ACHILLES

An EPSRC Programme Grant

READING GUIDE 6:

The role of data analytics in decision-making

ADDRESSING INFRASTRUCTURE'S ACHILLES HEEL

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Engineering and Physical Sciences Research Council

To cite this document use: Loveridge, F., Svalova, A., Helm, P.R., Armstrong, A. and Oakley, J. (2023). Reading Guide 6: The role of data analytics in decision-making. The ACHILLES Programme Grant Consortium, Newcastle University, UK, 8p

Newcastle University · Loughborough University · Durham University · University of Southampton · University of Bath · University of Leeds · British Geological Survey

Introduction

Long linear infrastructure, e.g. highways and railways, includes large numbers of dispersed earthwork assets. Depending on their age and history, it can be practically impossible to constantly maintain up-to-date condition information (Network Rail, 2018[A]).

However, this data, and models using it, play a vital role in predicting earthwork behaviour and guiding intervention decision-making, which must take account of both the likelihood and consequences of asset failures.

ACHILLES has developed novel surrogate models to help address uncertainty in earthwork assessment and make the most of limited data.

Key findings

Key findings from the data analytics for decision-making are:

- The absence of comprehensive historical data and records means that there is uncertainty in relation to past as well as future asset behaviour and interventions.

- Our surrogate model (or emulator, see also *Reading Guide 5*) takes account of various sources of uncertainty and can be used by asset managers to obtain information on earthwork condition and closeness to geotechnical failure. Comparison of the expected costs of slope failure with the expected costs of preventative intervention can help address uncertainty in relation to predicted time to failure.

