John Burland's Deep-Excavation- and Tunnelling-Related Research and Industry Involvement

J. R. Standing[1]
[1]*Department of Civil and Environmental Engineering, Imperial College, London, UK*
E-mail: j.standing@imperial.ac.uk

ABSTRACT: During the time that Professor John Burland was an expert witness for the Parliamentary hearings for the Jubilee Line Extension Project (JLEP), he realised that although tunnels had been constructed in London for more than a century, there were very few well documented case studies describing the response of buildings to tunnelling-induced settlement. Professor Burland had extensive knowledge of the effects of ground movement on buildings, having studied and published his seminal work with Professor Peter Wroth in the 1970s which he with others developed into a staged process for assessing potential structural damage from excavation-induced ground movements. Construction of the JLEP provided an ideal opportunity to compile a set of exemplary case studies (involving different structural forms, foundation types, tunnelling methods and geological conditions) and he harnessed this to its full extent. At the start, a number of 'gaps in knowledge' were identified and these were addressed over the following years of monitoring and data analysis. The research culminated in a two-volume book that is still widely referenced almost twenty years later.

In this paper a background to Professor Burland's tunnelling- and deep-excavation-related research is given and the gaps in knowledge are summarised along with how they were answered through the JLEP research findings. They are reinforced with other more recent tunnelling projects in London that he has been involved with, in particular the Crossrail project, thus furthering the understanding of ground and structural response to tunnelling, benefitting both industry and academia.

KEYWORDS: Deep excavations, Tunnels, Field monitoring

1. BACKGROUND

In many Civil Engineering situations, of which Geotechnical Engineering and Structural Engineering form sub-disciplines, there are often two primary considerations: (i) is the level of stability acceptable; and (ii) what are the resulting displacements. Both considerations need careful assessment when planning urban tunnelling projects. Engineers' understanding of stability is far more advanced than their ability to predict displacements. Historically methods of analysis for both have been developed based on observations: almost all engineering 'theory' initiates from observations. If the observations were made in a rigorous manner and well recorded, they will stand the test of time, while theories are frequently superseded.

For tunnelling in the urban environment both considerations are essential, but it is the prediction of displacements that is particularly challenging, even for the 'greenfield' case where there are no overlying structures present. Once there are structures present, predictions become far more difficult because of uncertainties in interaction and structural stiffness effects. In order to start developing prediction and analysis approaches, engineers working on the ground and structural response to tunnelling need to have a sound knowledge of both geotechnical and structural engineering. Often engineers working in the two camps do not communicate well. The interaction between the two groups has been one of John Burland's focal points during his career, very well summed up in papers that he wrote following the lecture he gave to mark his being awarded the Gold Medal (1997) of the Institution of Structural Engineers (Burland, 2004 and 2006).

Monitoring ground response to engineering works, particularly relating to stress relief (e.g. with deep excavations and tunnelling) have been one of John Burland's key research activities and one that has led to some major key findings. While at the Building Research Establishment (BRE: 1966 to 1980) he was involved with monitoring the response of Oxford Clay to deep excavations (29-m deep) within a brick pit (Burland et al. 1977; Burland et al. 1978) (see Figure 1). New instruments were developed for this study, in particular to measure horizontal and vertical surface and subsurface displacements (Burland et al. 1972; Burland and Moore, 1973). The findings provided detailed insight into the displacement and subsequent failure mechanisms that took place. Lessons from the application of these instruments and systems were used 20 and 40 years later for the instrumentation installed at two greenfield sites set up for the JLE and Crossrail research projects respectively.

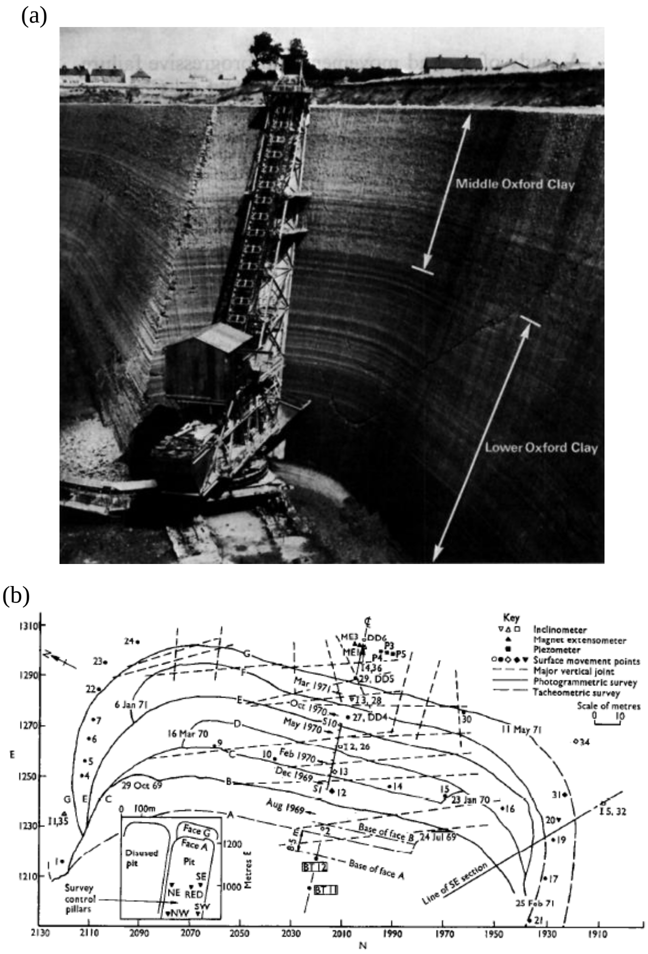

Figure 1 Saxon brick pit: (a) view of East face; (b) plan showing successive excavation stages and instrumentation layout (Burland et al. 1977)

Another deep excavation case study, that John Burland worked on while he was at Ove Arup and Partners, relates to the ground and retaining wall monitoring performed during the excavation for the basement of Britannic House in London Clay (Cole and Burland, 1972; Burland et al. 1979). As part of this project a steel casing was installed alongside the diaphragm wall where lateral displacements from the 'bottom-up' excavation in front of the wall were expected to be the greatest (Figure 2). Openings were cut into the casing at strategic levels to allow accurate measurements to be made between the wall and a plumb-line, accessed by a ladder running down the inside of the casing. In this way correlations could be made between the depth of excavation and the wall and ground displacements. The findings from these site observations were of great value as they led to the understanding that soil stiffness measured (at that time) in the laboratory over the small strain range far under-estimated those deduced from back-analysis of field monitoring data. This led to new developments in the local measurement of strain in laboratory soil testing and the more appropriate modelling of soil stress-strain relationships.

