MEASUREMENTS OF GROUND PRESSURE ON SPRAYED CONCRETE TUNNEL LININGS USING RADIAL PRESSURE CELLS

SUMMARY

The paper discusses the importance of tunnel lining stress measurement in the context of an overall tunnelling risk management process, and shows how these measurements may be obtained by using pressure cells. Well-designed and installed radial total pressure cells can provide reasonable estimates of the stresses on sprayed concrete linings if the influences of cell properties, installation effects, temperature changes and crimping are taken into account. Results of stress measurements using radial (earth) pressure cells made over 8 years during and after construction of the Terminal 4 station concourse tunnel (T4) and over 9 months for the Terminal 5 SWOT frontshunt tunnel (T5) are presented. These results are then discussed with reference to previous measurements of stresses on tunnel linings.

INTRODUCTION

Design must be managed through all phases of a project, from conceptual and detailed design, through construction and into operation. During conceptual and detailed design, the emphasis is on prediction. At the same time hazards are identified, risks are assessed and the management procedures to control risk during construction are formulated (1). According to the HSE (2), even with the best predictions, tunnel design calculations are at best semi-empirical and tunnel construction must remain observational. The HSE attributed the semi-empirical nature of design to the limits of current technology and lack of research. This extreme Keynesian view seems unrealistic, since it is hard to envisage a situation in tunnelling where all the variables are known and there is no uncertainty. Therefore, the design predictions must be verified and reviewed during construction as part of an “overall holistic surveillance” (3). This holistic approach to SCL tunnel design, based on risk management, prediction and verification, observation and modification is fundamental to good tunnelling practice and central to the NATM philosophy (4).

In recent years more emphasis has been placed on a ‘fully-engineered’ design, provided by calculation and in particular the use of numerical methods. Prescriptive design (what the HSE calls an empirical design based on precedent practice) has become less common (5). Using prescriptive design, the risks were difficult to assess as the variables controlling the performance were not known (2). Today the importance of prediction, observation and modification within a risk management framework is widely recognised, but the importance of verification may be lost if there is a general expectation in some quarters that designs should be accurate predictions.

For the reasons outlined above, it is necessary to use monitoring during construction to confirm that the design assumptions and predictions are reasonable. However, there is often an inconsistency between the way a tunnel is designed for ultimate limit state stress and the way its safety is monitored during construction by measuring displacements of a tunnel lining (6). It would seem more appropriate to measure stresses in a tunnel lining to verify its performance and to refine design criteria for future tunnelling projects (7). Thus the current dearth of estimates of stress in sprayed concrete tunnel linings impacts negatively on design.

Pressure cells provide a continuous measurement of stress from the moment the lining is sprayed and are therefore ideal for examining the evolution of ground load onto the lining at early age and into the long term. In a soft ground sprayed concrete lined (SCL) tunnel, it is likely that the most critical utilisation is at early age (8). Interpretation is required to remove various factors that influence the recorded stress and this will be described in the paper. Pressure cell readings over 8 years at Terminal 4 station concourse tunnel, and over 9 months at the Terminal 5 SWOT Frontshunt tunnel are then presented and discussed with reference to previous studies of stresses in tunnel linings.

RADIAL PRESSURE CELL DIMENSIONS

The dimensions of the Geokon 4850 series (9) pressure cells used in this study were typical of most pressure cells on the market and are shown in Fig. 1. The cells were 150 x 250mm and 6.3mm thick in total. The oil-filled cavity between the 3mm thick stainless steel plates was 0.3mm thick.

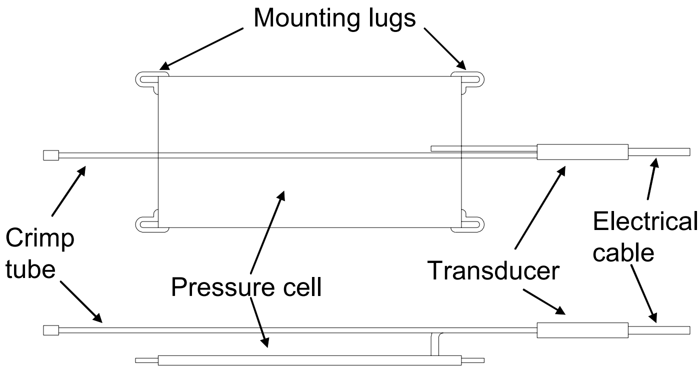


Fig. 1: Geokon 4850 series pressure cells

FACTORS AFFECTING THE PRESSURES RECORDED BY RADIAL PRESSURE CELLS

A commonly-held view is that pressure cells can only be used to measure changes in pressure and cannot reliably give absolute values (10, 11). However, radial pressure cells have been shown to give reliable absolute results (12).

The factors affecting recorded pressures were discussed by Clayton *et al*. (13). These are:

1. Cell properties.
2. Installation effects such as positioning, cavities or rebound accidentally sprayed into the lining.
3. Temperature changes.
4. Crimping.

Crimping involves crushing the crimping tube using a specially-made crimping tool. This forces a fixed amount of fluid into the pressure cell cavity. This is done to ensure that the cell is properly embedded in the sprayed concrete and no loss of contact has occurred during hydration. If good crimping records are kept, the increase in pressure caused by crimping can easily be removed.

This paper will focus on the determination of cell action factor (CAF) and temperature sensitivity. In addition, diagnosis of poorly-installed pressure cells so that they can be removed from the data set is explained.

Cell action factor (CAF)

Cell action factor (CAF) is defined as the ratio of recorded pressure to actual stress in the medium normal to the cell (14). Pressure cells for use on and in sprayed concrete linings are designed so that the stresses in the medium are not significantly modified by their presence, such that the CAF should be close to unity. The cells are made wide and thin, with a low aspect ratio, so that arching and end effects are negligible. It has been often stated that the ideal situation would be to design a pressure cell that has the same stiffness as the medium into which it is embedded (15, 11). But for a medium with a nonlinear response, for example soil, or for a medium with a stiffness that varies with age, for example sprayed concrete, this would be difficult to achieve (16).

