnel on the Jubilee line, where limited concrete spalling has been occurring at the radial joints due to high contact stresses, combined with a poor out-of-circular build which occurred as a result of

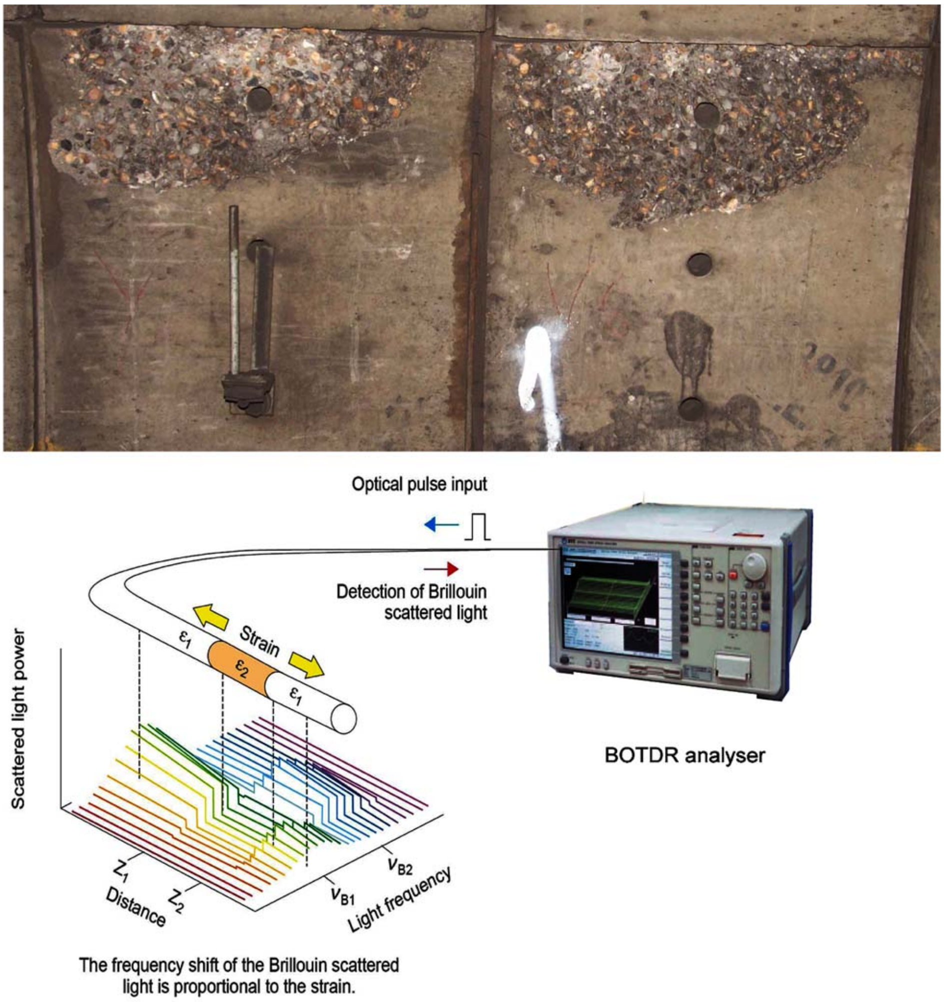

Fig. 31 Concrete lining spalling and BOTDR fibre optic monitoring

difficulties encountered during construction in the mid 1970s. The out-of-circular, or egg-shaped build has resulted in rotations of the 22 segments in the tunnel rings, and as the joint surfaces are slightly convex, this has meant that the contact point at joints has tended to migrate towards the intrados in the crown and the extrados at axis, giving rise to visible spalling towards the shoulders and crown of the tunnel and horizontal mid-segment cracks at axis. Tube Lines has installed vibrating wire instrumentation at joints which have already spalled or, because of the surveyed joint orientations, might be susceptible to spalling (Fig. 31). Furthermore, a trial of the Brillouin Optical Time Distance Reflectometry (BOTDR) fire optic monitoring has been installed (Fig. 30), with a view to extending this to all 360 rings in this section of tunnel, so as to be able to detect movement at any point (Cheung 2008). This instrumentation, as with the vibrating wire instrumentation, is linked to an Emergency Preparedness Plan, so that, should unexpected movement occur trains can be prevented from entering the area. In addition, heavy steel strapping has been designed and installed as a trial, and if further monitored movements occur which are approaching a predetermined critical trigger level, the pre-fabricated strapping can be installed almost immediately. In addition all parties are considering the most cost-effective replacement to this tunnel in the medium term.

7. Future measurement and monitoring requirements

Having now recently completed the tunnel assessment programme and having had some experience with a variety of measurement and monitoring techniques, Tube Lines tunnels team can look forward and outline a “wish-list” for future measurement and monitoring. Some of these wishes may be impractical, but others may be achievable within a reasonable timescale.