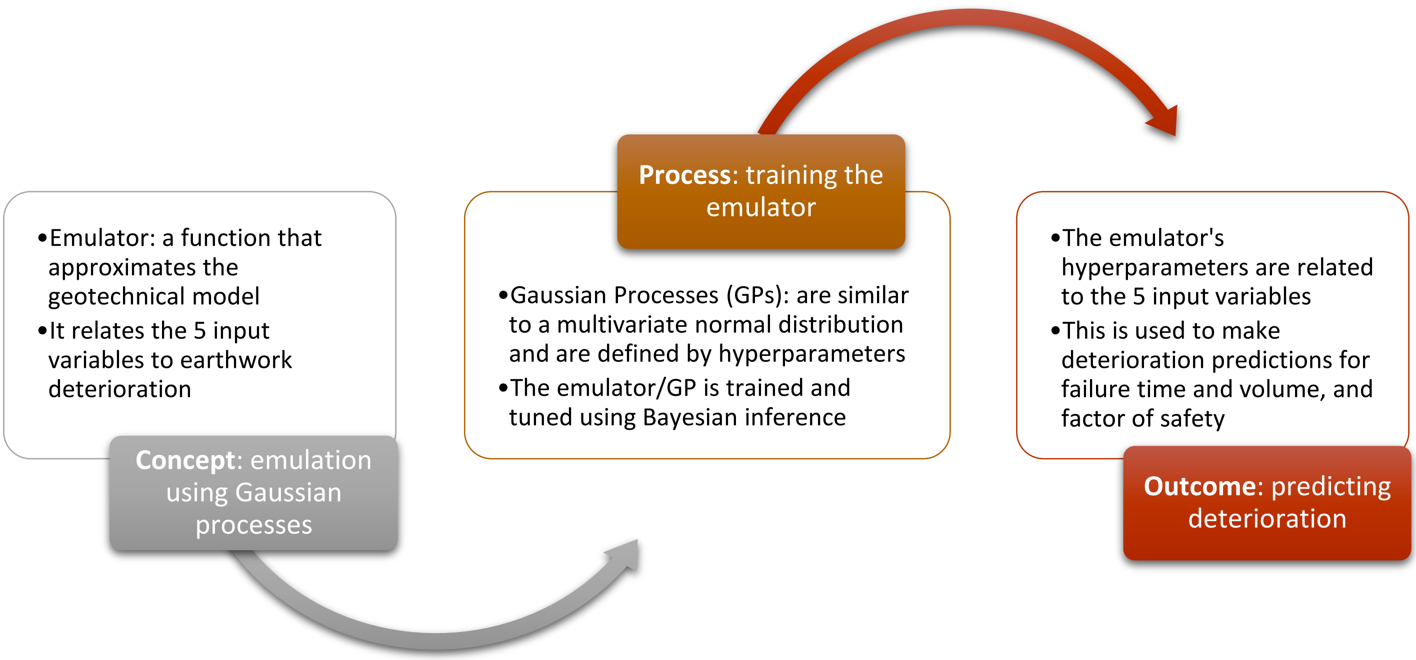

Figure 1: Summary workflow for building and training the emulator.

Our key developments in data analytics for decision-making

Our statistical emulator simplifies and accelerates analysis of infrastructure slopes

Routine slope stability analysis for embankments and cuttings is deterministic and generally takes two forms. Simple limit equilibrium analysis is very common and is suitable for large numbers of slopes, however it cannot capture long term deterioration processes. The alternatives include computationally-intensive numerical simulation, which can capture the appropriate processes but cannot be applied practically across a full earthworks portfolio [1,2].

Design charts, for example, showing time to failure (TTF) or factor of safety (FOS), could be developed based on advanced numerical simulation [3,4]. However, the amount of model runs which is needed to understand the (continuous) relationships between a combination of an earthwork's properties and deterioration is infeasible. Instead, we have constructed an emulator which estimates the relationship between input variables and TTF using a carefully designed training set of model runs. Using this set, we aimed to interpolate/estimate the relationship between earthwork properties and deterioration. In the training data set, we varied five *input variables* known to be strongly related to deterioration: slope geometry (height and angle), soil strength (c' and ϕ'), and permeability. The slope geometry ranges were adopted based on LiDAR scan data of the Great Western Main Line railway relating to slopes in high plasticity over-consolidated clays (height 4 to 20m, angles of 1V in 0.5H to 1V in 7.5H) with shear strength parameters and permeability were derived from the literature (c' of 3 to 10 kPa, ϕ' of 18.5° to 25° and permeability from 1.5×10^{-9} to 2.5×10^{-8} m/s) [e.g. 5 & 6]. The surrogate model was trained to emulate deterioration indicators, including TTF and factor of safety.

The emulation is performed using Gaussian processes (GPs) [5], which are summarised in Figure 1. GPs can be thought of as random functions which are designed to mimic a process of interest. GPs are controlled by hyperparameters (control parameters) which are, in turn, related to the input variables - this is how input-output relationships are modelled in the emulator. The hyperparameters are estimated using Bayesian inference and Markov chain Monte Carlo sampling.

The emulator makes rapid estimates of time to failure and factor of safety

Time to failure (TTF) is defined in our study as the time at which an earthwork reaches a factor of safety of one. We used our emulator to create time-to-failure maps for different scenarios (Figure 2). To provide confidence in the method we compared the outputs with the failure potential contours for Network Rail earthworks as reported in the Global Stability and Resilience Appraisal (Mellor et al, 2017[B]). The contours overlay very well with our predictions for an over-consolidated clay slope. TTF can also be transformed to obtain failure probability contours [6].

The emulator can also be used to derive factor of safety (FOS) time series (Figure 3). Our emulator approximates the FOS with a flexible family of curves and can capture convex and concave behaviours.

The emulator informs decisions about maintenance and repair interventions by rapidly comparing options

To be able to compare intervention options on a cost-benefit basis, information about the size of the failures to be repaired is required. We can also emulate failure area as a function of the input variables for application in these assessments. Using this, along with predicted TTFs with and without interventions enable the assessment of the comparative discounted whole-life costs of interventions at different times in an asset's lifecycle [7-9].

