ACHILLES: reducing earthworks failure risks and whole-life costs

Armstrong, John[1], Preston, John[1], Helm, Peter[2], Svalova, Aleksandra[2]

[1]Transportation Research Group (TRG), University of Southampton,
Burgess Rd., Southampton SO16 7QF, UK

[2]Newcastle University, Newcastle-upon-Tyne NE1 7RU, UK

Abstract

Vital transport and other linear infrastructure in Britain and elsewhere depends upon an extensive set of earthworks of varying age, condition and engineering quality. These earthworks are subject to normal deterioration, and these processes are exacerbated and complicated by the variable and unpredictable effects of climate change on weather patterns, particularly in the form of increased rainfall intensity and flooding. Railway earthworks are particularly vulnerable to these effects, given their typical age and the comparatively primitive engineering techniques used in their design and construction, as well as the increasing (pre-Covid) traffic levels to which they have been subjected. This paper describes research work being undertaken to improve the understanding of earthworks condition, deterioration and remediation, and to develop methods and tools to assist with the economic assessment of, selection from and prioritisation of alternative design interventions.

Keywords: Railways; Earthworks; Climate Change; Remediation; Economic Assessment

1 Introduction

In Great Britain, as elsewhere, society depends upon extensive networks of earthworks providing vital infrastructure. These earthworks, especially those in the railway networks built largely in the 19th century, are ageing and subject to deterioration, a situation that is exacerbated by climate change and increased rainfall intensity. To provide operational resilience now and into the future, an improved understanding of deterioration mechanisms and the effects of remedial measures is required, together with methods for assessing alternative interventions and identifying the most cost-effective options.

The ACHILLES (Assessment, Costing and Enhancement of Long-Lived Linear Assets) research programme [2] is a collaboration between six universities and the British Geological Survey, with guidance from industry. The programme aims to develop an improved understanding of earthworks performance and deterioration, and to enable the forecasting of asset behaviour and the identification of improved intervention strategies for reducing and ideally minimising whole-life asset and network costs, while maintaining acceptable levels of safety and serviceability.

Following this introduction, the background to and context for the work are set out. The overall objectives of ACHILLES are then summarised, and further details are provided of its aims with respect to engineering economics. The data sources being used, the planned methodology and initial results are then described, followed by some conclusions and a list of references.

2 Background and context

2.1 Background

Some 250 years of technological development since the start of the first Industrial Revolution have produced an infrastructural legacy of canals, railways, roads, flood defences and other assets (with associated maintenance liabilities), many of which include extensive earthworks: it is estimated [1] that approximately “two-thirds of the UK transport infrastructure network is supported by or adjacent to engineered slopes.” As they age, these long-lived linear assets (LLAs) inevitably deteriorate, and are now increasingly vulnerable to extreme weather events exacerbated by climate change, of the type tragically seen in July 2021 in Germany, Belgium and the Netherlands [3], and in central China. This is a particularly challenging issue for railway networks, given the age – most of Britain’s network dates from the nineteenth century – and extent of the earthworks involved. However, it is also becoming an issue for Britain’s major highway network, whose earthworks were engineered to higher standards than those of the railway network, but, in the case of much of the high-capacity motorway system, are now more than fifty years old.

Maintaining and renewing these assets to keep them in a safe operating condition is expensive, but responding to and repairing earthworks failures is much more so [1], especially when the costs of delay and disruption to affected users are considered. In the worst case, earthworks failures can result in injury and death to transport workers and the travelling public, as in the case of the Carmont derailment near Stonehaven in Scotland on 12 August 2020 [4].

2.2 Context

In its Earthworks Technical Strategy (ETS) [5], Network Rail, the infrastructure manager (IM) of Britain's national railway network, expresses its commitment "to continuous improvement in earthwork management", and notes that, while "longer term trends in earthwork safety events continue to reduce [i.e. to improve]", it "cannot be complacent", a cautionary note that was tragically borne out by the Carmont accident [4]. Network Rail is responsible for over 190,000 earthwork assets, extending over approximately 19,000 km [5], and its main challenges in this context include:

- *Improving the capability of the asset base to be more weather resilient*
- *Prolonged periods of wet weather that increase … the likelihood of asset failure*
- *Management of the infrastructure during short duration adverse/extreme weather events that can lead to rapid washout failures in granular slopes*
- *Rapid failures that develop and occur within a matter of minutes to hours*
- *Increased embankment traffic loading and tonnage growth*
- *Seasonal shrink-swell (desiccation) of embankments causing serviceability issues to track geometry*
- *Peat wastage of sub-surface soils that result in subsidence*
- *Natural … slopes beyond [Network Rail] infrastructure where potential hazards may exist*
- *Using available data to identify and fix the root cause rather than treating the symptom in the embankment, formation, drainage and track components of the rail system*
- *Effects of vegetation on soil and rock slopes*
- *Impacts of climate change*

The ETS identifies three main categories of earthworks investment:

