UNIVERSITY OF CAMBRIDGE

Transforming construction: impact case study

Benefits to industry: tunnelling framework tool for industry; optimisation of design; better-informed safety measures; potential cost savings on temporary works; understanding the risk

Going underground: A framework tool for tunnelling close beneath existing tunnels in clay

The challenge

Increasing urbanisation means growing pressure for more housing and supporting infrastructure in cities and towns. By 2050 the world population will be around nine billion, with two-thirds of that population living in cities. Such changes in society mean that creating space for underground living and storage could become increasingly relevant to relieve pressure on already densely-developed cities.

The strength of the tunnelling market internationally is high and the strong influence of British tunnelling in many parts of the world offers opportunity for the skills, technology and innovation currently serving this area of construction. Tunnelling underneath an existing tunnel in close proximity is a common recurring problem in cities with underground transportation networks. Understanding the behaviour of existing tunnels during excavation of new tunnel networks is vital to inform effective safeguards and temporary works.

Emerging fibre optic strain sensing technology and analytics that deliver timely data and information are being used to unlock new insights into the performance of tunnels. This data supports better-informed tunnel construction and is of value to asset owners seeking reassurance regarding the effects of new tunnels being dug in close proximity to existing tunnels, as seen during the Crossrail London development.

The Smart Tunnel

This case study builds upon a research project completed by the Centre for Smart Infrastructure and Construction (CSIC), a collaborator of the Laing O'Rourke (LOR) Centre at the University of Cambridge. In 2014, a team of CSIC researchers, led by the Deputy Director of the LOR Centre, instrumented a 40-metre section of the disused, 100 year-old, 3m-diameter cast iron Royal Mail Post Office railway tunnel (RMT) during the construction of Crossrail. Data on the behaviour of the existing RMT tunnel was collected during the construction of Crossrail's new Lower Access Tunnel (LAT) directly underneath the existing tunnel (with a 15° skew from a perpendicular undercrossing). The new tunnel was constructed using open-faced tunnelling with sprayed concrete lining. The LAT comprised a squatted elliptical tunnel with an equivalent circular diameter of 6.3m, which reduces to 5.78m at the point of undercrossing where both tunnels are essentially in contact (i.e. zero clear distance). The RMT was constructed wholly in London Clay, similar to the LAT except for the invert which toes into the Lambeth Group.

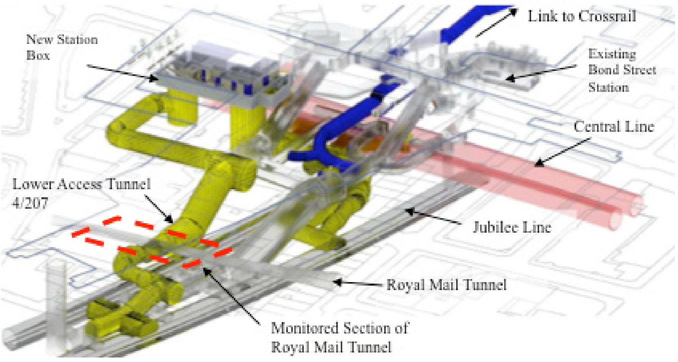

Figure 1: Underground three dimensional view of ond Street station upgrade scope of works

Never before had two tunnels been dug in London in such close proximity and parallel to each other over such a long distance. There was considerable uncertainty about the likely mode and levels of deformation to the existing tunnel network meaning contractors were forced to introduce a number of costly safeguards and temporary works based on predicted worst-case scenarios.

A range of monitoring technologies were installed inside the disused tunnel including Wireless Sensor Network (WSN) displacement transducers, fibre optic strain sensors and photogrammetric monitoring. This combined instrumentation created the world's first Smart Tunnel capable of measuring and monitoring the structural performance and stress levels of the older tunnel as the new, giant Crossrail tunnel was excavated below.

The data collected from the instrumentation, in sync with the construction programme, gave detailed information about the deformation of the RMT (longitudinally and in cross-section) offering a better understanding of the temporary work requirements for such tunnels. The feedback data provided a complete picture of the entire tunnel deformation that was not available before. The data from this award-winning project offered Crossrail an opportunity to make significant savings on future projects by more accurate planning of the required monitoring systems and the design of temporary works.

The next step

The digital age enables us to collect and analyse data to create Smart Infrastructure which brings better performance at lower cost. While significant, smarter information represents one step in a longer process. There is pressing need for the intelligent simulation, and condensing the output of that simulation, into a framework tool that can readily be used by industry to deliver impact and enable change in construction.

This case study consolidates the Smart Tunnel research to take the understanding of tunnel performance to a higher level and introduces centrifuge modelling to deliver a framework tool that is potentially a game-changer for the tunnelling construction industry. Advanced simulation allows a significantly deeper understanding of the fundamentals that govern the behaviour of existing tunnels when subjected to tunnelling-induced ground movements.

The simulation approach

A series of centrifuge model tests in clay were carried out to investigate the response of an existing tunnel at different clear distances to new tunnelling underneath. A three-dimensional staged tunnelling model was adopted to simulate a wide range of tail-void volume losses for the new tunnel construction whilst monitoring detailed three-dimensional soil surface settlements and tunnelling-induced strains in the existing tunnel lining. A detailed case study of a similar scenario (in a perpendicular direction) during the London Underground redevelopment of Bond Street Station was also available to enrich the analyses. The combination of field and centrifuge modelling data provided important new insights into the deformation mechanisms encountered in such complex tunnelling scenarios. Both perpendicular undercrossings and parallel piggy-back scenarios were considered.

