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On track: the future for rail infrastructure systems

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Rail travel in the UK has seen a renaissance over the past 15 years. However, realising its future potential will require increased capacity and customer satisfaction while reducing cost and environmental impacts. Following a review of recent UK railway history, this paper outlines the challenges facing the rail system in meeting its future roles and aspirations. It describes recent advances in understanding the behaviour of track, ballast and earthworks through field monitoring, laboratory testing and numerical simulations, and suggests ways in which performance might be improved.

1. Recent history of the UK rail network

Railways have been operating publicly and commercially in the UK for nearly 200 years, since the opening of the Stockton and Darlington railway in 1825. However, it is perhaps only in the past 5 years or so that we have come to recognise Britain's railways as both an asset for the future and an essential national infrastructure system, and that five decades of gradual decline has been reversed (Figure 1).

By the early 1960s, implementation of the British Transport Commission's modernisation plan (BTC, 1955) had seen £1·2 billion invested in infrastructure improvements, new rolling stock, and the replacement of steam locomotives with diesel and electric traction. However, this had done little to reduce the railway's perceived financial losses or stem the exodus of passengers and freight to road transport. For example, new freight marshalling yards built to replace the hundreds of local goods yards once found at nearly every station were redundant almost before they were completed, not least because the statutory rules of railway operation prohibited differential, market-based pricing so that the most lucrative traffic was easily lost to road hauliers. The rapid demise of rail freight during this period also made many of the new diesel locomotives redundant almost before they had been built.

Figure 1. London Overground – in the past 5 years Britain's railways have become recognised as both an asset for the future and an essential national infrastructure system

A different approach to reducing British Railways' perceived deficit was then adopted, encapsulated in the infamous Beeching report (BRB, 1963). The essence was to close 'loss-making' parts of the network until the core that remained operated at a surplus. Much has been written about the naivety of this approach, particularly in economic and social terms; the point missed was that the railway network is not only a system but part of a wider system of systems, and components cannot sensibly be considered in isolation. Thus there was no appreciation of synergetic effects (branch lines bringing traffic and revenue to the wider network), or the need to assess costs and benefits across the transport system and society as a whole.

Beeching's later report (BRB, 1965), focusing on the development of selected routes between major centres of population at the expense of others, was even more startling in its lack of vision and forethought. Its implementation led to the downgrading or closure of potentially strategic routes such as Basingstoke to Exeter, Uckfield to Lewes, Cambridge to Bedford and the Great Central north of Aylesbury. Some parts of the country were particularly badly affected, losing rail connectivity over large areas. This is illustrated by Figure 2, which contrasts the extent of the national rail network in and around Devon historically and today. Many of the abandoned routes have been lost for ever, with parts of the track bed sold and built on almost immediately after closure. Re-opening, where possible, comes at a substantial price.

By the end of the 1960s, the social and economic role of railways was beginning to be recognised. With this came an acceptance that it was unreasonable to expect all of the costs to be met directly from fares. The Transport Act 1968 (1968) paved

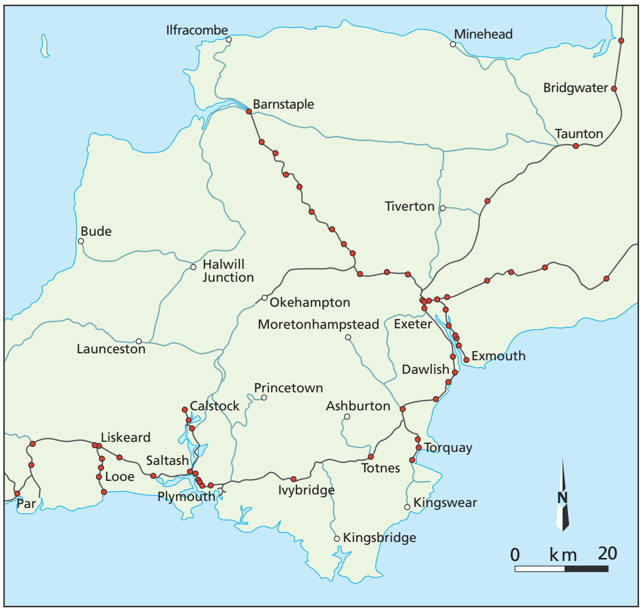

Figure 2. Railways in and around Devon; current network shown in black and principal closed lines in blue (not to scale; map courtesy Simon Blainey)

the way for the creation of passenger transport authorities to oversee public transport in large conurbations, and for un-remunerative but socially necessary parts of the rail network to be supported by grants. Notwithstanding some surprising casualties such as Winchester to Alton in 1973, the closure in the late 1970s and early 1980s of freight lines that had lost their passenger services a decade or so before (e.g. those in Devon and north Cornwall), and lingering threats (e.g. to the Settle and Carlisle line), the pace of closures slowed and eventually halted. Some closed routes are now in use as leisure footpaths and cycle ways, requiring the continued maintenance of significant bridges and viaducts (Figure 3).