- *Planned Renewal,* where an asset is strengthened to improve its slope Factor of Safety (FoS, i.e. the ratio of available shear strength to actual shear stress along a potential failure surface) to contemporary standards, "providing increased resilience and improving reliability"
- *Actively Failing Asset*, where, based on an inspection report or monitoring equipment outputs, asset renewal via "accelerated intervention" is undertaken to prevent catastrophic failure
- *Catastrophic failure*, where failure occurs and the asset is then renewed (with increased costs, levels of disruption and safety risk)

Network Rail is seeking to move from reactive interventions (the last two categories) to proactive planned renewals (the first category). The ETS quotes an earlier Transport Resilience Review [6] undertaken by the UK Department for Transport (DfT), which advocated the progressive strengthening of network resilience, and recommended that

> *Network Rail should maintain a strong focus on trialling newly available condition monitoring and slope stabilisation technologies, working with academic and other researchers and with other railway administrations, to improve its ability to identify and anticipate slopes that will fail and target remedial work as efficiently as possible. Network Rail should continue to commission academic research into possible slope stabilisation techniques.*

Similarly, Dijkstra et al. [1] note that, particularly in the context of climate change, it is "cost effective to develop tools that enable asset managers to prioritise … investments to maintain [network] resilience." The aims of the ACHILLES research programme are clearly consistent with these recommendations.

The 2017 Rail Technical Strategy (RTS) Capability Delivery Plan, produced by Britain's Rail Safety and Standards Board [7], set out twelve key capabilities, all of which were recognised by the ETS, with particular emphasis on the following three:

- *Minimal disruption to train services*
- *More value from data*
- *Accelerated research, development and technology deployment*

Again, ACHILLES also seeks to enhance these capabilities. The RTS has since been further updated [8], and continues to focus upon the optimisation of train services, the importance of data, business-driven innovation and a "digitally talented workforce."

The ETS briefly describes the Earthworks Safety Risk Matrix (ESRM) used to assess and manage safety risk. The ESRM categorises assets based on their condition (hazard category) and criticality (consequence of failure), and is central to Network Rail's Earthworks Policy, some of whose key objectives are to:

- *Prioritise sites with highest safety risk (informed by the ESRM)*
- *Optimise the number of assets improved in condition for a given level of funding*
- *Adopt a lowest whole life cost approach balancing operational and capital investment*
- *Adopt a proactive approach to intervene prior to reduction in level of service*

By meeting these and other objectives, Network Rail aims to "maintain and incrementally improve the earthwork asset resistance to the threat from adverse and extreme weather."

3 Objectives

3.1 Wider objectives of ACHILLES

The ACHILLES vision is "for the UK's infrastructure to deliver consistent, affordable and safe services, underpinned by intelligent design, management and maintenance," and it aims to provide the tools "to assess, monitor, design and repair the performance of the ground" upon which infrastructure depends. The programme addresses three main research challenges:

1. *Deterioration Processes*, i.e. the processes by which materials and assets degrade over time
2. *Asset Performance*, i.e. the performance of infrastructure assets with and without engineering interventions
3. *Forecasting and Decision Support*, i.e. the forecasting of asset (and network) behaviour with and without interventions and the identification of the most economically advantageous intervention strategies

These challenges are addressed through four complementary themes and workstreams:

1. *Performance and Deterioration (PaD)*
2. *Monitoring and Measurement (MaM)*
3. *Simulation and Modelling (SaM)*
4. *Design and Decisions (DaD)*

3.2 Specific objectives of Research Challenge 3 (SaM and DaD)

The work being undertaken by the University of Southampton's Transportation Research Group (TRG) focusses on Research Challenge 3 (Forecasting and Decision Support – with an emphasis on engineering economics) and covers both the SaM and DaD themes. It combines the outputs of geotechnical simulations with other data as inputs to the development of economic models of earthworks assets and networks with and without interventions, to enable the improved assessment and forecasting of whole-life costs under alternative intervention strategies.

As the owner of 190,000 earthworks assets, Network Rail cannot realistically maintain continuously up-to-date condition records, performance forecasts and optimised intervention plans for all assets, and must prioritise those assets that present the greatest safety risk, as noted above. Improved modelling of asset performance and whole life costs under alternative intervention strategies would therefore help Network Rail to meet the other three listed key objectives of its Earthworks Strategy, i.e. to take a proactive approach to asset intervention, balancing capital and operational costs to minimise whole life costs, and thus maximising improvement in asset condition for a given level of funding. These are the objectives of ACHILLES' SaM and DaD themes and workstreams, on which TRG's involvement is focussed (although staff from the University of Southampton are involved in all four workstreams). TRG's main planned contributions to the two workstreams are summarised in the flowchart shown in Figure 1, running from SaM 4.2 through to DaD 5.

TRG's work is based primarily on the outputs from the SaM 3 and SaM 4.1 condition modelling activities, undertaken by Newcastle University and shown in Figure 1 in the two data and process boxes with dashed outlines, combined with cost data inputs. The results of the simulations of earthworks behaviour with and without intervention will be combined with the cost data to perform economic cost-benefit analysis (CBA) of 'Do-Something' vs. 'Do Nothing'/'Do-Minimum' scenarios for individual assets and the routes and networks that they collectively form.

