Institution: University of Southampton

Unit of Assessment: 15 General Engineering

Title of case study: 15-32 Back on Track: Geotechnical Transport Infrastructure for the 21st Century

1. Summary of the impact

The transport of people, goods, and utilities (e.g. electricity, oil, gas and water) is essential to civilised life, and in turn depends on a robust, reliable and affordable infrastructure. Since 1995, the University of Southampton Geomechanics Group (SGG) has led the development of an enhanced, science-based framework for understanding the behaviour of geotechnical transport infrastructure through monitoring, modelling and analysis. The techniques we have developed have been used by the builders, owners and operators of transport infrastructure both nationally and internationally to develop improved understandings of infrastructure geotechnical behaviour both during construction and in service. This has led to substantial savings in build, maintenance and operational costs; the implementation of effective remediation and management strategies; and significantly improved infrastructure performance.

2. Underpinning research

In the mid-1990s, there was a perception within the construction industry that the loads in props used for the temporary support of large, deep excavations were uncalculable. To investigate this, **Powrie** (1995ff) and **Richards** (1995ff) developed methods for the continuous, detailed monitoring of prop loads, which we deployed during construction of the Jubilee Line extension stations at Canary Wharf and Canada Water, 1995-6 [3.1]. This gave a clear understanding of how prop loads and other structural stress resultants should be monitored if meaningful data are to be obtained; and identified the factors relating to pore pressure and lateral stress change that control them. Instrumentation for the continuous monitoring of pore pressures, lateral stresses and wall bending moments was developed during work on excavations for the Channel Tunnel Rail Link (now HS1) at Ashford, Kent, 1999-2001 [3.2]. By 2005, we had developed new instrumentation methods for the continuous monitoring of key stresses and stress resultants (lateral earth pressures, pore water pressures, prop loads and bending moments) associated with propped embedded retaining walls and retained excavations, and identified appropriate methods of analysis incorporated into industry guidance e.g. [3.3]. Richards has subsequently led the development of new monitoring methods to measure and understand dynamic loading events on foundations since 2002.

A significant area of development and application has been railway infrastructure, following EPSRC's drive in the wake of the Hatfield crash in 2000 to establish railway-relevant research in UK universities through Rail Research UK (a consortium of seven universities, led jointly by Southampton and Birmingham, with Powrie as PI and Southampton providing expertise in geomechanics and infrastructure) in 2003. Within and beyond RRUK, geotechnical railway infrastructure research at Southampton (backed by total funding of £14 million) has focused on two strands: the design and performance of ballasted track, and earthworks such as embankments and cutting slopes (also applicable to roads): Powrie, Richards, **Clayton** (1999ff), **Clarke** (1979ff), **Le Pen** (2012ff), **Priest** (2011-3), **Smethurst** (2012ff) and **Zervos** (2002ff). We have pursued a scientific and holistic approach to understanding track and earthworks behaviour, in contrast to the generally empirical and piecemeal approach that had prevailed over much of the previous 150 years.

Powrie and Richards, with Priest, Lock (to 2011) and Bowness (2003-6, deceased), developed novel instrumentation and associated data processing methods to measure dynamic displacements of the track and the underlying ground under load from passing trains. Geophones and digital image analysis were used to make measurements previously impossible or prohibitively expensive to obtain. These techniques were used alongside advanced numerical modelling to analyse the complex interactions between rails, sleepers, ballast and the ground [3.4]. The original

paper detailing the instrumentation and its use was awarded the Thomas Hawksley Medal by the Institution of Mechanical Engineers in 2008 – its highest award for a published paper – and paved the way for industry to put the new techniques into practice.

Concurrent research has focused on instrumentation and analysis of exemplar field sites associated with both roads and railways, to develop quantitative understandings of the impacts of vegetation and climate on cutting and embankment slopes, and of the effectiveness of stabilizing piles. Smethurst, Clarke and Powrie have developed an analytical model linking climate, light vegetation, soil water content and suction alongside a benchmark dataset of continuous records since 2002 from a road cutting near Newbury [3.5]. A later field trial (2006-11), funded by Network Rail and conducted in conjunction with engineering consultants Mott MacDonald, Arup and GeoObservations, investigated the effects of major vegetation removal from an embankment in Southend and extended the analytical model to trees.

Research supported by EPSRC, the construction industry and infrastructure owners has led to an understanding of the various mechanisms by which discrete reinforced concrete piles may act to stabilize embankments and cutting slopes [3.6], and to the development of a design method which has been used at locations including the Ironbridge Gorge UNESCO World Heritage Site.