By the time the UK's railways were privatised in the mid-1990s, the network seemed to be in a reasonably stable state with lines and especially stations more likely to re-open than to close. Nonetheless, the government's expectation at the time was one of managed genteel decline. In the event, both passenger and freight traffic on the UK's rail network have risen steadily since about 1996, including over the period 2007–2010 when gross domestic product fell (Figure 4). This trend is not uniformly apparent around the world: rail usage in Japan, Germany and Italy remained approximately constant over the same period, but started from a higher base. The number of passenger km travelled

Figure 3. Closed routes used as pedestrian and cycle paths can still require maintenance of significant structures

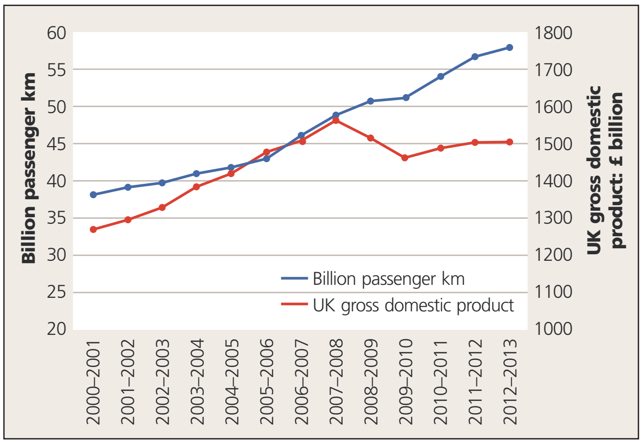

Figure 4. Billions of rail passenger-kilometres and UK gross domestic product (annual figures), 2000–2001 to 2012–2013 (DfT, 2013; ONS, 2014)

annually in the UK is now greater than at any time in the last 60 years on a network comprising around 30 000 km of main line track: roughly half what it was in 1950.

The reasons for the rise in rail use in the UK over the past 18 years are various. The average age of the train fleet has decreased and many older trains still in service have been refurbished, and higher-frequency, regular-interval 'clock face' timetables have become commonplace. Fares have increased above the general rate of inflation, but so have the costs of many alternative transport modes. Some services have become considerably faster, but others have become slower and connections poorer. There may have been structural changes in patterns of employment and work-related travel. Road congestion has also increased over the period and, facilitated by the widespread availability and use of portable electronic devices, time on a train can often be more usefully or enjoyably spent than time in a car.

The rise in the proportion of the world's population living in cities rose from 30% in 1950 to more than 50% in 2011 and is projected to reach almost 70% of an increasing total by 2050 (UN, 2012). This, and the emergence of global megacities with populations in excess of 10 million, has seen the construction of urban metro and rapid transit systems around the world. In the UK, the increasing dominance of London and the relative absence of strong regions seem to have created a demand for long-distance daily commuting. Figure 5 shows places within an hour's travel time by rail of a central London station: as living in London becomes increasingly expensive for ordinary people, the rail network enables the megacity to draw in and provide for the workers it needs from a wide hinterland – in this case, a substantial part of southern and central England.

Ridership on some rural lines has also increased dramatically – for example by 75% over the period 2002–2012 on branch lines in Cornwall and Devon. In some parts of the country, road alternatives remain poor. As the occasional re-opening of a regional line, often with passenger numbers much greater than had been forecast, shows, railways then have a vital role to play.