Doing nothing, or making the minimum required intervention, will save money in the short term, but may result in larger lifecycle costs (and potential failures) in the longer term. To meet Network Rail's key objectives (see above), it is important to identify the intervention options which maintain the serviceability and safety of the infrastructure, while reducing and ideally minimising lifecycle costs, and thus to provide decision support for the optimal design and intervention outcomes. The CBA results for individual assets will be aggregated at the route and network levels, and financial CBA will be extended to include end-user and environmental impacts to provide a wider social CBA. The results will be based on Whole Life Costs (WLCs) and will cover asset lives of up to 180 years.

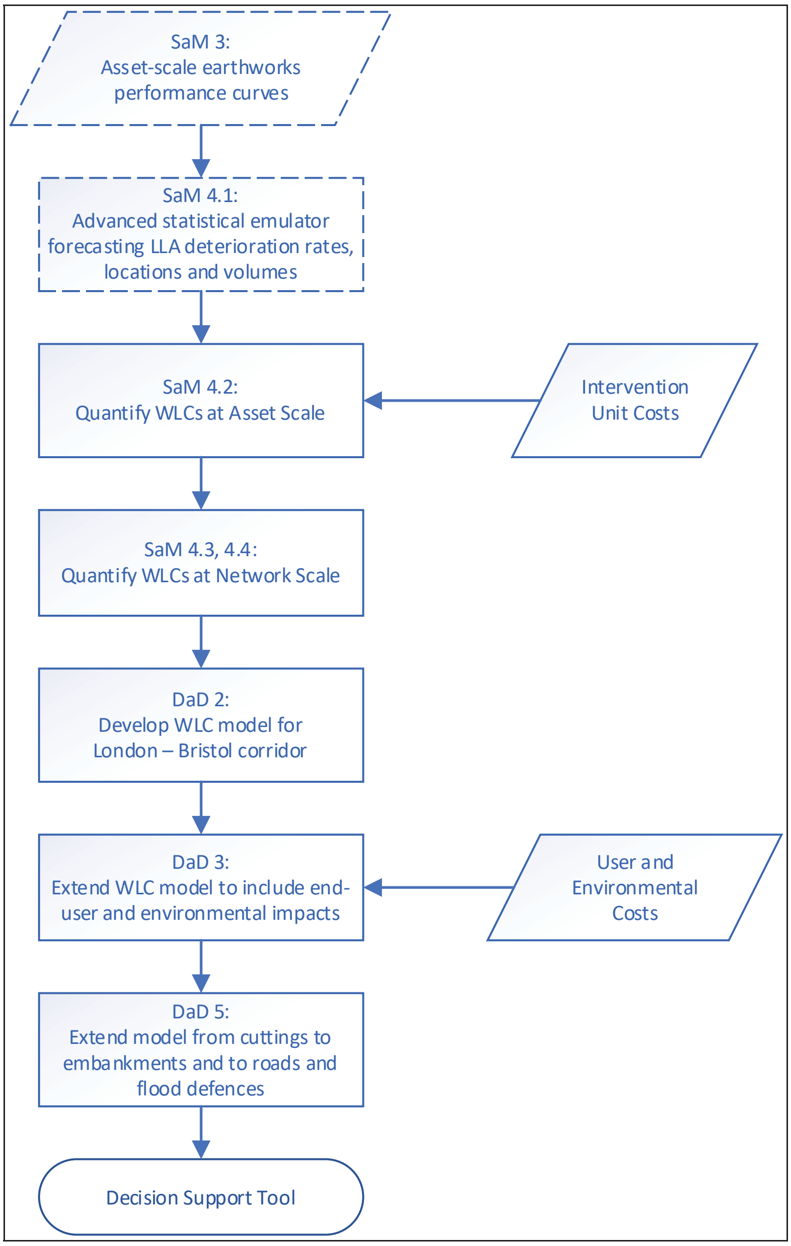


Figure 1: Outline process flowchart

The work being undertaken for SaM and DaD thus addresses the four listed key objectives of Network Rail's Earthworks Policy. The Great Western Main Line (GWML) railway alignment between London Paddington and Bristol Temple Meads, approximately 190km west of London, is being used as an initial case study.

Initial geotechnical modelling of railway cuttings will be extended to embankments and to other asset categories (primarily earthworks for highways and flood defences), and to include the anticipated impacts of climate change. The CBA process will be extended spatially and temporally to enable the provision of decision support for interventions in individual infrastructure assets and categories and, collectively, for an integrated approach to wider, mutually-dependent infrastructure systems under different climate change scenarios. The trade-offs between the costs and benefits of additional system information are also being considered as part of the DaD 3 workstream.