Since stress is not a directly measurable physical entity, pressure cells rely on "hard inclusion theory" to measure stress (17). This means that the ratio of pressure cell stiffness to medium stiffness is sufficiently high that variations in the medium stiffness become unimportant. Thus pressure cells are designed so that the CAF is insensitive to the stiffness of the medium. This was shown by Coutinho (18), using an elastic solution for a cylindrical inclusion embedded in an infinite medium to show that as long as the pressure cell has an overall stiffness greater than or equal to the stiffness of the medium, the CAF should be tolerably close to unity. Clayton *et al*. (13) used an axisymmetrical finite element model of a cylindrical pressure cell and then a conservation of volume calculation to take account of the filling liquid compressibility to show that values of CAF would be close to unity for typical values of concrete stiffness and cell dimensions.

A comparison of CAF found in previous studies is shown in Table 1. According to Glötzl (19), a typical oil-filled pressure cell with a 0.3mm thickness of filling liquid will have an equivalent Young's modulus of 50 GPa. This is higher than the secant modulus of most concretes. For all the theoretical models quoted in Table 1, except the numerical analysis by Woodford & Skipp (20), which was a parametric study, the Young's modulus of the concrete was taken as 30 GPa.

Experiment / Model		**CAF**
Load test of Glötzl radial cell at concrete-clay interface (20)		0.96
Air pressure calibration of Geokon radial cell (15)		1.0
Load test of 2 Geokon radial cells at sprayed concrete-clay interface (15)		>0.95
Load test of ready-mix concrete panel with 2 embedded Geokon tangential pressure cells (15)		0.87-0.99
Load test of sprayed concrete panel with 2 embedded Geokon tangential pressure cells (13)		1.08
Axisymmetric elastic FE analysis of Glötzl radial cell at concrete-clay interface (20)		0.78-1.18
Axisymmetric FE model of an embedded Geokon tangential cell (13)		0.95
Axisymmetric elastic solution (18)	Equivalent cell stiffness Ec = 50 GPa	1.01
	Ec = 20 GPa	0.99
	Ec = 10 GPa	0.95

Table 1: Experimental and theoretical values of cell action factor

The values of CAF in Table 1 suggest that the CAF of the pressure cells used in this study were tolerably close to unity. The large range of CAF values Woodford & Skipp (20) found in their numerical analysis was due to the unrealistic limiting values of Young's modulus they used in the parametric study.

Temperature sensitivity

As well as the sensitivity of the vibrating wire transducer to temperature change, which can easily be removed using the manufacturer's calibration, there is also the temperature sensitivity of the cell-medium system to consider. Unless the coefficient of thermal expansion of the cell fluid, cell casing and medium are all exactly the same, and the temperatures experienced by them are the same, pressure changes will be induced in the cell fluid by differential volume changes in the system.

Results from a sprayed concrete test panel from the T5 works containing tangential pressure cells (21) demonstrated that the tangential pressure cells were in fact very sensitive to very small changes in stress or temperature, and that consideration of temperature sensitivity could remove the apparent scatter in the data previously attributed to instability or inaccuracy. This improved confidence in the reliability of pressure cells.

Numerical modelling of an unrestrained sprayed concrete test panel has shown that temperature sensitivity of tangential cells is due to the concrete around the cell restraining the expansion of the stainless steel cell casing, and thus reducing the cavity volume and increasing the pressure of the cell fluid (22). Therefore, for tangential pressure cells, arching restraint is the dominant mechanism that causes temperature sensitivity and this needs to be removed from the data in order to obtain meaningful results.

For a radial cell at the interface between the sprayed concrete and the ground, arching restraint around the cell is likely to be much less important. However, as the temperature varies inside the tunnel and is likely to be relatively constant in the ground, the whole ring of sprayed concrete will expand and contract, increasing and decreasing the pressure measured by the radial cell at the sprayed concrete – soil interface.

Since the variation of radial pressure due to temperature changes represents a real pressure experienced by the lining it should not be removed from the data if absolute values are required. However, if it is desired to know whether the pressure exerted by the ground on the lining is changing over time, then the influence of temperature on the results needs to be accounted for.

RADIAL PRESSURE CELLS AT T5

20 oil-filled pressure cells were placed in 2 arrays in the Storm Water Outfall Tunnel (SWOT) frontshunt tunnel at Heathrow Terminal 5 (T5). The tunnel was a 40m long, 4.8m external diameter straight SCL tunnel from which a tunnel boring machine could be launched for the main drive. The tunnel begins from a shaft at 11.8m depth to the tunnel axis. The general layout of the tunnel and the positions of the pressure cell arrays are shown in Fig. 2.

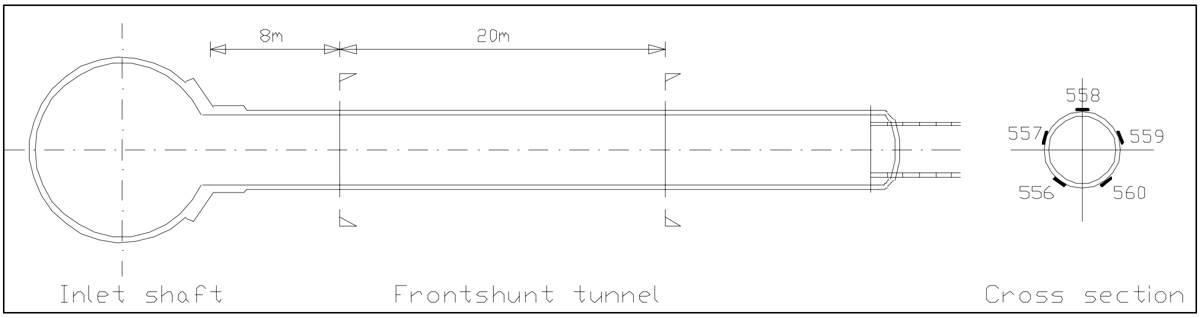


Fig. 2: Plan and cross-section of T5 pressure cell locations.

The tunnel is entirely within the London Clay, with approximately 5.5m clay cover from the tunnel crown to the overlying Terrace Gravels. Array 1 was positioned 8m along the tunnel and array 2 was positioned 20m further down. Each array consisted of 5 radial cells and 5 tangential cells.

A detailed description of the Lasershell™ excavation and support method can be found in Williams *et al*. (23).

INTERPRETATION

The value of temperature sensitivity may be estimated by taking several readings over a time period short enough that the effects of loading change may be ignored. All the radial pressure cells in array 1 had zero temperature sensitivity because they were reading zero pressure, i.e. there was not a good contact between the cell and the ground or lining. It is thought the method of installation was a major factor in this. Array 1 was installed by spraying the 75mm sealing layer, then chiselling out windows in which the cells were installed. It is thought this may have disturbed the clay locally. This was revised for array 2, where box-outs were used, as shown in Fig. 3, with much better results.