On main lines, speeds around the world continue to increase, resulting in rail replacing air travel for internal journeys between major urban centres over distances up to about 600 km. In considering the design of a new long-distance railway, it is

Figure 5. Serving the megacity – places inside the shaded area are within 1 h travel time by train from a central London station (map courtesy Simon Blainey)

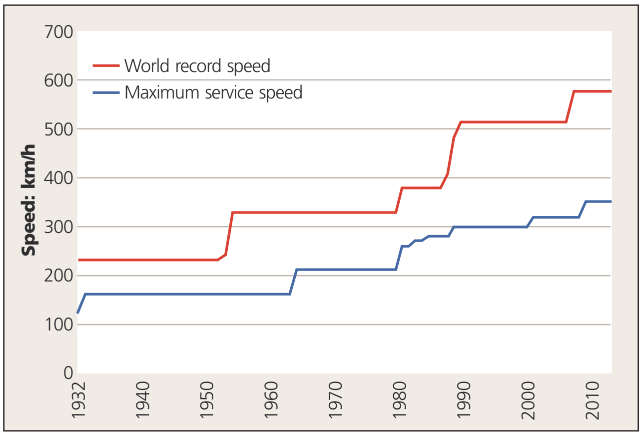

Figure 6. World record and maximum train service speeds, 1932–2012 (data mainly from Gourvish (2010))

instructive to reflect that today's world record is tomorrow's service speed (Figure 6).

2. Future challenges

Looking forward, it follows that rail has a role to play in travel that is

- intra-urban (metro and rapid transit systems)
- pan-urban (linking the megacity to its hinterland)
- extra-urban (the rural lifeline)
- inter-urban (high-speed, city centre to city centre).

There are numerous advantages offered by rail travel. It is perhaps the only form of long-distance rapid transport realistically offering zero carbon dioxide emissions (on electrified lines) at the point of use. It is inherently energy efficient (although increasingly challenged by road vehicles at full capacity), as a result of the low rolling resistance of steel wheels on steel rails.

Rail travel is cost effective, especially when the external costs of other modes in terms of the environment, human lives and health, and the capital value of road vehicles that spend most of the time not being used are taken into account (e.g. Kemp, 2007; Pritchard *et al.*, 2014).

Railways are also a more efficient use of land than motorways in terms of the number of people that can be moved per hour per metre width of the transport corridor, and can offer a higher-quality travel experience in terms of comfort, reliability and safety.

Exploiting the rail network will require improved industry performance in a number of areas, summarised in the Rail Technical Strategy (DfT, 2007) as the 'four c's'

- customers (2038 target: 99% of the customer experience to be 'good')
- carbon dioxide (total emissions to be at least halved, with zero emissions at point of use)
- capacity (to absorb the expected 2–3 times increase on 2008 demand)
- cost (whole life/whole industry costs to be halved).

Realising these improvements poses challenges for the infrastructure. For example, faster, more frequent and in some cases heavier trains introduced to improve capacity and customer satisfaction impose increasingly onerous loading cycles. Extending the railway's regular working day reduces the time available for maintenance by an ageing workforce less willing or able to carry out manual labour than in the past (although the effect of both of these is partly offset by increasing mechanisation).

The cost of the UK's railway system has risen in recent years, with an annual spend of some £3·5 billion on infrastructure maintenance and renewals accounting for about 40% of Network Rail's total (ORR, 2013). As the asset ages, maintenance costs might be expected to increase, while the McNulty report (McNulty, 2011) set the challenge of reducing annual operating costs by £2 billion by 2019.

Perhaps the biggest challenge of all is that an approximate 10% reduction in road traffic by modal shift to rail would mean a 100% rise in rail traffic; thus major increases in rail system capacity would be needed to accommodate any significant modal

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shift from road. This paper now considers how gaining a better understanding of the behaviour of some of the fundamental elements of railway infrastructure systems, and using it to improve design, can contribute to meeting these challenges.

3. Track

Most railway track in the UK and around the world is laid on a bed of stones, typically 28–50 mm in diameter, known as ballast. Ballast generally offers sufficient resistance to unwanted movement of the track, while still allowing adjustments in line and level to be made relatively easily when required. However, known problems with ballasted track are that with trafficking, gradual differential settlement of the ballast results in a loss of level and line of the track. This is traditionally restored by tamping – that is, lifting the track and squeezing the ballast laterally by means of vibrating tines inserted into it, to bring the ballast surface back up to the required level. Tamping disturbs the load-bearing structure of the ballast bed (Ahmed, 2014; Aingaran, 2014) and may damage the ballast particles (McDowell *et al.*, 2005), resulting in the increasingly rapid development of settlement with trafficking after each tamping cycle (Selig and Waters, 1994).