4 Data sources, methodology and initial results

4.1 Data sources

As indicated in Figure 1, the following data sources are being used:

- Predicted times to earthworks failure, with and without interventions, and predicted failure volumes (source: advanced statistical emulator)
- Geotechnical cross-sectional data along the London – Bristol route (source: Network Rail)
- Unit cost data for earthworks interventions and repairs – (sources: standard civil engineering data sources [9, 10] and bespoke industry advice as required)
- Timetable data as the basis for traffic volumes and the associated socio-economic costs of delays and diversions (source: Network Rail Open Data feeds [11])
- Other data and appraisal guidance will be also be used as and when required: these include the values of time specified in the Passenger Demand Forecasting Handbook (PDFH) [12] for Britain's railways, and the analysis guidance provided in DfT's WebTAG [13] online tool.

The earthworks condition and failure modelling being done by Newcastle University is based upon a combination of SHETRAN (Système Hydrologique Européen TRANsport), a finite difference hydrological model [14], and FLAC (Fast Lagrangian Analysis of Continua) with Two Phase Flow [15]. While this advanced geotechnical modelling is a very useful complement to, and potential partial replacement for, manual inspection and condition recording of earthworks, it is still computationally intensive and timeconsuming, and unsuitable for application individually to each of Network Rail's 190,000 earthworks assets. Variations in the model outputs in response to changes in the input parameters are therefore being investigated by means of Latin hyper cube methods, which enable the design space to be covered efficiently. These detailed modelling outputs then provide the inputs to a Gaussian process emulator, enabling the rapid interpolation of modelled behaviour across the full range of realistic model parameters, increasing the speed and coverage of the overall modelling process, and providing the required geotechnical inputs to the CBA of alternative options.

For each of the combinations of intervention strategy and climate change and rail traffic scenarios, the outputs from the analysis will indicate the likely timings, locations and, based upon slope heights and angles, volumes of expected earthworks failures (i.e. when Ultimate Limit State (ULS) FoS values are reduced to less than one). Graphical examples of the outputs are shown in Figures 2 and 3, with FoS values indicated by the colour-coded keys. The data illustrated by the Figures will form the geotechnical inputs to the CBA processes being undertaken in SaM 4.2 through to DaD 5.

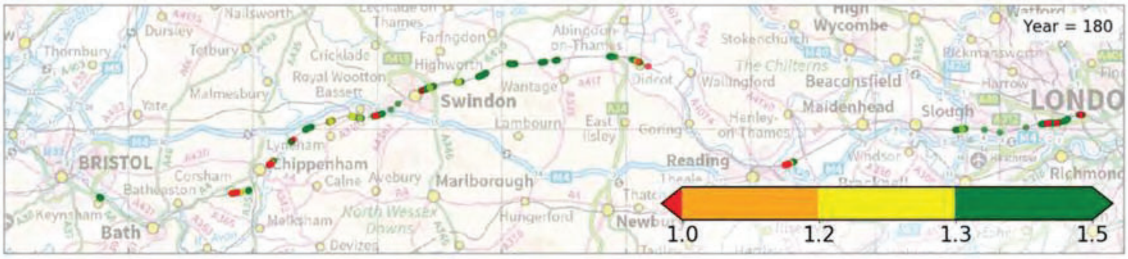


Figure 2: Earthworks vulnerabilities along the London – Bristol railway line in terms of ultimate limit state Factor of Safety

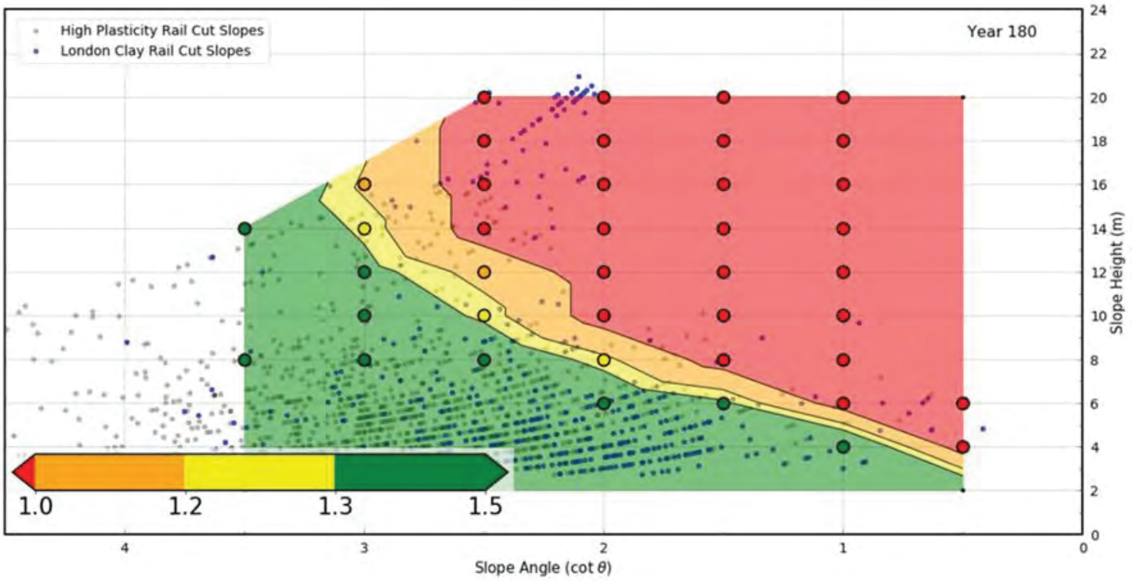


Figure 3: Estimated vulnerabilities and times to failure for a range of slope angle and height combinations