The emulator helps understand uncertainty in asset performance

Emulation was performed using Bayesian inference which helps quantify uncertainty based on prior expert knowledge. The uncertainty ranges that we obtain account for the uncertainty in the 'true' underlying model and variability in the model fit. Uncertainty also arises from the lack of comprehensive data on historic asset failures and interventions.

All estimations made using the emulator are obtained as probability distributions. Therefore, it is straightforward to make an estimate of the most likely time/form of deterioration as well as confidence intervals. The range of TTF values can be used to calculate the (increasing) cumulative probability of failure over time, which, combined with an estimated or assumed cost of failure, provides an increasing 'expected cost of failure' over time. Conversely, subtracting the cumulative probability of failure from one yields the reducing cumulative probability over time of the asset not failing, and multiplying this by an estimated or assumed cost of intervention produces a declining 'expected cost of intervention' over time.

An example is shown in Figure 4, where a cutting slope constructed in 1836 is assumed not since to have failed or to have undergone intervention. Aiming to intervene at the point when, or shortly before, the expected costs of failure equal and subsequently exceed those of intervention (in this case approximately 2036) is similar to the 'minimisation of maximum regret' (MiniMax Regret) (Winston, 2004[C]). This example, accounting for model uncertainty, considers only the economic factors informing decision making. The next *Reading Guide* [7] also discusses other factors to consider.

The approach illustrated below is consistent with consideration of both the likelihood of failure and its consequences, typical in asset management practice. It can be seen that higher expected failure costs and/or lower expected intervention costs incentivise early intervention, and vice versa. An inherent assumption of no past failures or interventions (based on a lack of data) tends to result in the prediction of the imminent need for intervention for a large number of assets and remains to be addressed.

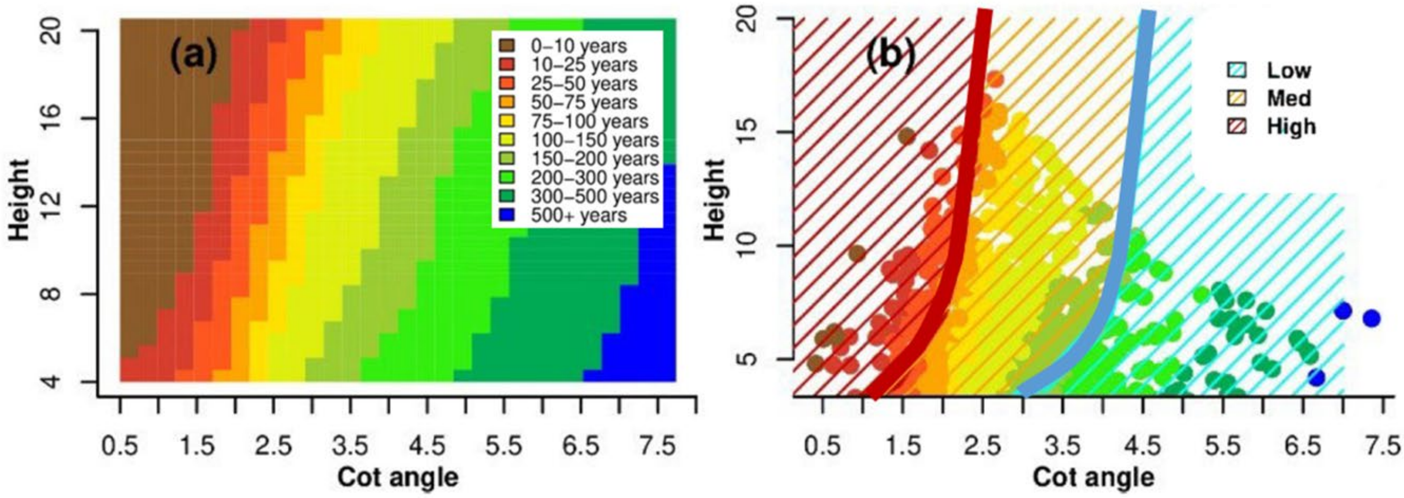

Figure 2: Estimated mean time to failure for high plasticity over-consolidated clay cuttings. (a) example TTFs for using the ACHILLES emulator; (b) comparable failure potential contours as reported in the Global Stability and Resilience Appraisal (Mellor et al., 2017[B]).