At some locations, especially on canted curves on high-speed lines with tilting trains, the ballast may migrate from the high end of the sleeper, coming to rest against the inside of the lower rail (Figure 7; Priest *et al.*, 2013). This results in a reduction in the resistance to lateral movement of the track especially in the unloaded state, hence a possible increase in the risk of track buckling. It also increases the potential for ballast flight or pick-up, described below.

On high-speed lines, ballast particles can become airborne (a phenomenon known as ballast flight or pick-up) as a result of ice dropping from the train impacting the ballast, or air turbulence perhaps coupled with ground-borne vibrations. This can damage the running surface of a rail (if a ballast fragment lands on the rail and is crushed by a train) and the undersides of trains (Quinn *et al.*, 2010).

Figure 7. Ballast migration on a canted curve – the high ends of sleepers are exposed and the displaced ballast has come to rest in a heap against the inside of the lower rail

Ballast can become clogged (‘fouled’) by fine particles from above (e.g. coal dust), below (e.g. clay) and within (due to attrition), resulting in a loss of permeability and general mechanical performance (Selig and Waters, 1994).

The need for tamping from time to time to restore the design geometry of ballasted track has led to the development of more robust and permanent track forms in which the rails are fastened to or embedded in a continuous reinforced-concrete slab. In the UK, this form of track is used mainly in tunnels and on bridges. Elsewhere, it has been increasingly used in connection with new high-speed lines. Initial costs (in terms of money, embodied energy or carbon dioxide emissions) are higher, but whole-life costs may be lower because of the reduced maintenance requirement (e.g. Kiani *et al.*, 2008; Zoeteman and Esveld, 1999). However, the projected difference either way is highly dependent on the ground conditions and the performance assumptions made (Mason, 2013).

Recent research funded by the Engineering and Physical Sciences Research Council (EPSRC) through the Track21 programme grant (www.track21.org.uk) is investigating the potential for system modifications to improve the performance of conventional ballasted track, by reducing the rate of permanent settlement due to trafficking and hence the need for tamping, towards the ideal of tampless track. Tests have been carried out in the Southampton railway testing facility (SRTF; Le Pen and Powrie, 2011) to investigate the accumulation of residual (plastic) settlement during up to 3 million loading cycles representative of an axle load of 20 t, for the following configurations

1. reference conditions (Network Rail standard ballast and a G44 reinforced-concrete sleeper)
2. as 1, but with an SNCF (Société Nationale des Chemins de fer Français)-type duoblock sleeper
3. as 1, but with under-sleeper pads to reduce ballast attrition
4. as 1, but with a modified ballast grading in which the proportion of smaller particles was increased in an attempt to improve particle interlocking
5. as 1, but with the shoulder slope reduced from ~45° to ~30°.

Test results suggest that interventions such as these could reduce the rate of permanent settlement with the logarithm of the number of load cycles by at least 30%. Pressure-sensitive paper placed under the sleeper shows that there are relatively few point contacts between a reinforced-concrete sleeper and the underlying ballast; the use of under-sleeper pads can mitigate this effect, which is also less pronounced on sleepers made of softer materials such as timber or plastic.

A further technique currently under investigation is the random fibre reinforcement of ballast. Triaxial tests on one-third-scale ballast indicate that the introduction of a suitable proportion of random fibres of an appropriate size has the potential to increase the stiffness and the peak strength, while suppressing dilation. Further details are given by Ajayi *et al.* (2014).

An interesting recent study carried out using the SRTF was an investigation into the effects of sand fouling of the ballast.

Measured quantities of sand were gradually introduced into a pre-existing ballast bed as the load was cycled. The sand had no effect on the mechanical behaviour of the ballast bed until it completely filled the voids below the sleeper soffit. After this point, the resilient (in-cycle) stiffness increased and the rate of accumulation of plastic settlement fell dramatically. If the reduction in permeability associated with the voids between the ballast particles becoming filled with sand could be tolerated and the resilient response softened by the provision of suitable rail pads, the near-elimination of ongoing plastic settlement might be viewed as advantageous.

Computationally efficient discrete-element simulations using ‘potential particles’ (Harkness, 2009; Houlsby, 2009), with shapes representative of real ballast (Figure 8), are being used to investigate phenomena such as ballast migration and the likely success of interventions such as changing the particle size distribution and the addition of random fibre reinforcements, on the basis of the underlying micromechanics.