7.1 Wireless monitoring of tunnel openings and cracks in segments

In situations where the position of a crack is known, or where it is understood where movement at a joint may occur, a glass tell-tale has traditionally been used. However, with the development of wireless sensor monitoring it is possible to specify some requirements for a wireless “tell-tale”. Ideally the concept would be a device up to the size of a credit card, part of which would be fixed across the crack or joint. In general the instrument would be “dead”, and would only come to life if a predetermined distortion (say 0.5 mm but adjustable) to the joint were to occur. It would then emit a radio signal or have an RFID tag which could be detected by a passing train or equipment carried by passing track inspectors, for example. This device would need to be cheap enough for maybe 1,000 to be installed and the key difference to a conventional wireless network would be that it would use little or no power except when something happens. It would appear that there are two important drawbacks to the existing generation of wireless sensors; firstly low-power wireless nodes have to be closer together than is ideal, and secondly the necessity to keep in contact at predetermined periods uses more power than can be supported by on-board batteries. Energy harvesting may offer a solution to this but it would appear that there are no simple sources of energy in a tube tunnel that can be easily and cheaply extracted.

7.2 Potential developments in electromagnetic stress measurement

Currently Tube Lines has used a non-contacting electromagnetic probe called Stressprobe for in situ stress measurement in cast iron tunnels. In fact the probe is used to measure the stress gradient in the flanges and the actual values of stress in the segment pan. This is sufficient information to enable a fairly complete stress picture to be constructed across and through the section, and for hoop load and bending moment on the segment to be calculated. However, while Stressprobe has been shown to work well in a uniaxial stress field in steel, the interpretation of a biaxial stress field in the segment pan is somewhat more difficult, and the quality of cast iron as well as the possible existence of residual stresses means that there is a lot of variability in the measured results. There is consequently a possibility that further development of this equipment could lead to an improvement of understanding of stresses in metallic tunnels. Tube Lines is currently planning to carry out some further measurements of this kit in a tunnel under the River Thames, where tidal effects will cause changes in the loading on the tunnel.

7.3 Improvements in sensor position measurement

Currently one of the best ways of monitoring tunnel displacement is using automatic total stations and optical prisms, as deflections in all directions can be monitored. Unfortunately in many running tunnels there is insufficient space for a total station. Ideally wireless sensors would be able to locate each other precisely in terms of direction or distance, or both. Currently sensors may be able to locate each other approximately, but perhaps there is a way to do this more accurately, and remove the need for a total station.

7.4 "Transparent" structure

The ultimate goal for non-destructive investigation is surely the ability to "see" what is inside a structure. While that is certainly a long term goal, it would be a huge bonus if it was possible to accurately "see" metallic structures buried in concrete or render. Surely if the mature technology exists to see into the human body, using ultrasound, we ought to be able to distinguish between substances such as steel and concrete, with such markedly different qualities. Currently, however, covermeter technology used by Tube Lines for this purpose is still quite limited.

8. Conclusions

Tube Lines has carried out a knowledge and investigation programme on 200 km of existing deep tube tunnels ranging in age from 10 to 120 years as required by the PPP contract with London Underground. As no such comprehensive assessment programme has been contemplated on tunnel assets in the UK before, an assessment methodology has been developed which is a combination of inventory, inspection, specialist and generic investigation, automated analysis and reporting.

The programme has involved a variety of investigative techniques, both destructive and non-destructive, and a number of high quality analysis techniques, and has been completed to time and under budget, with all reports delivered to the client.

The following general points can be made.

1. As civil infrastructure reaches maturity it is prudent for asset owners to consider putting more resources into assessing their infrastructure in some detail. This will enable them to determine any extra risks associated with factors of safety lower than modern standards due to environmental deterioration

of structural materials, inadequacy of design in the original construction, and changes in loadings.

2. Assessment of deep tube tunnels has enabled Tube Lines to re-evaluate risks associated with deficiencies in asset performance and to mitigate such risks by regular and more focussed inspection, monitoring and repair or rebuild where appropriate.

3. Periodic comprehensive analytical assessments of all elements of civil infrastructure will become a more important part of the whole life asset management of transport networks, in particular.

4. Such assessments will need to analyse all sub-assets using up-to-date methods of analysis. Investigations which consider the loadings and their effects, materials strengths and any changes in the structure or structural behaviour will need to form part of the assessments. These investigations will need to use high quality destructive and non-destructive techniques.

5. There is a need for further development of non-destructive techniques to investigate the competence of existing structures for which construction records may not exist or where actual stresses and material strengths are not known.

6. There is also a need for further development of monitoring techniques and whole life asset management methods which enable assets which may not satisfy modern assessment standards to exist within the operating railway environment without compromising safety.

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