Fig. 3: Installation of radial and tangential pressure cells within a box-out of the sealing layer.

The temperature sensitivity of the radial cells was estimated from the most recent data for each cell, when stress changes over the associated time period due to other factors were likely to be insignificant. The temperature sensitivity thus found was then assumed to be constant for all readings. Values of temperature sensitivity were typically between 6-7 kPa/°C. As mentioned previously, the temperature sensitivity adjustment is used to show if the ground load onto the lining is changing with time when readings are taken at different temperatures, but pressure induced by temperature is an important part of the absolute pressure and should not be removed if the value of absolute pressure is what is required.

Recorded pressures unadjusted for crimping are shown in Fig. 4 and these same pressures adjusted for temperature sensitivity are shown in Fig. 5. The temperature read by the thermistor attached to cell 557 is also shown in Fig. 4 to illustrate the dependence of the recorded pressures on the temperature. Before installation, the pressure is unaffected by temperature changes as expected. The cells did not become sensitive to temperature until after spraying.

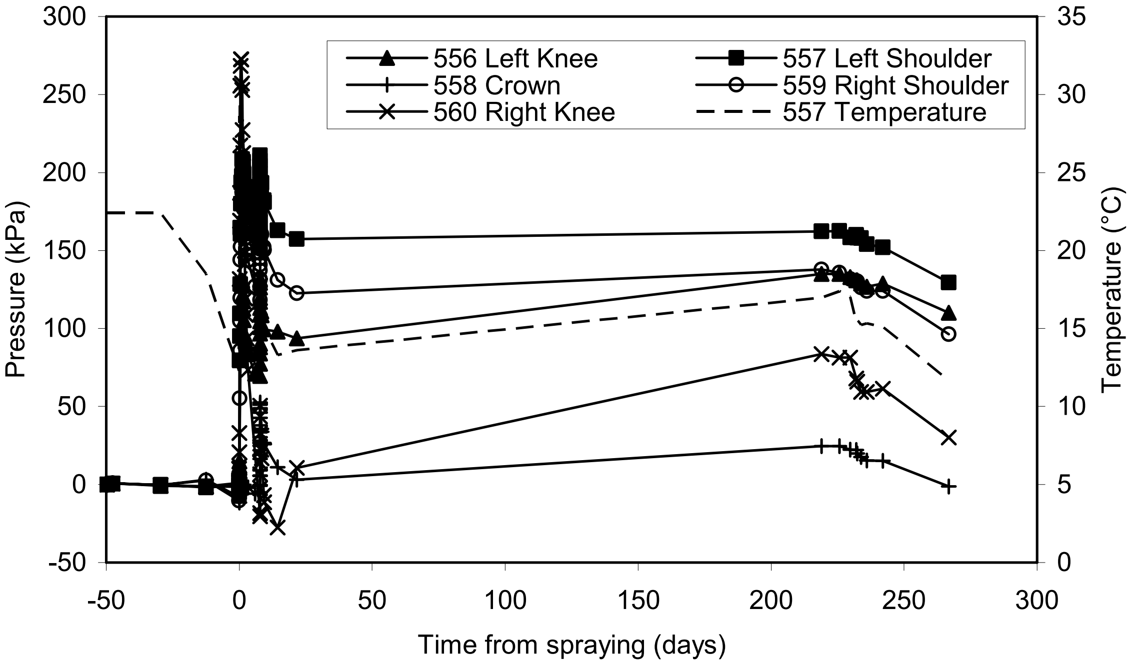


Fig. 4: Recorded pressures in T5 array 2 radial cells

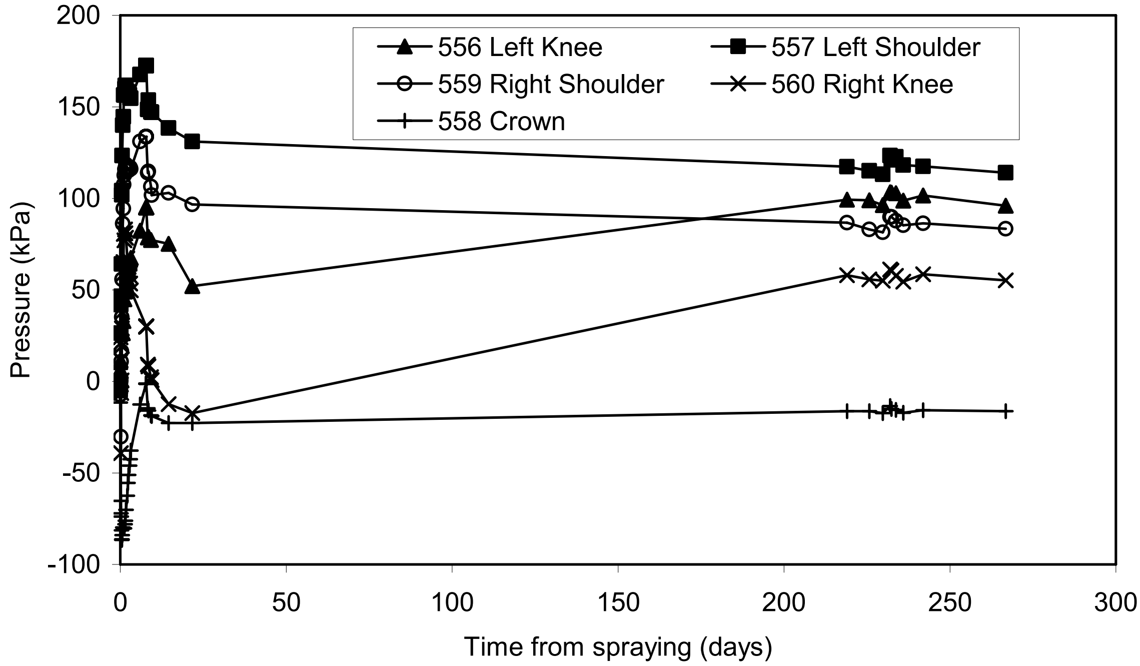


Fig. 5: Adjusted pressures in T5 array 2 radial cells.