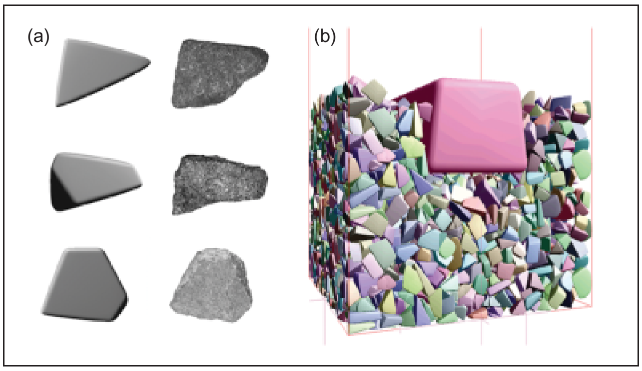

Figure 8. (a) ‘Potential particles’ with ballast-like shapes and (b) discrete-element method simulation of ballast migration

4. Switches and transitions

Switches and crossings (commonly abbreviated to ‘S&C’ or termed ‘points’) and transition zones from plain line onto hard substructures such as bridges, are particularly problematic. They typically make up less than 1% by length of the track on a network, yet consume perhaps 20% of the maintenance budget (Bouch *et al.*, 2010).

Switches and crossings are needed for operational flexibility; for example, to loop stopping trains into stations to enable fast trains to pass. The traditional form of construction is illustrated in Figure 9, which shows the swinging switch rails used to direct an oncoming train onto either the straight or the diverging tracks, and also the gap that trains must negotiate as they traverse onto the crossing nose. This gap results in potentially substantial

Figure 9. Switches and crossings outside Marylebone station, London showing swinging switch rails and gaps at crossing nose

Recent work suggests that on a congested, mixed-traffic railway, faster turnouts may not save enough time to create extra train paths. However, the radical redesign of switches and crossings could lead to more significant reductions in headway on high-speed lines

impact loads as each wheel traverses it, despite the efforts of designers to minimise the effect by adjusting the rail profile geometry and/or utilising swing-noses on high-speed lines. Impact loads increase with train speed and may result in accelerated geometry deterioration which – despite the specification of an increased ballast depth and the development of techniques such as stone blowing and specialist S&C tampers – can be difficult to counter.

Trains must generally pass onto the diverging line at a switch at a reduced speed; the resulting requirement for trains to brake or accelerate on the main line reduces capacity. Turnout speeds can be increased by increasing the radius of the turnout curve. However, this makes the crossing longer and in the case of a passing or station loop a greater length of track is needed for stopping trains to brake and accelerate within the loop, hence a greater initial capital cost.

Recent work suggests that at stations on a congested, mixed-traffic railway, faster turnouts may not save enough time to create extra train paths (Preston, 2013). However, the radical redesign of S&C could lead to more significant reductions in headway on high-speed lines (Goodall *et al.*, 2013). The relative benefits and costs associated with higher-speed turnouts must be considered on a case-by-case basis; operational tactics (on pathing), longer trains, progressive strategic improvements (e.g. gauge widening and the removal of bottlenecks) and the construction of new lines are likely to play at least as important a role in building capacity.

The real behaviour of switches and transition zones in terms of their vertical deflection under train loading may be investigated by monitoring dynamic displacements using geophones and digital image analysis of high-speed video images (Bowness *et al.*, 2007). For example, Le Pen *et al.* (2014) describe the use of these techniques to monitor the behaviour and effectiveness of conventional track maintenance at a level crossing.

Coelho *et al.* (2011) report even more unexpected and damaging behaviour measured at a transition zone in the Netherlands. Instead of giving a gradual change in subgrade stiffness between an embankment and a reinforced-concrete culvert passing under the track, the structure installed for that purpose led to a five-fold increase in dynamic displacements as the culvert was approached. There is clearly scope to use field measurement techniques such as those described by Bowness *et al.* (2007) to understand the real behaviour of switches and transitions and develop more cost-effective, lower-maintenance designs.

5. Earthworks

Much of the UK's railway network is supported on ageing earthworks of uncertain design and construction. Many embankments were built by simply end-tipping spoil from nearby cuttings. This resulted in a structure usefully conceptualised as clods of intact clay in a matrix of softened material (O'Brien, 2007).