The geotechnical cross-sectional data for the GWML between London Paddington and Bristol Temple Meads comprises 8,672 unique slope IDs, belonging to 1,907 distinct earthworks, many earthworks having been surveyed at multiple cross-sectional locations. Preliminary emulator outputs have been generated for 1,432 of these unique slope IDs, comprising cutting slopes classified as having high failure potential.

As indicated above, initial unit cost data for remedial and repair work to earthworks has been obtained from standard industry sources. Data is not readily available for some more specialist approaches, such as soil nails, necessitating additional advice from industry. More generally, the costs of interventions can be highly situation- and location-specific (some sites present much greater access challenges than others, for example), and so a 'one size fits all' approach to calculating costs is unlikely to be sufficient.

Timetable data for passenger and freight train services is being obtained from Network Rail's Open Data feeds. The data is being used to assess traffic flows along the route between London and Bristol.

The nature and application of the other data and appraisal guidance being used in the SaM and DaD workstreams of ACHILLES are considered and described in the following sub-section.

4.2 Methodology and initial results

The modelling and emulation processes generate performance (Factor of Safety) deterioration curves of the type shown in Figure 4. The curve shown is for an 8m high, 1/3.5 (cot $\Theta = 3.5$) cutting slope in over-consolidated high-plasticity clay. This is typical of the soil forming 374 of the cutting slope assets and 211 of the embankment assets on the line between London Paddington and Bristol Temple Meads.

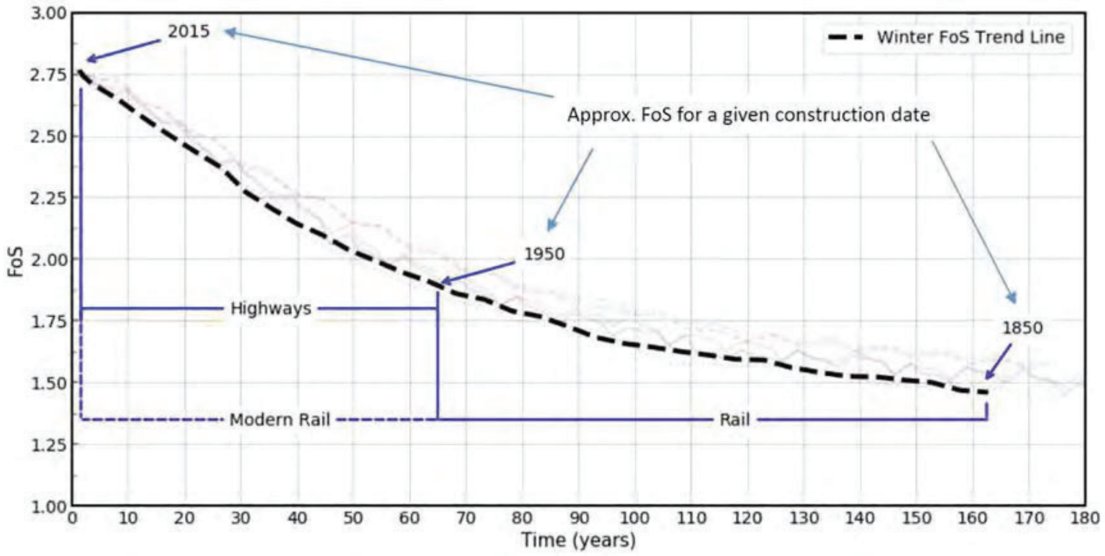


Figure 4: Example earthworks Factor of Safety (FoS) deterioration curve

The route between London and Bristol has been subdivided into nine 'constant traffic sections' (CTSs) for the purposes of subsequent socio-economic cost-benefit analysis. Each CTS comprises a section of the network between two junctions and/or termini, over which the number of passenger and freight trains operated does not vary (i.e. there are no intermediate junctions or termini between the endpoints of a CTS). The number of tracks on a CTS is also constant (or approximately so). The route subdivision is shown in Table 1.

Table 1: CTSs between London and Bristol

CTS No.	From	To	No. of Tracks	Length (km)
1	London Paddington	Airport Junction	4 – 6	17.9
2	Airport Junction	Reading	4	39.9
3	Reading	Didcot Parkway	4	27.6
4	Didcot Parkway	Swindon	2	38.9
5	Swindon	Wootton Bassett Junction	2	9.3
6	Wootton Bassett Junction	Thingley Junction	2	21.0
7	Thingley Junction	Bathampton Junction	2	13.7
8	Bathampton Junction	Bath Spa	2	3.6
9	Bath Spa	Bristol Temple Meads	2	18.5
Total				190.4

The geotechnical cross-sectional data and the associated preliminary outputs from the emulator have been mapped to the CTSs.