Although the estimates of temperature sensitivity were based on the readings taken in the long-term, they seem to be underestimated in the short-term where peaks due to the heat of hydration are still discernible. An explanation is that this is due to the large temperature gradients across the section during hydration. It is the average temperature across the section that determines the magnitude of ring expansion, and this is likely to be higher than the temperature measured at the extrados by the thermistor attached to the radial cell. Another explanation could be that the coefficient of thermal expansion at early age is higher than for mature concrete (24). The pressures began to stabilise once most of the hydration heat had dissipated, which took 3-4 days.

The crown radial cell may not have been crimped enough, since the recorded pressures in Fig. 4 are close to zero. Pressure cells cease to read changes in pressure below zero and a gap forms between the cell and the surrounding medium. Therefore these data from crown cell 508 cannot be trusted. To avoid this eventuality, crimping can be used to artificially raise the pressure by a known amount, which can later be deducted from the recorded pressure. The recorded pressure in right knee cell 560 similarly drops below zero after crimping. Although it later recovers to a positive value it may have missed some important pressure changes and the absolute value of pressure may not be reliable.

Concentrating on the change in pressure with time, the data in Fig. 5 show that although the pressures at the shoulders remain fairly constant with time and even decrease slightly, the pressure at the knee positions begins at a lower value and increases with time until they approach similar values.

The middle period of just over 6 months when no readings were taken was during the TBM drive. The junction box from which readings could be taken was rendered inaccessible until the drive was finished and the conveyor dismantled, meaning that a lot of potential detail was lost. This could have been remedied by the use of a datalogger with a storage module or computer link.

RADIAL PRESSURE CELLS AT T4

The T4 station concourse tunnel was constructed using a top heading - bench - invert excavation sequence, unlike the T5 SWOT frontshunt tunnel, which was excavated full-face with immediate ring closure. The T4 concourse tunnel was 64m long with a non-circular cross-section of 49m^2 area (more than twice the area of the T5 SWOT frontshunt), at a depth to axis of 17.2m. Primary support was provided by 350mm of sprayed concrete reinforced with two layers of steel mesh. Closure of the invert typically took 2-3 days and was within 5m of the face. Details of construction sequences, advance lengths and construction cycle timings can be found in van der Berg *et al*. (25). Pressure cells were installed at two monitoring sections, MMSI and MMSVIII. In each array there were 12 radial cells and 12 tangential cells.

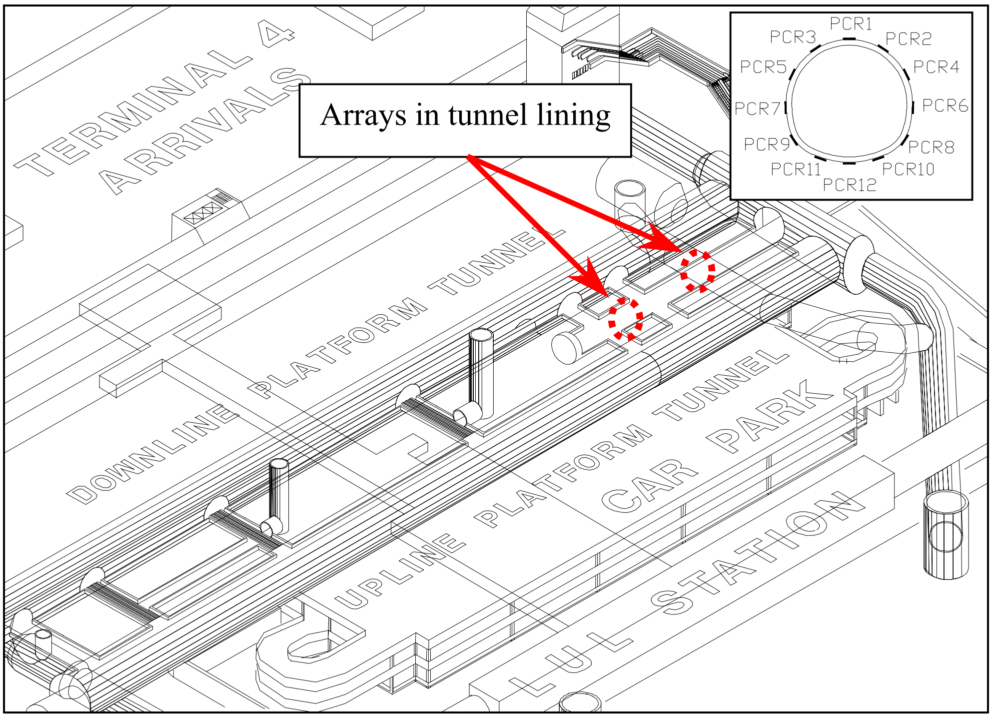
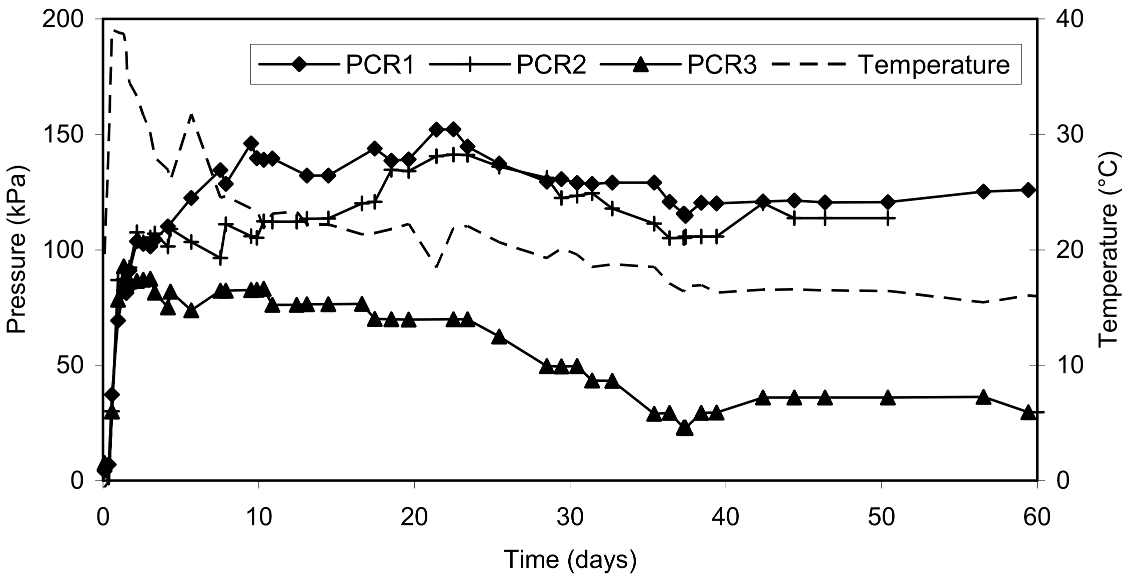
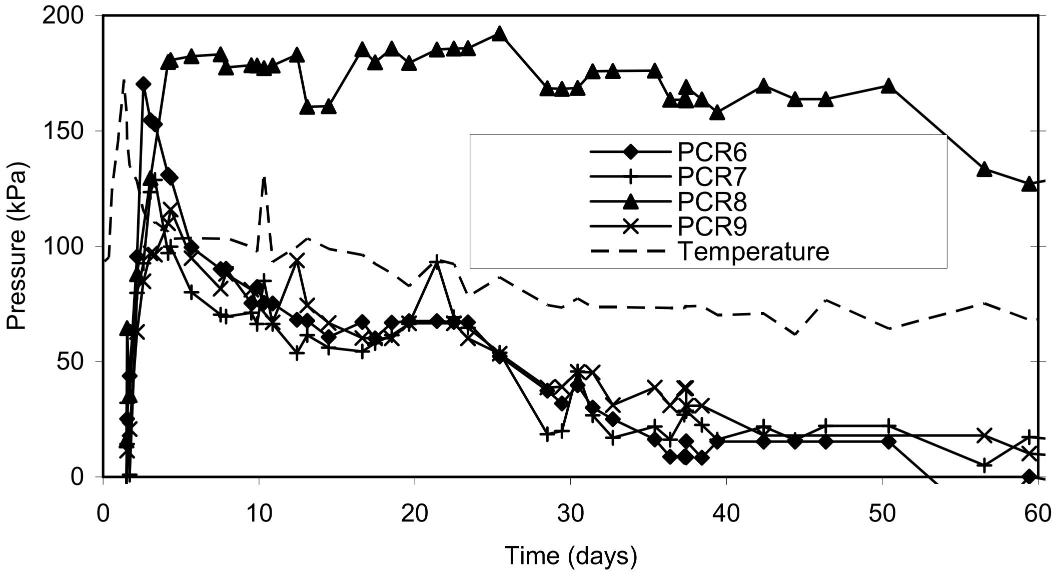