Clay fill embankments are subject to seasonal shrinkage and swelling as the loss of moisture through evapo-transpiration generally exceeds the effective rainfall in summer, and vice versa in winter. This causes variations in track level (Figure 10), resulting in speed restrictions being imposed. Smethurst *et al.* (2006, 2012) developed methods for the calculation of seasonal variations in moisture content from weather and vegetation data for a grass and shrub covered slope, with reference to a cutting on the A34 near Newbury. This work established a quantitative linkage between weather, vegetation and soil water content for a reasonably uniform clay. A clay fill embankment brings further complications in terms of characterising the soil and more extensive heterogeneity, which are currently being investigated in the EPSRC-funded project Ismarts (www.ismartproject.org).

Mature trees cause larger and more deep-seated seasonal changes in moisture content, owing to their greater water demand and deeper rooting zone. The effectiveness of tree removal as a control on seasonal shrinkage and swelling movements was investigated by Briggs *et al.* (2013b) in a field trial on a London Clay and ash fill Network Rail embankment near Southend on Sea, Essex.

The loss of suction associated with rewetting could adversely affect the stability of the embankment in the longer term; thus the removal of all of the trees from an earthwork slope is probably undesirable. Numerical simulations by Briggs (2011), in which the effect of trees was modelled by abstracting water from the rooting zone, have shown that seasonal shrink–swell movements can be substantially reduced and many of the benefits of deep-seated persistent suctions retained by leaving the trees in place over the lower third of the slope. Thus appropriate vegetation management can help maintain both the serviceability

Figure 10. Variations in track level due to seasonal shrinkage/swelling (courtesy Graham Birch)

Climate change means the incidence of embankment and slope failures during winter months is expected to rise

and stability of an earthwork. However, after a sustained period of exceptionally wet weather (e.g. a wet winter followed by a wet summer and a further wet winter), pore pressures must be expected to rise, increasing the possibility of embankment or cutting slope failure (Briggs *et al.*, 2013a).

With climate change predicted to bring more extreme patterns of weather, in particular wetter winters with more intense rainfall (Clarke and Smethurst, 2010), the incidence of embankment and cutting slope failures due to increased pore water pressures (i.e., the loss of pore water suctions) during the winter months must be expected to rise. This means that harder engineering-based slope remediation measures will in some cases be necessary to maintain the resilience of the infrastructure. An increasingly used method of slope stabilisation is the installation of discrete reinforced-concrete piles, spaced generally between two and four pile diameters apart (Figure 11). Uncertainties relating to the minimum spacing at which the technique is effective (above which the soil can flow through the gap between adjacent piles) and the mode of pile bending in the absence of a clearly defined slip surface within the soil have been investigated by the instrumentation of piles and the ground at three sites (Figure 12 and Table 1).

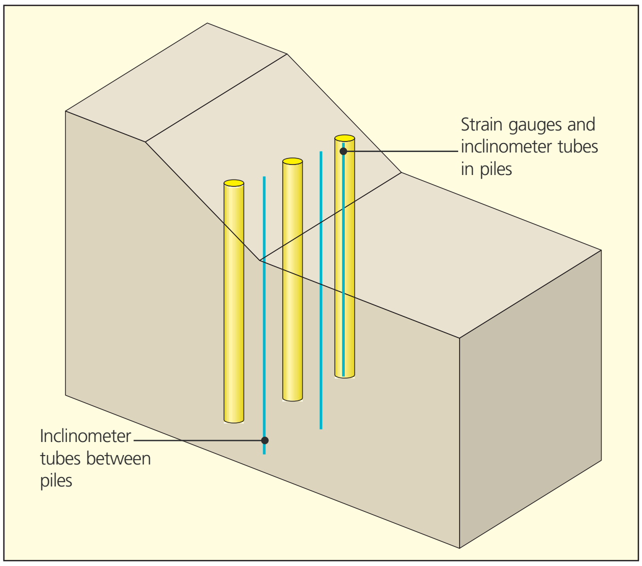

Figure 11. Schematic layout of discrete pile stabilisation scheme and typical instrumentation layout

Figure 12. Instrumented site at Grange Hill (courtesy Joel Smethurst)

Monitoring at these sites, together with earlier geotechnical centrifuge model tests carried out by Hayward *et al.* (2000) and finite-element modelling by Kanagasabai *et al.* (2011), have indicated that piles can be spaced at up to three to four pile diameters (centre to centre) and retain the benefit of three-dimensional effects. Appropriate mechanisms of behaviour for use in design calculations have also been identified. As a result, estimated cost savings of 10–15% compared with conventional solutions are already being realised (O'Brien, personal communication 1 October 2013).