Pre-Covid timetable data has been processed and weekday, Saturday and Sunday passenger and freight services in each direction on each CTS have been identified and stored in a database for subsequent use. The process is being repeated for the current timetable and standardised for future use: one of the ongoing challenges facing the railway industry is to establish when, and at what level and mix, with-/post-Covid traffic volumes and trends are likely to stabilise.

As well as providing predictions of locations, times and sizes of earthworks failures under a 'Do-Minimum' or 'Business as Usual' (BaU) scenario, the geotechnical modelling and emulation processes will be used to predict the service life extensions resulting from 'Do Something' interventions in the form of earthworks remediations undertaken at different points in asset lives. This will produce outputs of the type represented in Figure 5, where a simple pore pressure equilibration model is used to predict the extensions to an asset's serviceable life resulting from the introduction of improved slope toe drainage at different times in its original serviceable life.

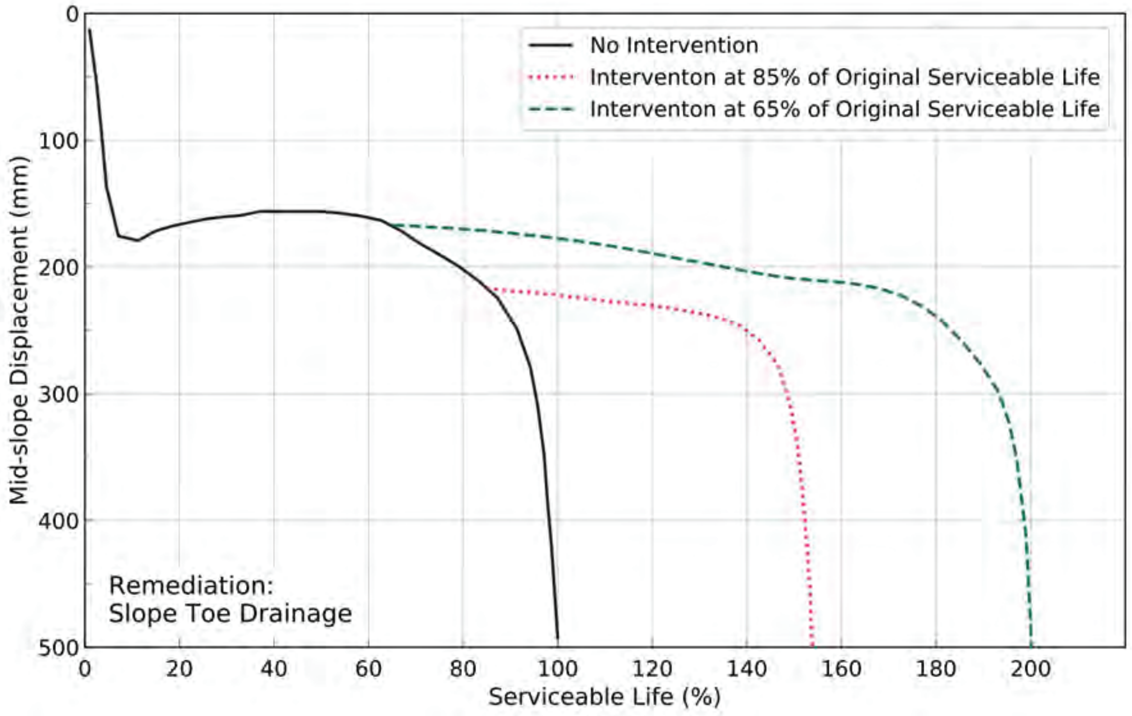


Figure 5: Alternative drainage interventions and their effects on mid-slope horizontal displacement in a simple pore pressure equilibration model (no climate boundary conditions)

As indicated in Figure 1, the outputs from the emulator (SaM 4.1) will be combined with unit cost data in SaM 4.2 to assess the variations in asset WLCs under BaU and alternative 'Do Something' intervention scenarios, thus providing a comparison between the economic outcomes of alternative asset management strategies. In the subsequent stages of SaM, the results for individual assets will be combined and scaled up to determine and assess alternative WLC outcomes at a network scale. This work makes use of and builds upon experience gained in related collaborative work undertaken by the University of Southampton for the ITRC (Infrastructure Transitions Research Consortium) and NISMOD (National Infrastructure Systems Model) projects [16].

This Simulation and Modelling work provides the basis for elements of ACHILLES' Design and Decisions workstream, in which the modelling and assessment of engineering economics will be extended in DaD 2 and combined in DaD 3 (see again Figure 1) with user impact and environmental cost data to produce a WLC model and decision support facility for the GWML between London and Bristol, including end-user and environmental impacts.

This work in DaD will include but also move beyond the standard economic assessment approaches being taken in SaM, i.e. the industry-standard Civil Engineering Standard Method of Measurement (CESMM) and Rail Method of Measurement (RMM), and the use of unit costs of materials, equipment and labour. It will again include assessment of alternative Do-Something options relative to each other and to BaU, but will extend the analysis to include operational and embodied CO_2, and also the wider environmental impacts of modal shift between road and rail travel in response to disruptive events and system improvements.