3. References to the research (best 3 are starred)

[3.1]* Measurement and analysis of temporary prop loads at Canary Wharf underground station, east London (2000). M Batten and W Powrie. *Proc ICE (Geotechnical Engineering)* **143**(3), 151-63 Awarded the Institution of Civil Engineers Telford Medal 2001

[3.2]* Pore water pressure and horizontal stress changes measured during construction of a contiguous bored pile multi-propped retaining wall in Lower Cretaceous clays (2007). D J Richards, W Powrie, H Roscoe and J Clark. *Géotechnique* **57** (2), 197-205

[3.3] *Embedded retaining walls: guidance for economic design* (2003). 390pp. A R Gaba, B Simpson, W Powrie & D R Beadman. CIRIA Report C580. London: Construction Industry Research and Information Association, ISBN 0 86017 580 4

[3.4] Measurements of transient ground movements below a ballasted railway line (2010). J A Priest, W Powrie, L Yang, P J Gräbe and C R I Clayton. *Géotechnique* **60**(9), doi: 10.1680/geot.7.00172

[3.5] Seasonal changes in pore water pressure in a grass covered cut slope in London Clay (2006). J A Smethurst, D Clarke and W Powrie. *Géotechnique* **56**(8), doi:10.1680/geot.2006.56.8.523

[3.6]* Monitoring and analysis of the bending behaviour of discrete piles used to stabilise a railway embankment (2007). J A Smethurst and W Powrie. *Géotechnique* **57**(8), doi: 10.1680/geot.2007.57.8.663

4. Details of the impact

Over the period 2007-09, the methods of pore pressure and bending moment monitoring we had developed were employed directly by the SGG to assess the performance under variable tidal loading of the twin-walled cofferdam for the St Germans pumping station on the River Ouse in East Anglia, for main contractor Costain. This was at the time the largest excavation in Europe. Pore pressures, bending moments and wall movements were monitoired continuously using systems developed and specified by SGG, and used in connection with a detailed finite difference analysis carried out by SGG in association with Mott MacDonald to draw up a plan for safe working within the cofferdam and, if necessary, controlled flooding to ensure its stability under a potential extreme loading event. The adoption of our research enabled the project to be completed safely and on time, saving an estimated £15 million but more importantly mitigating the very real risk potentially posed to a large section of East Anglia during an anticipated spring tide storm surge event [5.1].

Methods developed by Richards to measure and understand dynamic loading events on foundations have been applied to investigate the uplift capacity of electricity transmission tower foundations in response to a line breakage, as part of National Grid's campaign to assess and if necessary upgrade their network for the effects of climate change. The better understanding of the dynamic uplift capacity of transmission tower foundations resulting from the research has led to a moratorium on strengthening, and an estimated cost saving of £5-35 million p.a. since 2006 [5.2].

Research monitoring track-train interactions contributed to the decision to modify the wheel profile on the Hitachi Class 395 trains used on the High Speed 1 (HS1) line between London and Folkestone, which forms part of the Eurostar link to Europe. All switches and crossings (S&C, commonly known as "points") have sensors to indicate the position of the blade or nose (open or closed). The introduction of the Hitachi Class 395's – the UK's fastest commuter trains, with a top speed of 140 mph – caused 'points flicker', whereby a sensor would indicate the switch to be open when it was in fact closed. As faulty S&C were responsible for both the Potters Bar and Grayrigg disasters, in 2010 the HS1 team asked SGG to assist in identifying the cause of the fault. A further issue was the susceptibility of the new trains to "hunting" (unstable lateral oscillation of the bogies) in tunnels, which was causing considerable passenger discomfort and alarm. A six-month field trial, using the novel instrumentation techniques developed at Southampton [3.4], established that a combination of the wheel profile and the suspension settings played a major role in both problems, leading to a number of Hitachi trains being fitted experimentally with different profile wheels. These were closely monitored over several weeks to assess the effect of the new wheel profiles and suspension setting on hunting and points flicker. The investigation was carried out jointly by the University of Southampton, the NR wheel-rail interface team, S&C manufacturers Vossloh Cogifer, Hitachi and the train operating company South-Eastern. Results demonstrated the success of the modifications, which were subsequently implemented across the entire Class 395 fleet of 174 vehicles (29 × 6 car units) [5.3]. Other studies for HS1 have included investigations into ballast flight, jointly with Birmingham [5.4]. In Europe, ProRail, part of Dutch railway infrastructure owner NS Railinfratrust, has used SGG's research (in collaboration with Deltares) to control rising maintenance costs by identifying true mechanisms of track deterioration to inform appropriate long-term remedial measures [5.5].