Centrifuge modelling

In order to make comparisons with the collected field data, a series of three-dimensional centrifuge tunnelling tests in clay were carried out in the 10m beam centrifuge of the Schofield Centre (University of Cambridge) at 100g to investigate the deformation mechanisms at realistic prototype scale stresses.

Two tests were carried out with a clear distance between two tunnels at 0.5D and 1.5D respectively to investigate the difference in response at varying clear distances.

The modelling specs

The diameter of the existing tunnel was kept constant at 60mm along with a standard cover-to-diameter ratio (C/D) for the new tunnel of unity. As tunnelling is inherently a three-dimensional process, an approximate three-dimensional tunnelling model system was designed to simulate the tunnelling sequence of a 62mm diameter tunnel in a series of five, 2D long advancements. The existing tunnel model was made of a 60mm (OD) aluminium tube with a 1.5mm wall thickness. A series of strain gauges were installed internally to measure five points of longitudinal bending strains (DDL series) and two instrumented cross sections of five bending strain sensing points. A bespoke centrifuge package of internal dimensions 750mm (W), 600mm (L) and 440mm (D) was designed and built for this test series to minimise soil disturbance during model preparation. Speswhite kaolin clay was used and was preconsolidated at 1g to a maximum effective vertical stress of 400kPa in the centrifuge package to create realistic tunnelling conditions.

Cross sectional bending moment

Based on results from both centrifuge tests, a linear correlation is obtained between bending moments and the mobilised stress ratios for each of the critical locations of crown, springline and invert. Comparison was made with section No. R11027 of the RMT which sits directly above the new LAT tunnel; the results, which showed good agreement, was found for both springlines and crown.

Longitudinal bending moment

As volume loss is triggered directly below the existing tunnel, the soil above the existing tunnel moved around the circular tunnel and into the cavity of the new tunnel in a comparable way to soil moving around a circular pile.

Results and framework

The approximate three-dimensional tunnelling simulations carried in clay using novel centrifuge modelling techniques were in good agreement with field data obtained from the instrumentation systems. Based on the field and centrifuge modelling results, the following conclusions could be made:

- the magnitude of bending moments in the longitudinal direction is larger in comparison to its cross section, making it more critical to be assessed for perpendicular undercrossing
- the longitudinal deformation mode of RMT is a combination of both bending and shearing with the former being dominant
- the existing segmental cast iron lining of RMT responded more flexibly in the longitudinal direction than in the cross section due to compressible caulking between consecutive rings
- radial and circumferential flanges of cast iron segments distort to accommodate bending deformation which reduces strains within bolt connections
- good transferability of the pipelines assessment method has been validated by both centrifuge and field data with the inclusion of an axial component
- a mobilised strength design approach has been proposed (the framework tool) to evaluate bending moment based on cavity contraction theory. This allows quick assessment with standard, readily available input parameters to yield realistic cross sectional bending moments that are consistent with field observations.

This approach effectively allows tunnelling-induced cross sectional bending moment assessments to be carried out for any known tunnel diameter and assumed volume loss, and for any clear distances between the tunnels paving the way for wide industry adoption.

Benefits to industry

The framework tool is a potential game-changer for the tunnelling industry. It enables designers to vary parameters and check results from simulation which is not possible in the field. Field data can be used in a simulation to compare and verify results.

The output of this research is transformative. The framework, which has been published by and presented to *Géotechnique*, the world's premier geotechnics journal, can now be applied to multiple projects by the tunnelling construction industry. Designers can refer to the framework to optimise tunnel design, predict and avoid problems. Asset managers can be reassured that an existing tunnel will not be adversely affected by new tunnelling excavation when referring to the framework.

Understanding the behaviour of existing tunnels during excavation of new tunnel networks will better-inform effective safeguards and temporary works during construction, making tunnelling projects safer and reducing costs through well-informed decisions.

LAING O'ROURKE CENTRE
for CONSTRUCTION ENGINEERING
and TECHNOLOGY

The Laing O'Rourke Centre for Construction Engineering and Technology, in the University of Cambridge Department of Engineering, was launched in 2011 with industry partner Laing O'Rourke to fulfil a shared vision of transforming the construction industry through innovation, education and technology.

Case study

This case study is based upon a research paper published by and presented to *Géotechnique* (Volume 67 Issue 9, September, 2017, pp. 795-807), Symposium in print: Tunnelling in the Urban Environment, by C. Y. Gue, M. J. Wilcock, M. M. Alhaddad, M. Z. E. B. Elshafie, K. Soga, and R. J. Mair. Chang Ye Gue is a PhD student at the Laing O'Rourke Centre for Construction Engineering and Technology.

Further details

For more details about this case study contact:

Centre Manager
Laing O'Rourke Centre for Construction Engineering and Technology
Department of Engineering
University of Cambridge
Tel: +44(0)1223 332812
Email: centre.manager@construction.cam.ac.uk
Website: www.construction.cam.ac.uk