Figure 2 Photograph (taken August 1963) showing basement construction of Britannic House with strutting: observation casing and access scaffolding visible on left (Cole and Burland, 1972).

The findings and experience gained from both case studies were implemented for the design and analysis and monitoring of the Palace of Westminster for the construction of the House of Commons (New Palace Yard) car park where it was vitally important to safeguard the adjacent national heritage structures. At this time the importance of using a 'top-down' construction process for projects with deep basements was starting to be appreciated and again was confirmed through the detailed monitoring that took place. The car park construction involved installation of a diaphragm wall box and king piles prior to excavation which took place in stages beneath successive floors which were cast as each appropriate level was reached (Burland and Hancock, 1977). Predictions of ground and structural movements were made in advance and checked subsequently at specific stages using the monitoring data. The initial predictions were made (Ward and Burland, 1973) based on the back-analysis model used for Britannic House with a linear stress-strain soil response. Differences between the predictions and the field observations led to the realisation that a non-linear relationship was necessary (Burland et al. 1979). Both the measurement of small strains and the use of non-linear stress-strain relationships are now common practice in modern geotechnical engineering.

In the above case studies, great care was given to the detailed geotechnical description and characterisation of the soils encountered: the Oxford Clay and London Clay. At the clay pit, observations could be readily made, and samples taken. At the Palace of Westminster, in addition to conventional ground investigation boreholes a shaft was sunk from which John Burland compiled a detailed log of the stratigraphy. During the observations for the latter, particular note was made of a horizon within the London Clay where water-bearing silt and sand seams were present. In view of the potential risks they posed, the diaphragm walls and the under-reams for the king piles were extended to well below this horizon (refer to Figure 3). Similar use was made of this observation when designing the foundations of the nearby QEII conference centre (Burland and Kalra, 1986). These careful observations were referred to again when assessing the reasons for large volume losses in Westminster during the JLE tunnelling (discussed in the next section of this paper).

(a)

(b)

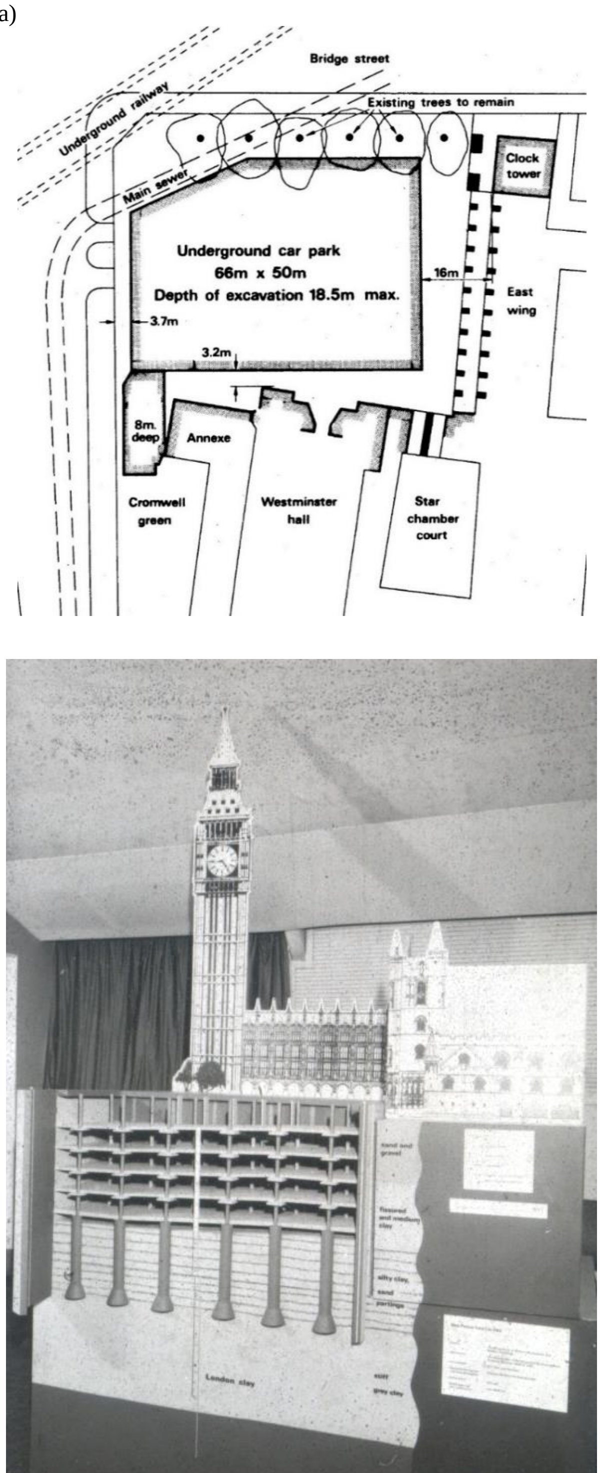

Figure 3 Underground car park at Palace of Westminster: (a) plan view of the works; (b) model showing basement levels and stratigraphy (Burland et al. 1979).

The knowledge and experience gained from these early projects involving deep excavations and full-scale field monitoring, in conjunction with the work that John Burland undertook with Professor Peter Wroth (Burland and Wroth, 1974), led to the ideas put forward in the seminal paper by Burland, Broms and De Mello (1977) presented at the 9th ICSMFE in Tokyo. Burland and Wroth (1974), looked at the onset of cracking and the development of subsequent damage in brick masonry walls through prototype-scale models tested in a structures laboratory at BRE. The findings and damage framework put together from their work were expressed in terms of 'critical tensile strains' at which cracks initiated. Burland et al. (1977) advanced the concept by putting forward the idea of using a 'limiting tensile strain', more closely linked with serviceability state and allowing different materials to be considered. This tied in well with the idea of expressing damage in terms of its 'ease of repair', an approach that was adopted subsequently by BRE and the Institution of Structural Engineers.