Fig. 6: Isometric view and cross-section of Terminal 4 Station pressure cell locations

On inspection of the recorded pressures, unlike the T5 radial cells, no peak was discernible due to hydration heat. This indicated that temperature sensitivity of radial cells may be dependent on ring closure, verifying the hypothesis that the dominant mechanism in temperature sensitivity of radial cells is the expansion and contraction of the completed ring against the ground. The first 60 days after installation of MMSI are shown in Fig. 7.





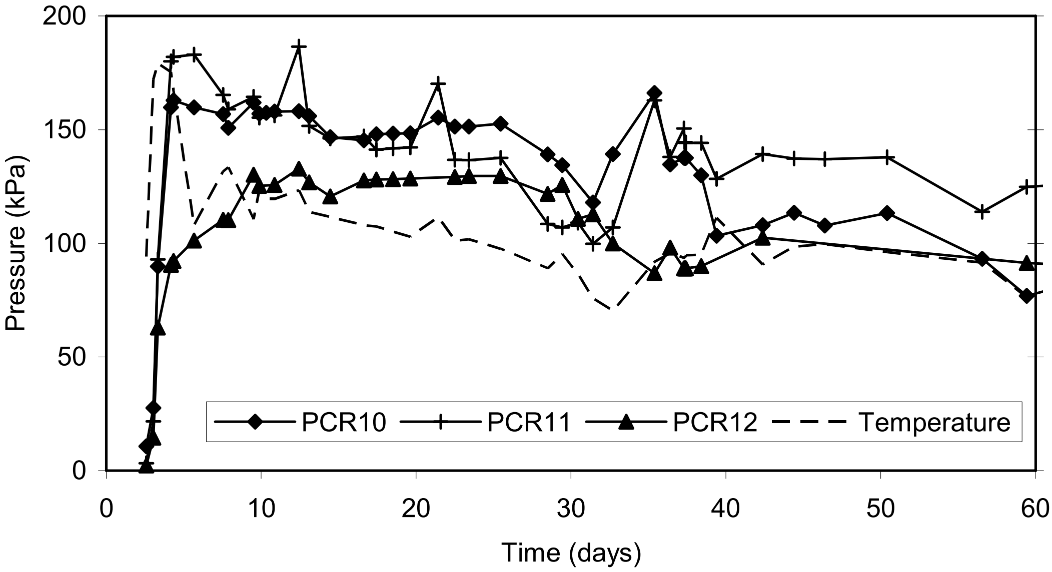


Fig. 7: Recorded pressures on the (a) top heading, (b) bench, and (c) invert at MMSI, T4

In Fig. 7(b), 3 of the 4 bench radial cells show a dramatic decline in pressure over the first 25-30 days. This only occurred at MMSI and so is not a function of the construction sequence, which was the same at MMSVIII. It can only be caused by the underpassing of the downline vent tunnel (Fig. 6).

Readings have also been taken up to the present time; that is over approximately 8 years since construction. The results of all the radial cells in MMSI that survived past the construction period are shown in Fig. 8. The temperature measured by the thermistor attached to PCR7 is also shown. The long-term variations in pressure from 3 months onwards appear to be mainly due to temperature.