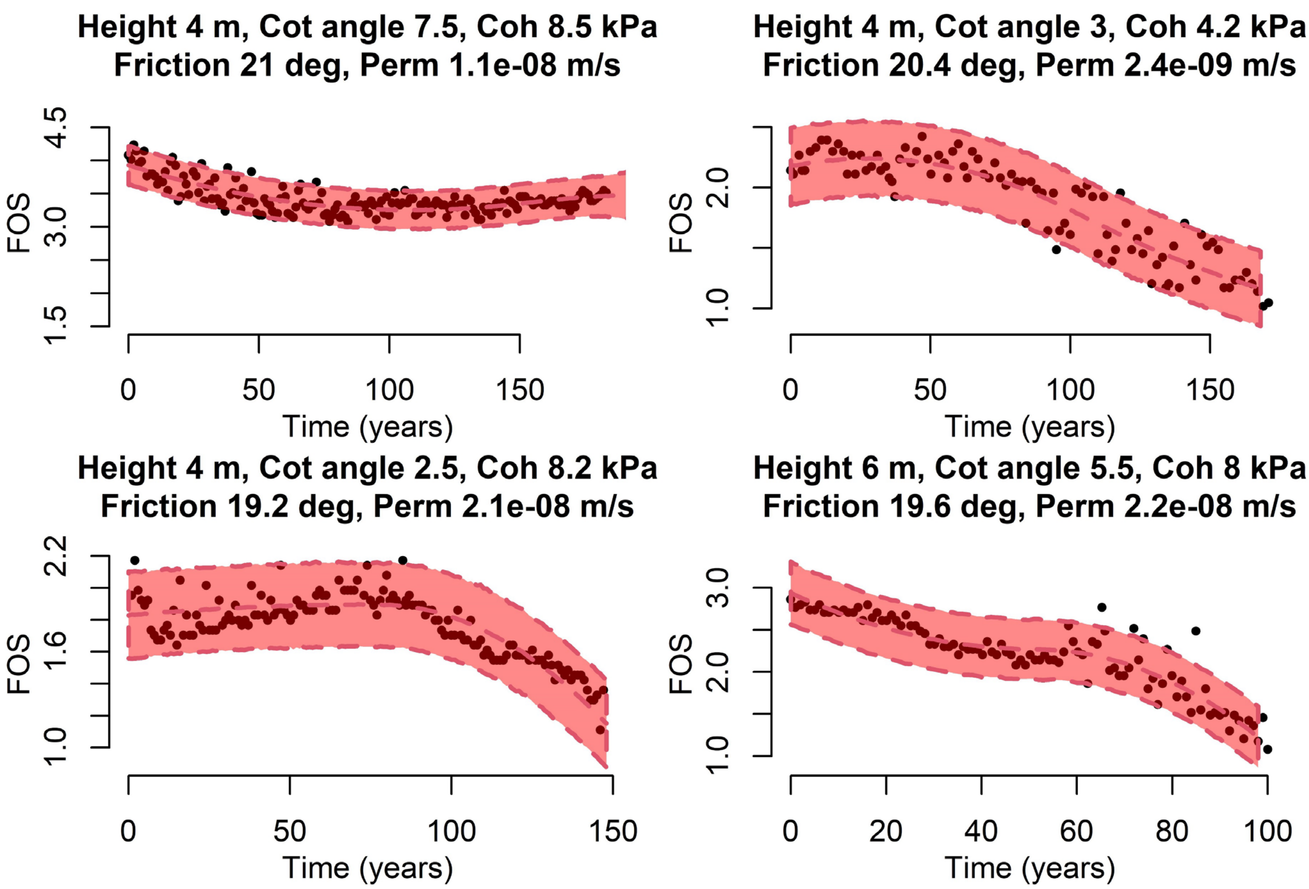

Figure 3: FOS time-series produced using the emulator. Dashed lines indicate the mean and the most likely 95% region. The abbreviations "Coh" and "Perm" indicate cohesion and permeability.