John Burland joined the academic staff at Imperial College in 1980, being appointed as Professor of Soil Mechanics and soon afterwards taking over as head of the Soil Mechanics Section. He continued the work that he started at BRE, and became more involved with research related to tunnelling projects, e.g. the Bell Common cut-and-cover tunnel (Potts and Burland, 1983; Craig et al. 1985; Parker et al. 1986 and Burland and Hellings, 1986).

A framework with which to describe and predict building damage was becoming an essential requirement for new tunnelling projects in the urban environment where building owners were becoming more aware of and concerned about potential damage to their properties from tunnelling-induced ground movements. Burland and Wroth (1974) had quantified damage using ranges of critical tensile strain and deflection ratio based on elastic beam theory, where buildings were represented by weightless elastic beams. An essential link between tensile strains and building damage was provided by Boscardin and Cording (1989) using a series of case studies involving different structural forms and degrees of damage.

It was this framework that was used to assess whether damage was likely to occur from the proposed tunnelling for the Jubilee Line Extension in the early 1990s, as described by Burland (1995) and Mair et al. (1996). A staged procedure was adopted in which buildings at low levels of risk were eliminated at an early stage of assessment and those predicted to be subjected to more than aesthetic damage could be investigated in more detail using the elastic beam theory approach. A fundamental and conservative aspect of the assessment was that it was assumed at this stage that the building would deform to the same degree as the greenfield condition, i.e. without taking into account any influence from the building stiffness or ground-structure interaction.

Given the developments that Prof Burland had been intimately involved with in developing the framework for assessing excavation-induced ground movements and potential damage and the extensive knowledge and experience he gained from a range of high-profile construction projects, it is not surprising that he was called upon as an expert witness during the parliamentary hearings that took place prior to the bill being approved for the JLEP to proceed.

2. JUBILEE LINE EXTENSION PROJECT

It became evident to Professor Burland during the parliamentary hearings that, although tunnels had been constructed in London since the Brunels' Thames Tunnel (completed in 1843: Skempton and Chrimes, 1994) and subsequently for more than a century and a half with the development of the London Underground Limited (LUL) tunnel network, there was a dearth of good quality case studies concerning ground and structural response to tunnelling activities. There were only very limited case studies of greenfield ground response and even fewer covering structural response. He realised that in earlier projects, although monitoring had been undertaken, the records had only been used to check and control works at that time and no further formal compilation and analyses of the data had been completed. Additionally, the very early tunnels were intentionally aligned beneath streets help to avoid building damage.

John Burland discussed this issue with Dr Brian Mellitt, Chief Engineer of LUL and Dr Robert Mair of the Geotechnical Consulting Group (GCG), and the initiative to set up a major research project to address this was conceived. The project was to be run in conjunction with the JLEP with direct interaction with Lionel Linney, the Senior Geotechnical Engineer there. The research was financed through the government's CMR LINK programme (Construction Maintenance and Refurbishment) where funding was only made available providing it was matched by equivalent contributions from industry, with a view that this would indicate its perceived usefulness and value (Jardine et al. 2001; Burland et al. 1996). Fin Jardine, Senior Research Manager in Ground Engineering at CIRIA (Construction Industry Research and Information Association), headed up the liaison with industry, management of the project and also the technical editing and compilation of the results and their dissemination to the sponsors. A research team comprising members from the JLEP and Imperial College was set up with Professor Burland as the academic lead.

At the outset a series of 'gaps in knowledge' was identified, based on the questions posed and experience gained during the parliamentary hearings. There were six broad headings (listed by Burland, 2001a).

Subsidence trough (i): The shape and magnitude were to be confirmed for various scenarios and a better understanding was needed of how horizontal displacements and strains developed in the ground. Clearer information was also needed about when superposition could be used for situations with multiple tunnels.

Ground-structure interaction (ii): Few reliable case studies existed of how the stiffness of a structure and the interaction between foundations and underlying ground influenced the shape and magnitude of the subsidence trough and horizontal strains. In particular, information about cases with piled foundations was very scarce.

Protective measures (iii): A number of traditional and novel methods were available at the outset of the project. Of the latter, there were proposals to use compensation grouting, a relatively new technique, on numerous buildings where potential damage was predicted.

Damage (iv): Most of the previous research on damage had related to construction settlement and not subsidence or heave where horizontal strains play a major role. There was little known about the forms of damage and how and where it initiated and then propagated.

Remedial measures (v): This was considered to be a subjective area where a range of approaches could be adopted, many without proven effectiveness both in the short and long term.

Long-term effects (vi): Prior to the JLEP there were few concerns about long-term tunnelling-induced settlements. Frequently it was assumed that following a set time period after tunnel construction, long-term ground movements would be negligible.

In order to investigate these various gaps in knowledge, a detailed appraisal was made of buildings judged to be affected by the JLE tunnelling between Green Park where the extension started and Canada Water stations. The route was walked to view the different structures in conjunction with plans showing contours of greenfield settlement predictions. About thirty structures were identified, representing different structural forms, foundation types, styles and ages. As the geology changed from west to east, from London Clay to the Lambeth Group and Thanet Sands, different tunnelling methods were to be adopted which added another variable to investigate. These structures ranged from the very grand, such as the Ritz Hotel, the Treasury and the Palace of Westminster to rather mundane office buildings such as Elizabeth House to very modest housing in the east of London. Instrumentation was installed, surveying systems set up and background monitoring commenced. Greenfield reference control sites were also set up in St James's Park and Southwark Park (refer to Figure 4). Intense monitoring continued for the duration of the works with the field data being concurrently processed and analysed and detailed case studies compiled to produce 'interim reports' which were sent to the JLE team and funders. Eventually these interim reports were collated, edited and refined and the two-volume 'blue book' published (Burland et al. 2001).