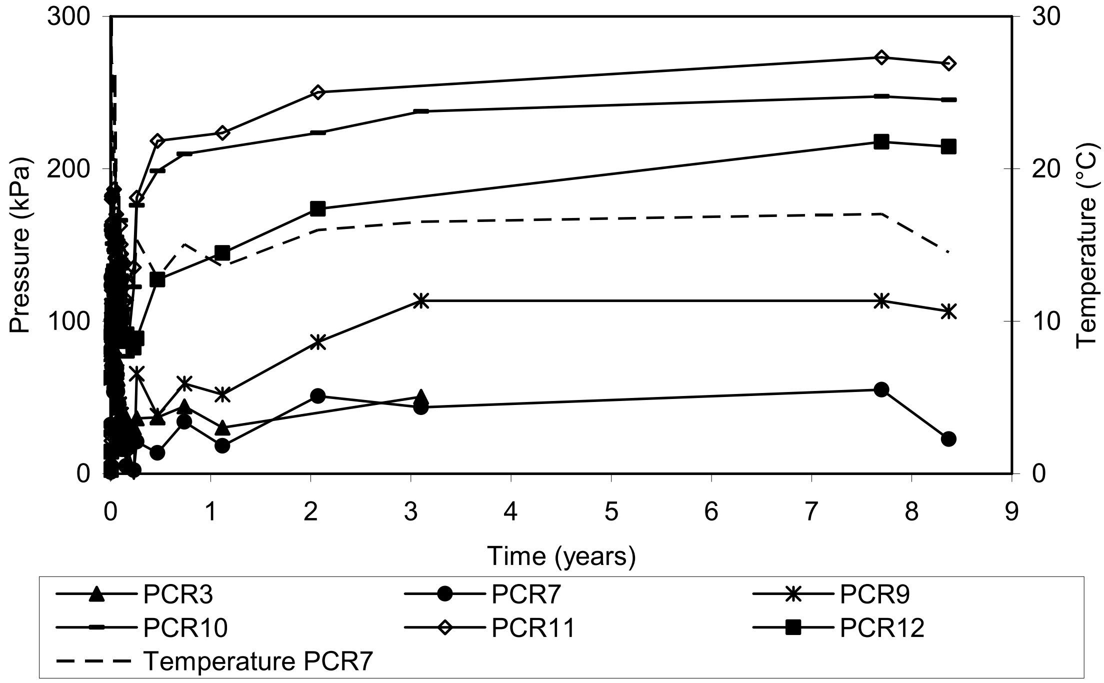


Fig. 8: 8 years of recorded pressures at T4 MMSI

The radial pressure cells in MMSVIII are shown in Fig. 9. These radial cells had a much better survival rate, with all 12 still functioning.

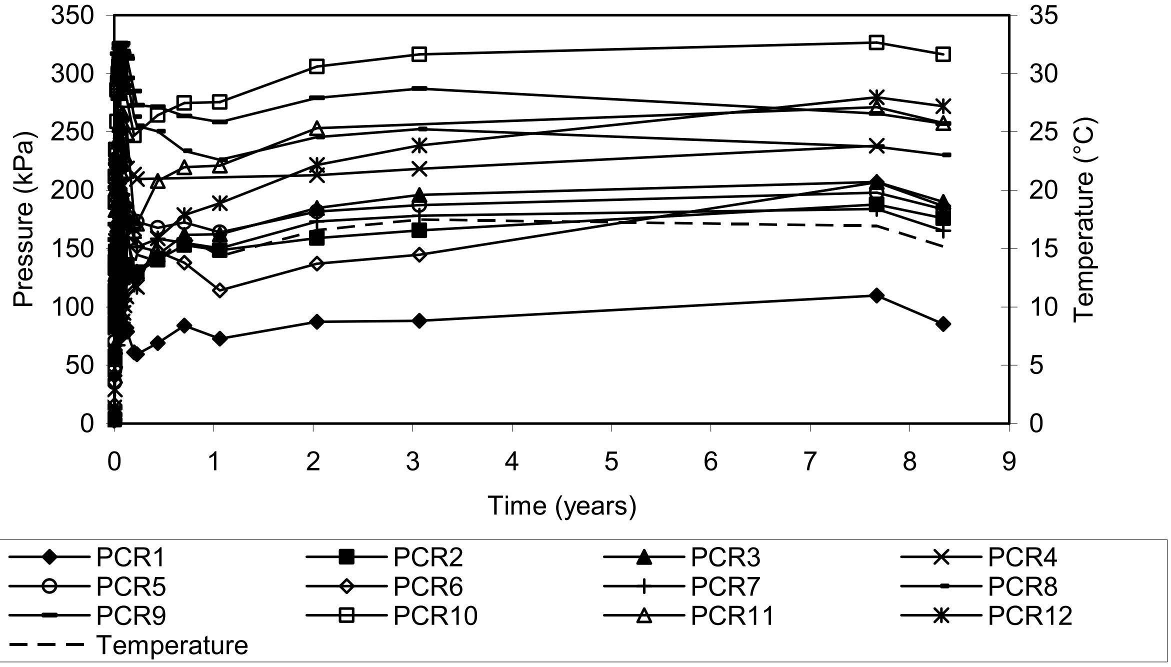


Fig. 9: 8 years of recorded pressures at T4 MMSVIII

DISCUSSION

The radial ground pressures shown relative to the undisturbed *in situ* stress state prior to construction, measured at 2 weeks, 3 months and 8 years are presented in Fig. 10, Fig. 11 and Fig. 12. These figures are unadjusted for temperature sensitivity but have been adjusted for crimping. The temperature at 3 months and 8 years was approximately the same, but at 2 weeks it was approximately 5°C higher on average. Concentrating on Fig. 11, which has the most complete data set, there is very little change in pressure with time, except at the invert where there is a substantial change over the long-term. This is also evident in Fig. 10 and Fig. 12. This is because the greatest degree of unloading occurs at the invert during construction (43), resulting in high negative excess pore pressures. With time these excess pore pressures dissipate, causing the clay to swell.