In addition to, and feeding into the wider social and environmental impacts of disruptive events, the analysis in DaD will include the consideration of disruption costs associated with both asset failures and the maintenance (and renewal/enhancement) activities required to prevent them. This analysis will be based upon the affected traffic volumes (as indicated by the timetable and other data) and the associated values of time specified in PDFH [12] and WebTAG [13]. It is also intended to include consideration of the railway industry-specific Schedule 4 and Schedule 8 compensation systems for planned and unplanned disruptions, respectively; however, these systems were developed in the context of Britain's privatised railway structure and with a view to incentivising improved performance from both the infrastructure manager (i.e. Network Rail) and the passenger and freight train operators. As the structure of Britain's railways moves towards a more integrated model in response to the recently-published Williams-Shapps Plan for Rail in Britain [17], Schedules 4 and 8 may no longer be relevant, and this aspect of the work for DaD may be subject to revision.

Because of the uncertainties inherent in earthworks behaviour (particularly for older railway infrastructure) and the impacts of climate change, a probabilistic approach will be taken to the analysis, using ensembles of inputs to Monte Carlo simulations to determine the range of likely economic and carbon impacts associated with BAU and a range of selected Do-Something options, as seen in Figure 5.

Using a whole life costing approach [18], these results in turn will enable the comparison of the costs of earthworks failures and the associated unplanned disruptions to services with the capital and operating costs of different preventative interventions, including the costs due to the associated planned disruptions to services. The trade-offs between engineering and compensation costs are an important factor in the development of improved maintenance strategies [19]. This approach will also enable the assessment of trade-offs between the marginal abatement costs of an intervention and the marginal avoided costs of damage due to failure.

Ironically, the repair of earthworks failures may in some respects be easier and quicker than their prevention, since the affected line is typically closed to normal traffic, providing relatively unrestricted access to the site, and enabling ‘round the clock’ working without the need to accommodate train services [20]. However, the design and implementation of the remedial works have to be undertaken quickly, and at short notice, with potentially much higher mobilisation and implementation costs [1], and reduced opportunity for an optimal outcome. This is all in addition to the negative consequences for users of the infrastructure and the associated compensation costs and reputational damage, as well as the potentially serious safety risk presented by an infrastructure failure, as illustrated by the Carmont derailment [4].

In the course of DaD 5, the analysis will be extended from an initial focus on cuttings to include embankment slopes, and then also from railway infrastructure to include earthworks in highway and flood defence contexts. In the context of the London – Bristol study, the initial analysis and results obtained for the railway alignment will be adapted and extended to the parallel road corridor (primarily the M4 and M32 motorways). The approach and results will then be generalised to include all relevant categories of long-lived, long linear assets and to increase the geographic coverage to the national level, and to cover a range of different analytical timescales.

5 Conclusions

Transport and other vital infrastructure in Britain and around the world depends on an extensive system of earthworks. These are of varying age and quality of original construction, are subject to processes of natural deterioration, and are increasingly vulnerable to the effects of climate change. Railway cuttings and embankments, having mostly been built in the 19th century and to relatively primitive engineering standards, are particularly prone to the effects of deterioration and climate change.

The ACHILLES research programme addresses many of the challenges faced by the owners and maintainers of earthworks assets. It provides improved understanding of earthworks deterioration processes and asset performance, with and without interventions, and develops geotechnical and economic forecasting and decision support capabilities needed to maintain earthworks in a safe and serviceable state in a cost-effective manner. The programme is consistent with Network Rail’s increasingly proactive approach to infrastructure maintenance and renewals, and the Simulation and Modelling (SaM) and Design and Decisions (DaD) workstreams address several of the specific objectives set out in Network Rail's Earthworks Technical Strategy [4] and in different iterations of the Rail Technical Strategy [7, 8].

Initial work in the SaM and DaD workstreams is focussing on the GWML railway between London and Bristol, which has been sub-divided into nine 'constant traffic sections' for the purposes of the initial analytical process. Detailed geotechnical modelling and statistical emulation techniques are being used to predict locations, volumes and expected times of earthworks failures of (initially) cutting slopes along the route, with and without interventions. These results are being combined with unit cost and other socio-economic data to assess alternative whole-life cost outcomes, and will be extended to eventually provide the guidance and decision support required to minimise whole-life costs at asset, route and network levels, while maintaining infrastructure serviceability and operational safety.

Acknowledgments

ACHILLES is funded by the UK Engineering and Physical Sciences Research Council (EPSRC). The authors are also grateful to their colleagues on the ACHILLES research programme for their input and support.