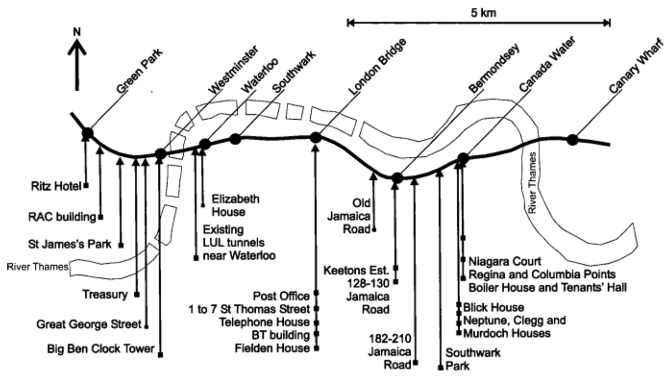

Figure 4 Location of case study buildings and control sites along the JLE (Jardine, 2001).

Examples from the findings of the project were presented by Professor Burland in the final chapter of volume 1 of the blue book (Burland, 2001b) and by Professor Robert Mair in his theme lecture (Mair, 2003) at the international conference on 'response of buildings to excavation-induced ground movements' held at Imperial College to launch the book. The focus on the gaps in knowledge, both those originally formulated, and others identified during the research, continued during the conference by way of discussion sessions specifically covering them (Burland, 2003). These discussions were assiduously compiled and recorded in the conference proceedings (Jardine, 2003), providing another important source of information.

Professor Burland pointed out that it should be possible to transfer the many important findings from the study to other tunnelling scenarios not just in London but worldwide and this has indeed been the case.

With regard to the gaps in knowledge, the following summary covered the main findings. (i) Volume loss was identified as the key quantity to control with respect to the maximum settlements but that its magnitude depended on a number of factors. At the St James's Park control site, the values measured were much higher than those used in the design predictions (Standing et al. 1996) and various reasons were put forward for this. The comprehensive greenfield measurements confirmed that the empirical approach to predicting ground response worked well and that superposition was only appropriate if the tunnels were far enough apart. (ii) The influence of building stiffness and ground-structure interaction was evident from a number of the case studies, that showed that greenfield deflection ratio values reduced depending on the relative stiffness between the structure and the soil. It was observed that buildings behaved more flexibly in hogging than sagging. An important observation was that only very small horizontal strains were transferred to the buildings, especially those with continuous foundations (e.g. raft), even though the ground just beneath the foundations strained in the same way as measured at the control green field sites. All of these observations have significant implications on predicted damage, greatly reducing its potential. (iii) Compensation grouting was shown to be very controllable and to work very well as a protective measure, prior to, during and after tunnelling. It was pointed out that this method is expensive and time-consuming and had been used extensively throughout the project but in view of the observations re (ii) it may not have been necessary in many cases. (iv) Very little damage was reported during the works and that observed was at the most 'slight' (Category 2 – see Burland, 1995). It was noted that in the cases where damage was reported, it often occurred at connections / junctions between adjacent buildings rather than in the continuous fabric of the structure itself. The accuracy and frequency of monitoring allowed transitory building deformations to be assessed (e.g. longitudinal subsidence trough) and in some cases these deformations were more severe than the permanent ones. It was also established through careful background research that a building's history (genesis) also influenced its response and potential damage. (v) As the damage reported was minimal there was little opportunity to observe or comment on regarding remedial measures. (vi) The long-term ground and structural response were monitored for a number of the structures and the greenfield control sites. In some cases, the settlements increased greatly but usually with widening troughs and negligible changes in slope or deflection ratio. In his summing up, as well as discussing how the gaps in knowledge had been addressed, Professor Burland also commented on the value of monitoring techniques that had been used and developed, reflecting again his career-long interest in this subject.

The summary above, distilled from Professor Burland's closing chapter, is a very abbreviated form of the overall findings produced from this major research project. The lessons learnt have been used extensively in the planning of other subsequent major urban tunnelling projects and were disseminated extensively (e.g. Burland et al. 2001; Standing and Burland, 1999; Standing et al. 1999). Additionally, the monitoring data and case studies were interrogated further in subsequent years, especially in the calibration and validation of numerical analyses, by numerous academic institutions and industry practitioners. Some of these studies are covered in the following section.

Before closing on matters relating to the JLEP, it is worth noting that Professor Burland was a specialist advisor to the project throughout the construction works (within a team including Dr Brian Simpson, Dr Robert Mair, Mike King and David Harris). One of their main concerns was the construction of the running and subsequently station tunnels and the massive box excavation for Westminster Station directly alongside the Big Ben Clock Tower (see Figure 5). The ground movements from these various activities were offset by using very carefully controlled compensation grouting (Harris et al., 1999; Harris, 2001) (refer Figures 6 and 7).

3. SUBSEQUENT TUNNELLING- AND DEEP-EXCAVATION-RELATED WORK

Running almost concurrently with the JLEP project was detailed numerical research work on the modelling of ground and structural response to tunnel construction, led by Professor David Potts using the Imperial College Finite Element Program (ICFEP) developed by him. At that time numerical analyses generally predicted greenfield subsidence troughs that were too wide and too shallow. Numerous approaches to overcoming this were investigated (e.g. Addenbrooke et al. 1997) and although not directly involved with this work, Professor Burland took a keen interest in it. The findings from the JLEP case studies were used extensively then and later to calibrate and validate ICFEP analyses (and many others worldwide).

A major development came from a detailed numerical parametric study to investigate the effect of building stiffness on the tunnelling-induced subsidence trough (Potts and Addenbrooke, 1997). The approach formulated was used very successfully and to great effect in the 'class A' predictions made for two of the case study buildings (Burland, 2001b), demonstrating the value of taking this into account. In the methodology developed, two relative ground-structure stiffness 'parameters', relating to bending and axial stiffness, are used to formulate design charts. These charts provide modification factors that can be applied to values of greenfield deflection ratio and horizontal strain estimated from conventional empirical approaches. The stiffer the structure, the smaller the corresponding deflection ratios and horizontal strains (reflected by decreasing magnitude of the modification factor) and hence the less likelihood of damage occurring. The modification factors for axial stiffness, for applying to greenfield strains, are less than 0.1 for the range of axial stiffness values considered, which correlated directly with the very small horizontal strains observed from the JLEP field monitoring.