6. Bridge scour

Bridges over rivers and estuaries can be vulnerable to the removal by flowing water of sediment from around the foundations of their supports – a process known as scour. Failures associated with scour over the past decade or so include those at Beighton, Yorkshire (2003), the Malahide Viaduct, County Dublin, Eire (2009), and Feltham, London (2009). These and others are discussed by Maddison (2012). At present, monitoring and assessment of scour around bridge pier foundations is usually carried out visually by specialist divers. However, inspection can

Site location	Year of instrumentation	Type of structure	Slope geology	Typical rate of movement of pile top: mm/year	Accumulated downslope movement as at 2010: mm
Hildenborough, Kent (Smethurst and Powrie, 2007)	2001	Pile-stabilised embankment	Weald Clay	5	50
Mill Hill East, London (London Underground Northern line)	2004	Pile-stabilised embankment	Anglian Till	1	5
Grange Hill, Essex (London Underground Central line)	2006	Pile-stabilised cutting slope	London Clay	4	20

Table 1. Instrumented pile stabilised slopes

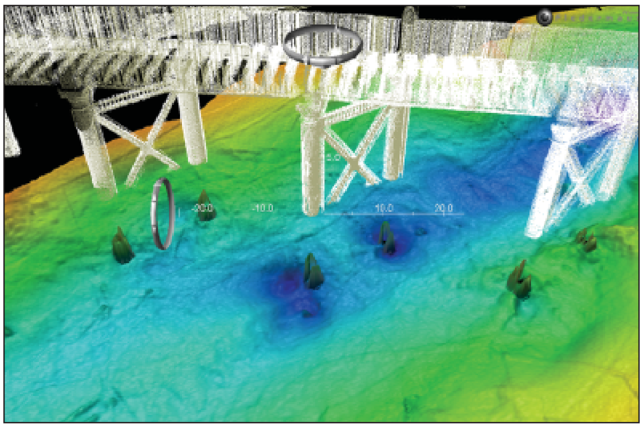

Figure 13. Sonar images of a river bed, showing scoured areas around bridge piers in dark blue

be hazardous (especially in the fast and turbulent flow conditions likely to cause scour), expensive and unreliable as underwater visibility is often poor.

Recent trials carried out by Kongsberg Maritime, Network Rail and the University of Southampton have demonstrated the potential for obtaining high-resolution river bed profiles using multi-beam sonar scanning, and for the long-term monitoring of identified scour features using a bridge-mounted, long-immersion sonar system (Figure 13). Three-dimensional digital river bed and localised high-resolution profiles can be analysed to determine bed volume changes associated with scour activity and used to direct more detailed long-term inspections as appropriate. This approach shows much promise as a reliable and cost-effective digital condition monitoring technique for scour, which overcomes the limitations of current qualitative risk-based assessments.

7. Conclusions

Rail travel has seen a renaissance in the UK over the past 15 years or so. Electrified railways represent perhaps the only form of long-distance mass transport that can realistically be free of carbon dioxide emissions at the point of use, as well as an efficient, safe and potentially attractive travel option. In the future, railways have an increasingly key role to play in metro (urban), megacity (pan-urban), rural (extra-urban) and intercity (inter-urban) transport.

Together with the application of numerical simulations, data obtained through monitoring and measuring the behaviour of real structures are enabling the development of both lower-maintenance and more-resilient designs, and pro-active regimes of preventative maintenance and repair

Meeting expectations will be a challenge: a 10% modal shift from road to rail would approximately double current rail usage in the UK. It seems doubtful that such an increase in capacity could be achieved with the current infrastructure; a combination of enhancement strategies, including longer trains, progressive opportunistic improvements to remove bottlenecks and the construction of new lines, will be required. Nonetheless, the improvement of existing infrastructure so that it is able to carry more frequent, faster and heavier trains with less need for maintenance, and is better able to withstand the effects of an increasingly volatile climate, will have a major role to play.

Understanding track, ballast and sub-base behaviour through observation and science can lead to improvements in design and performance. Other infrastructure, especially earthworks, may be of uncertain design, construction and condition, causing further problems for railway operation and maintenance planning.

Monitoring and measurement using techniques such as geophones, digital image analysis and sonar imaging have a crucial role in understanding the condition and performance of railway infrastructure. Together with the application of numerical simulations, the data obtained through monitoring the behaviour of real structures are enabling the development of both lower-maintenance and more-resilient designs, and pro-active regimes of preventive maintenance and repair.

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