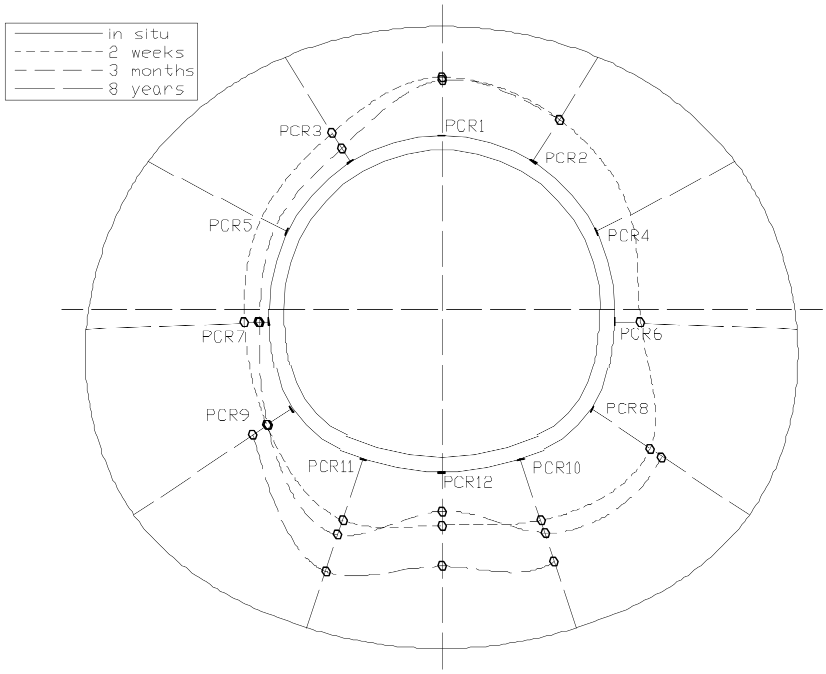


Fig. 10: Radial pressures at MMSI at 2 weeks, 3 months and 8 years

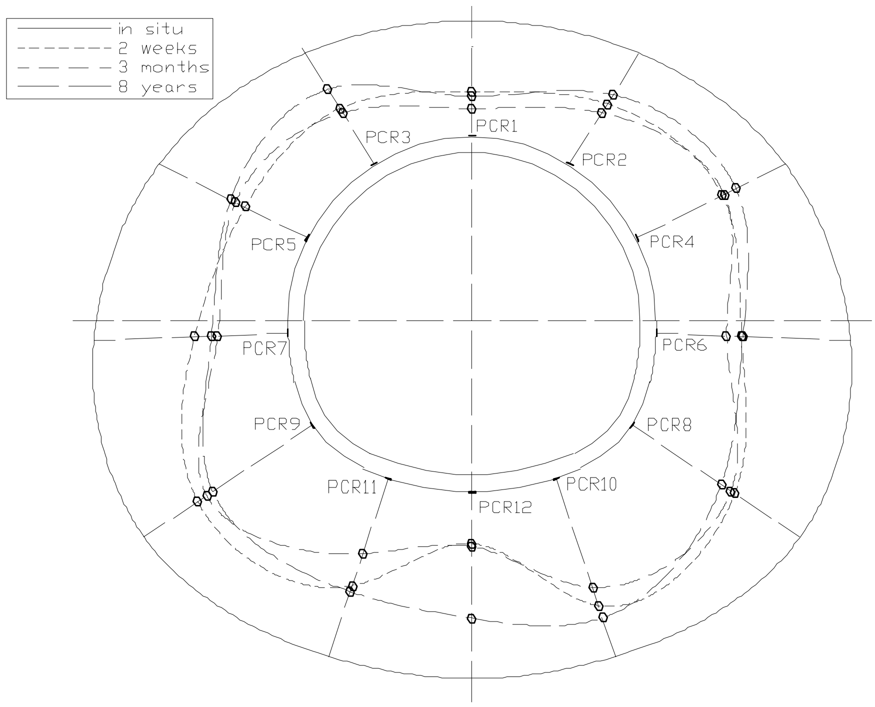


Fig. 11: Radial pressures at MMSVIII at 2 weeks, 3 months and 8 years

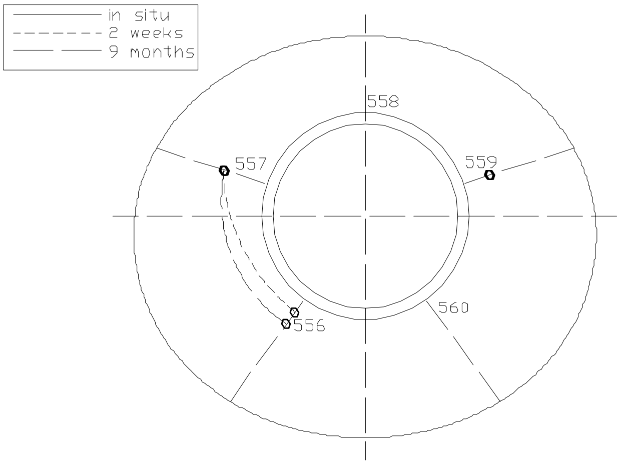


Fig. 12: Radial pressures at T5 Array 2 at 2 weeks and 9 months

Expressed as a percentage of the undisturbed *in situ* stress, the mean of the MMSVIII radial cells after 3 months, when adjacent construction work had ceased, was 48% and at 8 years was 57% with a standard deviation of 13% in both cases. This variation is of a similar order to the ± 25% reported by Belshaw & Palmer (26) for radial cells behind the segmental concrete lining of the Thunder Bay tunnel, but much less than the standard deviation of 250 kPa about a mean of 250 kPa found at 3 months after construction by Bonapace (27) for radial cells installed in the sprayed concrete tunnels of the Jubilee Line Extension.

The T5 data adjusted for temperature sensitivity (Fig. 5) show that most of the load came onto the lining in the first 2 days. Once temperature gradients across the section set up by the hydration heat had equalised, the pressures in the shoulder radial cells barely changed at all from then on. However, the radial pressure measured by the cells at knee level showed an increase with time. The maximum pressure in all the T5 radial cells was measured when the temperature peaked during hydration.

At T4, because the construction method was different, the load came onto the lining more slowly, with closure of the invert being the controlling factor. Once the invert was closed, the pressures stabilised within about 36 hours. For the next 3 months, pressures changed, and this could be attributed to adjacent ongoing construction works as well as temperature changes. Therefore, it appears that the ground pressure did not increase in the long-term for either of the two different construction methods employed at T4 and T5, except around the invert of the tunnel.

This was not found by Bonapace (27), where radial stresses increased from a mean of 250 kPa at 3 months to 350 kPa at 12 months. Barratt *et al*. (28) found considerably larger increases in load over time in the Jubilee Line at Regent's Park; in 19.5 years the load increased by approximately 2 to 3 times the load at 2 days, the majority of this load increase occurring in the first 3-4 years. They found similar increases in load in an Oxford Sewer in overconsolidated clay. In contrast, long-term stress measurements in the Heathrow Cargo tunnel in London Clay by Muir Wood (29) over 600 days showed a less than 10% increase in load after the first 2 days. Similar measurements in an instrumented ring by Bowers & Redgers (30) over 100 days showed a less than 30% increase in load.

Ward & Chaplin (31) and Ward & Thomas (32) came to the conclusion that a lining would eventually carry the full overburden pressure acting hydrostatically, based on measurements of stress in existing cast iron and concrete segmental linings 50 or more years after construction. Previously, Skempton (33) had measured full overburden pressure acting on a tunnel in stiff fissured clay only a fortnight after construction. However, few measurements, if any, since that time have shown more than 70% overburden acting on a tunnel, even after several years (e.g. 26, 27, 28, 29, 30).