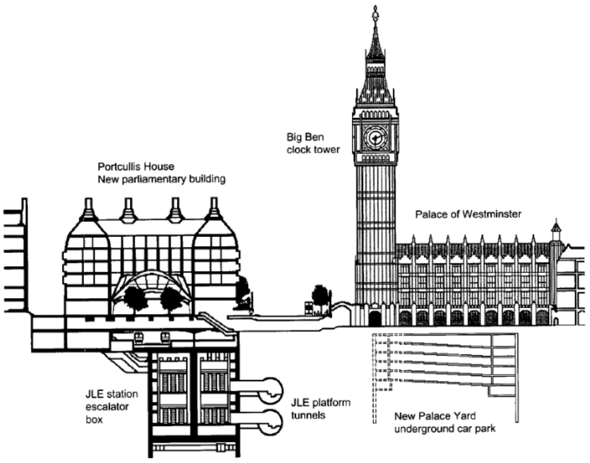

Figure 5 JLEP works affecting the Big Ben Clock Tower and the Palace of Westminster (Harris, 2001).

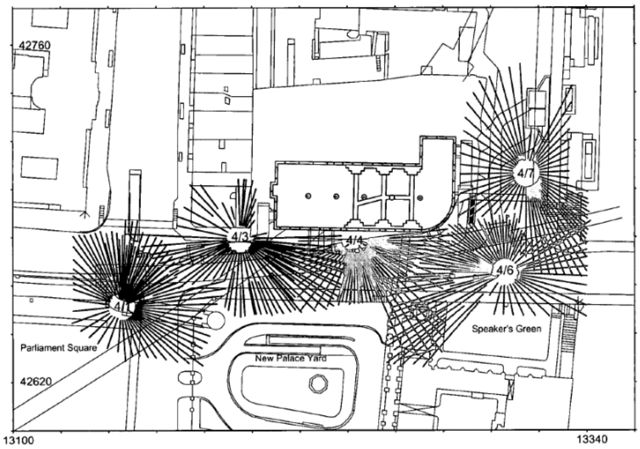

Figure 6 Plan view showing JLE Westminster station, grouting shafts and tubes-à-manchette arrays (Harris, 2001).

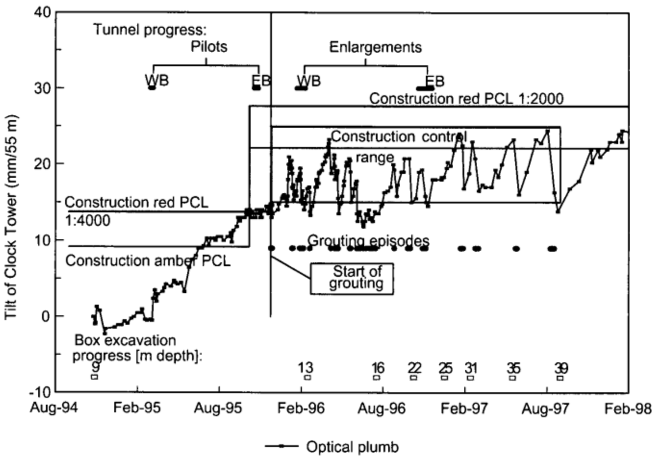

Figure 7 Control of the tilt of the Big Ben Clock Tower using compensation grouting (Harris, 2001).

The original work written up by Potts and Addenbrooke was subsequently extended to investigate the effects of: building weight (Franzius et al. 2004, 2005a) which was not considered in the original study; soil anisotropy and K_0, (Franzius et al. 2005b); and three-dimensional effects (the original analyses were run under plane-strain conditions) and twist (Franzius et al. 2006a, 2006b). The aim of these studies was to try to understand why subsidence troughs from numerical analyses did not reflect what was observed from field monitoring and also to investigate aspects of building response observed during the JLEP research. Twist was seen in a number of structures where the tunnel passed beneath them obliquely and was usually transitory but potentially damaging. John Burland was directly involved with these studies with David Potts and Trevor Addenbrooke. This work is still widely cited and the value of its original concept is clearly evident from the number of alternative but essentially very similar approaches proposed by others.

Apart from the studies of ground response to tunnelling using numerical analysis with ICFEP, Professor Burland also worked closely with others who used other theoretical approaches such as the anisotropic elastic model adopted by Puzrin et al. (2012) and discrete element modelling, which was used to provide insight into mechanisms of ground response (Bym et al. 2013). It is worth noting that in many of the numerical studies referred to above and many of those undertaken internationally, reference is made to Rob Nyren's PhD thesis, supervised by Prof Burland, which covered the compilation and analysis of the monitoring data from the St James's Park greenfield site (Nyren, 1998, see also Nyren et al. 2001). Rob Nyren was one of the key members of the research team who helped with monitoring project-wide as well as the control sites – his thesis must be one of the most widely cited in tunnelling circles.

The larger than expected volume losses of 3.3% and 2.4% measured at the control site at St James's Park, were of great concern. It was feared that these would be put forward as new values to consider for future tunnelling projects, rather than the 2% used for the JLEP predictions. A consequence of this could be a greatly increased reliance on complex, time-consuming and expensive mitigation measures such as compensation grouting. John Burland discussed this with Keith Beattie of LUL (who had taken over as Chief Engineer after Brian Mellitt's retirement), resulting in funding being granted to investigate the causes for these excessive volume losses. It was known that the tunnelling method had partly contributed, the study was to focus on whether the geology and ground conditions had also played a role. Five pairs of boreholes were drilled across St James's Park and a detailed study of the soil conditions made. It was established that there were significant differences in the London Clay from one side of the park to the other (Standing and Burland, 2006). This work led to a completely different appreciation of the London Clay and has led to changes in how geotechnical and tunnelling engineers assess it.

Both during and subsequent to the JLE research project Professor Burland has been actively involved in tunnelling research, despite being 'semi-retired' during the later studies. He supervised research work related to the Heathrow Express (Barakat, 1998)) and more detailed analyses of some of the JLEP case studies (e.g. Taylor, 2007), some of these were also further studied under Professor Mair's supervision at Cambridge University. Numerous other publications originated from the JLEP research case studies (e.g. Burland et al. 2004; Standing et al. 2003a and 2003b; Taylor et al. 2002a and 2002b).