Literature

[1] Dijkstra, T., Dixon, N., Crosby, C., Frost, M., Gunn, D., Fleming, P. and Wilks, J. (2014): *Forecasting infrastructure resilience to climate change*. Proceedings of the Institution of Civil Engineers - Transport 167:5, pp269-280

[2] ACHILLES (2021): Welcome to ACHILLES [online]. Available from https://www.achilles-grant.org.uk/ [Accessed 30 March 2021]

[3] RailTech.com (2021): After the flood: rail repairs will cost billions [online]. Available from After the flood: rail repairs will cost billions | RailTech.com [Accessed 21 July 2021]

[4] Network Rail (2021): *Resilience of rail infrastructure* [online]. Available from Stonehaven - Network Rail [Accessed 1 April 2021]

[5] Network Rail (2018): *Earthworks Technical Strategy* [online]. Available from https://www.networkrail.co.uk/wp-content/uploads/2018/07/Earthworks-Technical-Strategy.pdf [Accessed 5 July 2021]

[6] DfT (2014): Transport Resilience Review: A review of the resilience of the transport network to extreme weather events [online]. Available from Transport Resilience Review (publishing.service.gov.uk) [Accessed 6 July 2021]

[7] RSSB (2017): Rail Technical Strategy: Capability Delivery Plan [online, login required]. Available from https://www.sparkrail.org/Lists/Records/DispForm.aspx?ID=24868 [Accessed 7 July 2021]

[8] RTS (2021): Rail Technical Strategy [online]. Available from https://railtechnicalstrategy.co.uk/ [Accessed 7 July 2021]

[9] AECOM (eds.) (2021): Spon's Architects' and Builders' Price Book 2021. Boca Raton: CRC Press.

[10] RICS (2021): BCIS Schedule of Rates [online]. Available from https://www.rics.org/uk/products/data-products/bcis-construction/bcis-schedule-of-rates/ [Accessed 16 July 2021]

[11] Network Rail, 2012. Data Feeds : Network Rail [online]. Available from http://datafeeds.networkrail.co.uk/ [Accessed 20 July 2021]

[12] Rail Delivery Group (2020): About the Passenger Demand Forecasting Handbook [online]. Available from https://www.raildeliverygroup.com/pdfc/about-the-pdfh.html [Accessed 19 July 2021]

[13] DfT (2021). WebTAG [online]. Available from https://www.gov.uk/guidance/transport-analysis-guidance-webtag [Accessed 19 July 2021]

[14] Ewen, J., Parkin, G. and O'Connell, P.E., 2000. SHETRAN: Distributed River Basin Flow and Transport Modeling System. J. Hydrol. Eng. 5, 250–258. https://doi.org/10.1061/(ASCE)1084-0699(2000)5:3(250)

[15] Itasca, 2016. Fast Lagrangian Analysis of Continua v. 8.0 - User's Guide, 6th ed. Itasca Consulting Group Inc., Minneapolis

[16] Pant, R., Hall, J. W. and Blainey, S. (2016). Vulnerability assessment framework for interdependent critical infrastructures: case-study for Great Britain's rail network. European Journal of Transportation and Infrastructure Research, 16(1), 174-194 https://doi.org/10.18757/ejtir.2016.16.1.3120

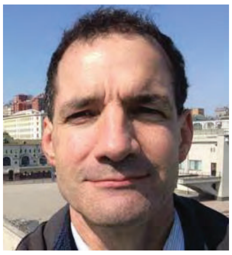
[17] DfT (2021). Great British Railways: The Williams-Shapps Plan for Rail [online]. Available from https://www.gov.uk/government/publications/great-british-railways-williams-shapps-plan-for-rail [Accessed 20 July 2021]

[18] Reid, J. M. and Clark, G. T. (2000). A whole life cost model for earthworks slopes. Prepared for Quality Services, Civil Engineering Division, Highways Agency. TRL Report 403. Transport Research Laboratory, Crowthorne.

[19] Armstrong, J. and Preston, J. (2020). Balancing railway network availability and engineering access. Proceedings of the Institution of Civil Engineers – Transport, 173(4), 209-217 https://doi.org/10.1680/jtran.19.00045

[20] Li R (2017) Phase-based Planning for Railway Infrastructure Projects. PhD thesis, Technical University of Denmark, Lyngby, Denmark. See http://orbit.dtu.dk/files/143903449/RuiLi_PhDThesis.pdf

Authors



Armstrong, John

John Armstrong is a Senior Research Fellow at the University of Southampton's Transportation Research Group. He works primarily in railway operations planning and analysis, and in engineering economics.

Preston, John

John Preston is Professor of Rail Transport at the University of Southampton. His work in rail is focussed on demand forecasting, cost estimation and operations planning.

Helm, Peter

Peter Helm is a Research Associate at Newcastle University. His background is in geotechnical engineering and modelling and his current work is focussed on the modelling of geotechnical infrastructure deterioration, subject to annual weather cycles.

Svalova, Aleksandra

Aleksandra Svalova is a Research Associate in Statistics at Newcastle University. Her background is in statistical modelling and analysis, and her current work is focussed on the development of a probabilistic surrogate model for the computationally-expensive numerical modelling of cuttings in London Clay-type material.

Preferred language of presentation: English

Presenter: John Armstrong