Field studies and finite element analyses by O'Reilly *et al*. (34) showed that if the tunnel lining is more permeable than the soil, then it will act as a drain, increasing consolidation settlement. Since the permeability of London Clay is typically 10^{-10} to 10^{-11} m/s, many tunnels in London Clay, even once grouted, have been assumed to act as drains (35). Gourvenec *et al*. (36) measured pore pressures around a cast iron tunnel (part of the Northern Line built in 1924) in London Clay. They found that only slight seepage was occurring, and only very locally; pore water pressures corresponding to the far field were reached within 1.5m from the tunnel. Therefore, when a high-quality sprayed concrete is used which has a very low permeability of less than 10^{-12} m/s, and particular attention is paid to the integrity of the joints, then the tunnel is unlikely to act as a drain in London Clay.

It is often assumed that a lining acting as a drain will attract less load because the pore pressure is reduced. However, Atkinson & Mair (37) showed by a simple calculation involving seepage stresses that the loads acting on a lining are the same whether the lining acts as a drain or is impermeable, as long as the water table is unaffected by the seepage flows and the flow net is approximately radial. A further condition (see also (38)) is that the strains after installation of the lining are small.

Mair & Taylor (39) reported that in open face tunnelling, (which includes conventional sprayed concrete tunnelling without compressed air), where there is significant unloading of the ground, the magnitude and distribution of excess pore pressures depend on the degree of unloading and the strength and stress history of the clay. In the case of overconsolidated clays such as London Clay, excess pore pressures are nearly always negative, e.g. (40), (41), (42). In this case, swelling rather than consolidation would be expected, resulting in no discernible post-construction surface settlements.

However, around the tunnel, swelling caused by the dissipation of negative excess pore pressures can increase the pressure on the lining. 3D numerical modelling of the T4 concourse tunnel by Thomas (43) indicated that post-construction negative excess pore pressures were higher in the vicinity of the invert. Pore pressures at the axis and crown became negative during excavation but were to a large extent reversed at these locations as the face advanced past the section in question and load was thrown back onto the new lining. This fits the pattern of total pressure changes over the long-term measured by the radial pressure cells in this study.

Sprayed concrete lined tunnels in London Clay such as those at T4 and T5 typically have a volume loss of approximately 1.0% (44), whereas older tunnels with bolted cast iron or concrete wedgeblock linings such as those investigated by Skempton (33), Barratt *et al*. (28) and Ward & Thomas (32) may have had a volume loss considerably higher than this of at least 1.5% and possibly as much as 3.0% or more (45). The Heathrow Cargo Tunnel, which had very little increase in load with time, was constructed with an unusually high degree of face support and had a volume loss of only 0.2% (45). Similarly, the sprayed concrete tunnels in this study had volume losses of less than 1.0%. Therefore, there appears to be a link between the volume loss and the length of time that ground load continues to increase post-construction. Since undrained behaviour is immediate, for open-face tunnelling without face support in overconsolidated clay the magnitude and extent of negative excess pore pressures can only be controlled by limiting the span of unsupported ground. This can be achieved by closing the invert as close to the face as possible. Contrary to the tunnelling philosophy (in highly-stressed rock for example) that allowing the ground to deform will reduce the load acting on the lining, it seems that for tunnels in overconsolidated clay, delaying the installation of support, although sometimes resulting in a reduced load in the short term as shown by Negro *et al*. (46), could in fact increase the load acting on the tunnel lining in the long-term.

CONCLUSIONS

Radial pressure cells can be used successfully to measure stresses acting on the sprayed concrete lining. No other method of stress measurement will give the continuity of readings and the accuracy required for design verification. Although the installation of pressure cells does cause a delay to tunnelling progress, once they are installed they can be read remotely without further disruption. In order to achieve the same level of detail of the load development curve using a back-calculation of convergence monitoring would require a high frequency and high accuracy of readings in the first 2-3 days and could potentially obstruct work even more.

It is recommended that care is taken in the installation of radial pressure cells, and in particular the amount of disturbance of the soil should be minimised. The quality of installation can be assessed by consideration of the slope of the crimping curve or the value of temperature sensitivity. Fluctuations in recorded pressures are not an indication of unreliability and can usually be attributed to temperature variations, adjacent construction and other events such as compensation grouting. Once construction ceased, the readings were very stable.

Radial pressure cell readings over 8 years at the Terminal 4 station concourse tunnel and over 9 months at the Terminal 5 SWOT frontshunt tunnel generally showed very little increase in load in the long-term once hydration heat had dissipated, except around the invert.

The distribution of negative excess pore pressures caused by unloading during construction can explain the disparity between previous studies, some of which show very little increase in load in the long-term and some of which show quite considerable increases in load in the long-term. Estimates of volume losses for these tunnels would seem to support this theory, and leads to the conclusion that there is no benefit to be gained by allowing the ground to deform.

The principle of strictly controlling deformations in soft ground tunnelling is not new, and Peck argued that since the amount of deformation at which the strength of the ground has yet to be mobilised had not been found in tunnelling, deformations should be kept to a minimum (47). This view is still held today, for example in the recent BTS Tunnel Lining Design Guide (48), and the data presented in this paper unequivocally supports it. The best way to minimise deformations in a sprayed concrete lined tunnel is to close the invert as close to the face as possible. It is not necessary to allow deformation to occur to encourage ‘arching’ of the ground and thereby reduce the load on the tunnel. In soft ground, this approach will only lead to larger deformations, potentially higher long-term loads and higher risk of failure or damage to surface structures during construction.

The measurement of stress should be an integral part of a holistic risk management process for sprayed concrete tunnelling. It provides valuable information to complement the deformation measurements and provide a full picture of the ground and sprayed concrete lining behaviour. It also provides valuable information about the development of load both in the short-term and long-term that will inform the design of future tunnels.

Notation and abbreviations

CAF	Cell Action Factor
E_c	Equivalent Young’s modulus of the cell
E_m	Young’s modulus of the medium
HSE	Health and Safety Executive
NATM	New Austrian Tunnelling Method
T4	Terminal 4 Station Concourse Tunnel
T5	Terminal 5 Storm Water Outfall Tunnel Frontshunt

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