Most railway track, both in the UK and worldwide, is founded on ballast. This is a traditional form of construction, but its performance limits are increasingly being tested as train speeds and weights and intensity of trafficking increase. In 2006, SGG was approached by Network Rail to investigate areas of sporadic and unexplained ballast movement ("ballast migration") on the UK West Coast Main Line, apparent following the introduction of tilting trains. Reported incidences of track and train-wheel faults had been increasing at certain curves, owing to the gradual migration of ballast from the high to the low rail potentially leading to trapping of ballast particles between the wheel and the rail. A field investigation by the Southampton Geomechanics Group using our track monitoring techniques, and analysis of the results, identified the potential causes of the problem. Continuing work funded by Network Rail through the *Future Infrastructure Systems* Strategic Research Partnership aims to devise a range of appropriate remediation techniques [5.6, 5.7].

Our expertise in ballasted track has been used in the design and specification of a new, 400 km-long railway line across the Arabian desert. Facing a maintenance bill of millions of pounds, Etihad Rail, the promoter and eventual operator of this new rail link in the United Arab Emirates, were seeking to mitigate the problem of sand ingress into the ballast reducing the life of both trains and track. In 2011, SGG developed laboratory test apparatus and procedures to investigate how sand ingress will affect the performance of the ballast bed. This led to the award of a recently-completed £106k research contract by the design and build contractor Saipem-Dodsal-Tecnimont JV, the results of which have helped shape a set of transformative track specifications with the potential for realising significant savings in future maintenance costs [5.8].

Monitoring and analysis of the influence of vegetation, weather and climate on the behaviour of

infrastructure embankments and cuttings have influenced the standards that guide industry practice. Work in collaboration with Network Rail, LUL and Mott MacDonald has demonstrated that the removal of mature vegetation has the potential to destabilise some earthworks structures during the winter, with both the species and proximity of vegetation and the underslope drainage conditions having a significant influence [5.9]. SGG has developed and validated models enabling the interactions between these and climate/weather to be quantified. Both Network Rail and LUL are now using the understandings gained to identify the most appropriate type of vegetation for particular slopes and to define their management strategies for lineside vegetation [5.7, 5.10].

Collaboration with Mott MacDonald led to the development of an improved design approach for discrete pile stabilisation of earthworks. Our research demonstrated that piles could be spaced further apart than previously thought, providing infrastructure owners with substantial cost savings through the need to install fewer piles. Savings of £2.4 million and 6 months in time have been identified on two jobs for LUL alone, and projected cost savings of £65-100 million over a five year period [5.10]. Increased confidence in the approach led to its successful use to stabilize part of the Ironbridge Gorge UNESCO World Heritage site.

Through their engagement and leadership of RRUK, researchers at Southampton have had a pivotal impact on the revitalisation of railway research in UK universities and its pull-through into industry. Southampton academic staff were instrumental in the formation of the successor organisation RRUKA, now being funded and run by RSSB to act as a link between research organisations and the UK rail industry. We led an EPSRC Feasibility Account, which resulted in the development of at least six new research projects involving UK universities and the UK rail industry, including SUSTRAIL and SPECTRUM [5.7]. Powrie contributed to UK Government policy in rail through his membership of the Railway Technical Strategy Steering Group, providing industry-wide support and advice for the Railway Technical Strategy 2012.

5. Sources to corroborate the impact

Note: references to papers are in professional journals and illustrate impact in addition to the actual research

[5.1] Technical Director, Costain Ltd

[5.2] New Tower Design Lead, National Grid

[5.3] Head of Track Engineering, Network Rail (High Speed) Ltd.

[5.4] A full-scale experimental and modelling study of ballast flight under high-speed trains (2010). M Hayward, C J Baker, F Schmid, J A Priest and W Powrie. *Proc IMechE Part F, Journal of Rail and Rapid Transit* **224**(F2). doi: 10.1243/09544097JRRT294

[5.5] An assessment of transition zone performance (2011). B Coelho, P Hölscher, J A Priest, W Powrie and F Barends. *Proc I Mech E Part F, JRRT* **225**(F2). doi: 10.1177/09544097JRRT389

[5.6] The effect of enhanced curving forces on the behaviour of canted ballast track (2013). J A Priest, W Powrie, L Le Pen, P Mak and M Burstow. *Proc IMech E Part F, JRRT* **227**(3). doi: 10.1177/0954409712458623

[5.7] Director, Systems Engineering, Network Rail

[5.8] *Shah – Habshan – Ruwais Railway Project – Contract C301 (stage 1), Sand Mitigation Measures Efficiency Track Resilience Test* (2013). J A Priest, L M Le Pen, W Powrie, G Cesaretti and R Taglioli. Final Report to Etihad Rail

[5.9] Wet winter pore pressures in railway embankments (2013). K M Briggs, J A Smethurst, W Powrie and A S O'Brien. *Proc ICE Geotechnical Engineering*. doi:10.1680/geng.11.00106

[5.10] Professional Excellence Director, Transportation Unit, Mott MacDonald