More recently John Burland was part of the Imperial College research team looking into the effect of tunnelling on existing tunnels. This study was run in conjunction with Crossrail and focussed on existing tunnels lined with grey cast iron segments (specifically the LUL Central line near Lancaster Gate station). The scope of the project was diverse with: field monitoring at a greenfield site in Hyde Park (Wan et al. 2017a, 2017b, 2019), monitoring of the Central and Northern line tunnels (Yu et al. 2015); structural testing of a half-scale segmental grey cast iron ring (Yu et al. 2017); numerical analysis of the field conditions and structural testing; and advanced testing of London Clay samples from Hyde Park (references cited are those that John Burland was directly involved with). This major project, as with that run for the JLEP, has been a great success, a summary of the main findings is given by Standing et al. (2015).

Professor Burland has supervised and helped co-supervise numerous MEng and MSc tunnelling-related research projects, especially since the JLEP research. He has taken a keen interest in the long-term ground response at St James's Park and Elizabeth House since tunnelling was completed, both sites are still being monitored. It is completely evident that his tunnelling research has also extended well into the long term and his 'monitoring' and contributions are continuing.

4. FINAL REMARKS

Professor John Burland's research into deep excavations and tunnelling has extended over a period of more than fifty years. During this time, he has made major contributions to the fields from numerous perspectives. Field monitoring underlies all of these, being the 'yard stick' against which to: assess construction techniques and workmanship; understand and confirm ground and structural response to tunnelling and deep excavations and proposed deformation mechanisms; and calibrate and validate theoretical and numerical analyses. His seminal work with Professor Peter Wroth paved the way to classifying and quantifying damage and has led to an objective approach to predicting the severity of damage caused by underground works. The JLEP research is one of the most extensive (if not the most extensive) studies of ground and structural response to tunnelling and deep excavations and many previous 'gaps in knowledge' were elucidated from the findings. Professor Burland has also been intimately involved with and contributed to the prediction of these same responses through approaches using empirical, theoretical and numerical analyses. With evolving tunnel boring machine technology, ever increasing tunnel diameters and concerns and tolerance stipulations about existing infrastructure and overlying assets, there is still a great deal to learn. John Burland will without doubt continue to pursue his studies in this challenging field with his usual enthusiasm, clarity of thought and expression and careful diligence.

5. REFERENCES

Addenbrooke, T. I., Potts, D. M. and Puzrin, A. M. (1997). "The influence of pre-failure soil stiffness on the numerical analysis of tunnel construction." Géotechnique, Vol. 47, No. 3, pp 693-712.

Baraket, M. A. (1996). "Measurements of ground settlement and building deformations due to tunnelling." PhD thesis, Imperial College, University of London.

Boscardin, M. D. and Cording E. G. (1989). "Building response to excavation-induced settlement." Journal of Geotechnical Engineering, ASCE, Vol. 115, No. 1, pp 1-21.

Burland, J. B. (1995). "Assessment of risk of damage to buildings due to tunnelling and excavations." Proc. 1st Int. Conf. on Earthquake Geotechnical Engineering (ed. K. Ishihara) Balkema, Rotterdam, pp 1189-1201.

Burland, J. B. (2001a). "Assessment methods used in design. Chapter 3 of Building response to tunnelling: case studies from construction of the Jubilee Line Extension, London. Vol.1 Project and methods." CIRIA Special Publication 200. CIRIA and Thomas Telford, London, pp 23-43.

Burland, J. B. (2001b). "Results of the research. Chapter 21 of Building response to tunnelling: case studies from construction of the Jubilee Line Extension, London. Vol.1 Project and methods." CIRIA Special Publication 200. CIRIA and Thomas Telford, London, pp 315-344.

Burland, J. B. (2003). "Closing address. Proceedings of the international conference on response of buildings to excavation-induced ground movements, London." (ed. F. M. Jardine) CIRIA Special Publication 201, CIRIA, pp 155-162.

Burland, J. B. (2004) "Interaction between structural and geotechnical engineers." Proc. of the joint structural division annual seminar - new perspectives in the design and construction of foundation structures. The Hong Kong Institution of Engineers and the Institution of Structural Engineers, pp K1-K28.

Burland, J. B. (2006) "Interaction between structural and geotechnical engineers." The Structural Engineer, Vol. 84, pp 29-37.

Burland, J. B., Broms, B. B. and De Mello, V. F. B. (1977). "Behaviour of foundations and structures." Proc. 9th Int. Conf. on Soil Mechanics and Foundation Engineering, Tokyo, Vol. 2, pp 495-546.

Burland, J. B. and Hancock, R. J. R. (1977). "Underground car park at the House of Commons, London: geotechnical aspects." The Structural Engineer, Vol. 55, pp 87-100.

Burland, J. B. and Hellings, J. E. (1986). "The measurements of soil parameters relevant to tunnelling in clays - discussion." Canadian Geotechnical Journal, Vol. 23, No. 3, pp 399-400.

Burland, J. B. and Kalra, C. J. (1986). "Queen Elizabeth conference centre – geotechnical aspects." Proc. ICE, Part 1, Vol. 80, pp 1479-1503.

Burland, J. B., Longworth, T. I. and Moore, J. F. A. (1977). "Study of ground movement and progressive failure caused by deep excavation in Oxford Clay." Géotechnique, Vol. 27, No. 4, pp 557-591.

Burland, J. B., Longworth, T. I. and Moore, J. F. A. (1978). "Study of ground movement and progressive failure caused by deep excavation in Oxford Clay - discussion." Géotechnique, Vol. 28, No. 3, pp 357-358.

Burland, J. B., Mair, R. J., Linney, L. F., Jardine, F. M., Standing, J. R. (1996). "A collaborative research programme on subsidence damage to buildings: prediction, protection and repair." Proc. Int. Symp. Geotechnical Aspects of Underground Construction in Soft Ground (eds. R. J. Mair & R. Taylor) Balkema, Rotterdam, pp 773-778.

Burland, J. B., Mair, R. J., Standing, J. R. (2004). "Ground performance and building response due to tunnelling." Proc. Skempton Conference on Advances in Geotechnical Engineering, London (eds. R. J. Jardine, D. M. Potts & K.G. Higgins). Thomas Telford, pp 291-344.

Burland, J. B. and Moore, J. F. A. (1973). "The measurement of ground displacements around deep excavations." Proc. Symp. On Field Instrumentation, British Geotechnical Society, London, pp 70-84.

Burland, J. B., Moore, J. F. A. and Smith, P. D. K. (1972). "A simple and precise borehole extensometer." Géotechnique, Vol. 22, No. 1, pp 174-177.

Burland, J. B., Simpson, B. and St John, H. D. (1979). "Movements around excavations in London Clay." Proc. 7th European Conf. on Soil Mechanics and Foundation Engineering, Brighton, BGS, Vol. 1, pp 13-30.

Burland, J. B., Standing, J. R. and Jardine, F. M. (eds) (2001). "Building response to tunnelling: case studies from construction of the Jubilee Line Extension, London. Vol.1 Project and methods; Vol. 2 Case studies." CIRIA Special Publication 200. CIRIA and Thomas Telford, London.

Burland, J. B., Standing, J. R. and Jardine, F. M. (2001). "Assessing the risk of building damage due to tunnelling - lessons from the Jubilee Line Extension, London." Proc. 14th Southeast Asian Conference on Geotechnical Engineering, Hong Kong, (eds. Ho and Li). Swets and Zeitlinger, Lisse, pp 17-44.

Burland, J. B. and Wroth, C. P. (1974). "Settlement of buildings and associated damage." Proc. Conf. on Settlement of Structures, Cambridge. Pentech Press, London, pp 611-654.

Bym, T., Marketos, G., Burland, J. B., O'Sullivan C. (2013). "Use of a two-dimensional discrete element line-sink model to gain insight into tunnelling-induced deformations." Géotechnique, Vol. 63, No. 9, pp 791-795.

Cole, K. W. and Burland, J. B. (1972). "Observation of retaining wall movements associated with a large excavation." Proc. 5th European Conf. of Soil Mechanics and Foundation Engineering, Madrid, Vol I/1, pp 445-453.

Craig, R. N., Thomas, H. S. H., Mair, R. J., Ward, W. H., Tedd, P., Temporal, J., Burland, J. B., Howard, A. J., Boden, J. B., Bateman, T. and Haselden, G. K. (1984). "Observations on the behaviour of a pilot tunnel in London Clay as the main tunnel was driven – discussion." Proc. ICE, Part 1 – Design and Construction, Vol. 76, pp 571-588.

Franzius, J. N., Potts, D. M., Addenbrooke, T. I. and Burland, J. B. (2004). "The influence of building weight on tunnelling-induced ground and building deformation." Soils and Foundations, Vol. 44, No. 1, pp 25-38.

Franzius, J. N., Potts, D. M., Addenbrooke, T. I. and Burland, J. B.

(2005a). "The influence of building weight on tunnelling-induced ground and building deformation - discussion." Soils and Foundations, Vol. 45, pp 168-169.

Franzius, J. N., Potts, D. M. and Burland, J. B. (2005b). "The influence of soil anisotropy and K_0 on ground surface movements resulting from tunnel excavation." Géotechnique, Vol. 55, No. 3, pp 189-201.

Franzius, J. N., Potts, D. M. and Burland, J. B. (2006a). "The response of surface structures to tunnel construction." Proc. ICE Geotechnical Engineering, Vol. 159, No. 1, pp 3-17.

Franzius, J. N., Potts, D. M. and Burland, J. B. (2006b). "Twist behaviour of buildings due to tunnel induced ground movement." Proc. 5th Int. Conf. on Geotechnical Aspects of Underground Construction in Soft Ground, Amsterdam (eds. Bakker, Bezuijen, Broere and Kwast). Taylor and Francis, London, pp 107-113.

Harris, D. I. (2001). "The Big Ben Clock Tower and the Palace of Westminster. Chapter 28 of Building response to tunnelling: case studies from the Jubilee Line Extension, London: vol. 2: case studies," (eds. J. B. Burland, J. R. Standing & F. M. Jardine). CIRIA and Thomas Telford, London, pp 453-508.

Harris, D. I., Mair, R. J., Burland, J. B. and Standing, J. R. (1999). "The use of compensation grouting to control movements of Big Ben Clock Tower during construction of JLE Westminster Station." Proc. Int. Symp. Geotechnical Aspects of Underground Construction in Soft Ground, IS-Tokyo '99, (eds. O. Kusakabe, K. Fujita and Y. Miyazaki). Balkema, Rotterdam, pp 225-232.

Jardine, F. M. (2001). "Introduction to the case studies. Chapter 22 of Building response to tunnelling: case studies from the Jubilee Line Extension, London: vol. 2: case studies," (eds. J. B. Burland, J. R. Standing & F. M. Jardine). CIRIA and Thomas Telford, London, pp 345-350.

Jardine, F. M. (ed) (2003). "Proceedings of the international conference on response of buildings to excavation-induced ground movements, London." CIRIA special publication 201, CIRIA, London.

Jardine, F. M., Burland, J. B. and Standing, J. R. (2001). "Introduction. Building response to tunnelling: case studies from the Jubilee Line Extension, London: vol. 1: projects and methods," (eds. J. B. Burland, J. R. Standing & F. M. Jardine). CIRIA and Thomas Telford, London, pp 1-8.

Mair, R. J. (2003). "Research on tunnelling-induced ground movements and their effect on buildings – lessons from the Jubilee Line Extension Project." Proc. Int. Conf. On Response of buildings to excavation-induced ground movements, (ed. F. M. Jardine). CIRIA Special Publication 201, London, pp. 3-26.

Mair, R. J., Taylor, R.N. and Burland, J. B. (1996). "Prediction of ground movements and assessment of risk of building damage due to bored tunnelling." Proc. Int. Symp. Geotechnical Aspects of Underground Construction in Soft Ground, London (eds. R. J. Mair & R.N. Taylor R.N.). Balkema, Rotterdam, pp 713-718.

Nyren, R. J. (1998). "Field measurements above twin tunnels in London Clay." PhD thesis, Imperial College, University of London.

Nyren, R. J., Standing, J. R., Burland, J. B. (2001). "Surface displacements at St James's Park greenfield reference site above twin tunnels through the London Clay (Chapter 25). Building response to tunnelling: case studies from the Jubilee Line Extension, London: vol. 2: Case studies," (eds. J. B. Burland, J. R. Standing & F. M. Jardine). CIRIA and Thomas Telford, London, pp 387-400.

Parker, F. J., Tiplady, J., Newland, R. M., Sriskandan, K., Lowndes, J. F. L., Selfe, M. A., Burland, J. B., Potts, D. M., Symons, I. F., Gregg, D. J., Doran, D. K., Taylor, M. S., and Peck, R. J. F. (1986). "M25 Northeast Sector – Holmesdale and Bell Common tunnels – discussion." Proc. ICE Part 1 – Design and Construction, Vol. 80, pp 785-800.

Potts, D. M. and Addenbrooke, T. I. (1997). "The influence of an existing structure on the ground movements due to tunnelling." Proc. ICE Geotechnical Engineering, Vol. 125, No. 2, pp 109-125.

Potts, D. M. and Burland, J. B. (1983). "A numerical investigation of the retaining walls of the Bell Common tunnel." TRRL Supplementary Report 783, Transport and Road Research Laboratory, Crowthorne.

Puzrin, A. M., Burland, J. B. and Standing, J. R. (2012). "Simple approach to predicting ground displacements caused by tunnelling in undrained anisotropic elastic soil." Géotechnique, Vol. 62, No. 4, pp 341-352.

Skempton, A. W. and Chrimes, M. M. (1994). "Thames Tunnel: geology, site investigation and geotechnical problems." Géotechnique, Vol. 44, No. 2, pp 191-216.

Standing, J. R., Addenbrooke, T. I. and Burland, J. B. (1999). "The assessment of ground and building response to tunnelling, risk of damage and structural monitoring." Proc. Int Congress on Urban Heritage and Building Maintenance - Problems and Possibilities, Delft, pp 31-62.

Standing, J. R. and Burland, J. B. (1999). "Monitoring of surface movements induced by underground works - recent experiences." XIth Pan-American Conference on Soil Mechanics and Geotechnical Engineering, Brazil. ABMS, pp 621-628.

Standing, J. R. and Burland, J. B. (2006). "Unexpected tunnelling volume losses in the Westminster area, London." Géotechnique, Vol. 56, No. 1, pp 11-26.

Standing, J. R., Gras, M., Taylor, G. R., Gupta, S. C. and Burland, J. B. (2003a). "Response of the former Lloyds bank building, St Jamess, London, to tunnel step-plate junction construction." Proc. Int. Conf. on Response of Buildings to Excavation-induced Ground Movements, (ed. F. M. Jardine). CIRIA, London, pp 575-592.

Standing, J. R., Gras, M., Taylor, G. R., Gupta, S. C. and Burland, J. B. (2003b). "The response of buildings in Park Place to underground excavation and compensation grouting - a case study from the Jubilee Line Extension, London." Proc. Int. Conf. on Response of Buildings to Excavation-induced Ground Movements, (ed. F. M. Jardine). CIRIA, London, pp 553-574.

Standing, J. R., Nyren, R. J., Burland, J. B. and Longworth, T. I. (1996). "The measurement of ground movements due to tunnelling at two control sites along the Jubilee Line Extension." Proc. Int. Symp. Geotechnical Aspects of Underground Construction in Soft Ground, London (eds. R. J. Mair & R.N. Taylor R.N.). Balkema, Rotterdam, pp 751 - 756.

Standing, J. R., Potts, D. M., Vollum, R., Burland, J. B., Tsiampousi, A., Afshan, S., Yu, J. B.Y., Wan, M.S.P. & Avgerinos, V. (2015). "Investigating the effect of tunnelling on existing tunnels." Proc. Conf., Underground Design and Construction, Hong Kong, IOM3, Hong Kong Branch, pp 301 – 312.

Taylor, G. R. (2007). "Building response to tunnelling-induced ground subsidence: some case studies from the Jubilee Line Extension." PhD thesis, Imperial College, University of London.

Taylor, G. R., Burland, J. B., Choy, C., Standing, J. R. and Allen, R. (2002a). "Building response to underground construction: the New City Court case history." Proc. Int. Symp. on Geotechnical Aspects of Underground Construction in Soft Ground, Toulouse, (eds. R. Kastner, F. Emeriault, D. Dias and A. Guiloux). Spécifique, Lyon, pp 269-277.

Taylor, G. R., Franzius, J. N., Burland, J. B. and Standing, J. R. (2002b). "Assessing the historic movements within buildings - two case studies from the Jubilee Line Extension Project." Proc. Int. Symp. on Geotechnical aspects of Underground Construction in soft Ground, Toulouse, (eds. R. Kastner, F. Emeriault, D. Dias and A. Guiloux). Spécifique, Lyon, pp 263-268.

Wan, M. S. P., Standing, J. R., Potts, D. M. and Burland, J. B.

(2017a).“Measured short-term ground surface response to EPBM tunnelling in London Clay.” Géotechnique Vol. 67, No. 5, pp. 420-445.

Wan, M. S. P., Standing, J. R., Potts, D. M. and Burland, J. B. (2017b). “Measured short-term subsurface ground displacements from EPBM tunnelling in London Clay.” Géotechnique, Vol. 67, No. 9, pp. 748-779.

Wan, M. S. P., Standing, J. R., Potts, D. M. and Burland, J. B. (2019). “Pore water pressure and total horizontal stress response to EPBM tunnelling in London Clay.” Géotechnique, Vol. 69, No. 5, pp. 434-457.

Ward, W. H. and Burland, J. B. (1973). “The use of ground strain measurements in civil engineering.” Phil. Trans. Royal Soc., London, A274, pp 421-428.

Yu, J., Standing, J. R., Vollum, R., Potts, D. M. and Burland, J. B. (2015). “Stress and strain monitoring at Tottenham Court Road Station, London, UK.” Proc. ICE – Structures and Buildings, Vol. 168, No. SB2, pp 107-117.

Yu, J., Standing, J. R., Vollum, R., Potts, D. M. and Burland, J. B. (2017). “Experimental investigations of bolted segmental grey cast iron lining behaviour.” Tunnelling and Underground Space Technology, Vol. 61, pp 161-178.