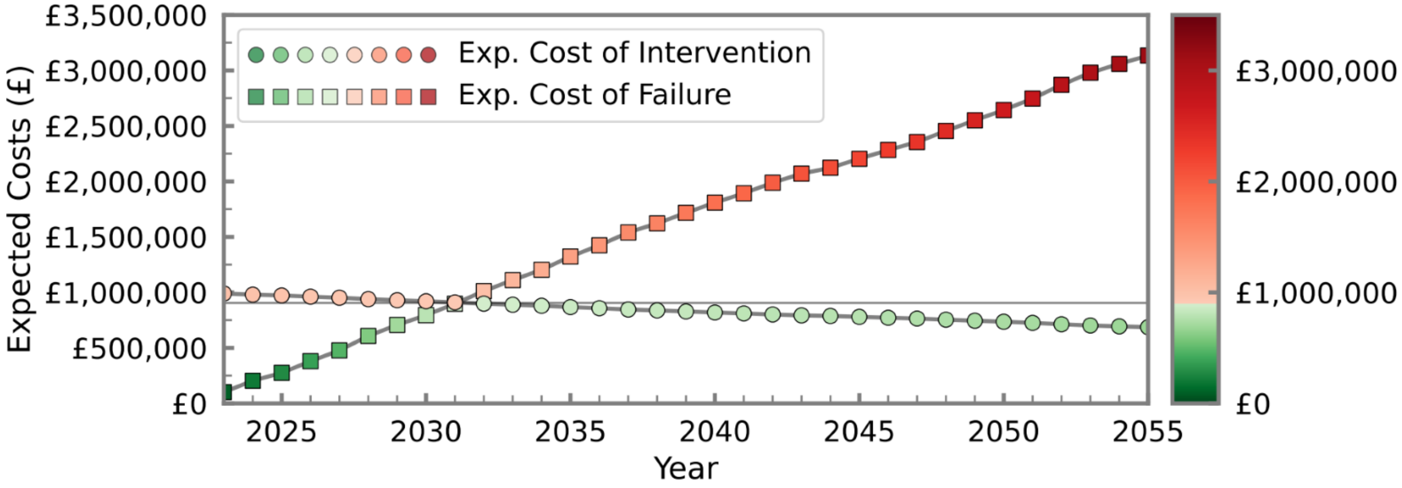

Figure 4: Expected costs over time of asset failure vs. intervention accounting for uncertainty.

Link to ACHILLES emulator app

asvalova.shinyapps.io/ACHIMULATOR/

The ACHIMULATOR is an online interface to the emulator for TTF prediction. It is based on a simplified version of the methodology in [5] to enable instant calculations. Work is ongoing to extend the ACHIMULATOR's functionality to FOS prediction.

Further reading

Please also refer to the other ACHILLES reading guides where you can find out more about what we have achieved. *Reading Guide 1* explains the context of the ACHILLES Programme Grant. *Reading Guide 2* describes how we have achieved a deeper understanding of deterioration affecting the clay materials that we focused on. *Reading Guide 3* extends our understanding of deterioration to the long linear geotechnical asset scale. *Reading Guide 4* outlines the ways in which we can assess the condition of our long linear geotechnical assets. *Reading Guide 5* provides an overview of the design tools that ACHILLES has developed. *Reading Guide 7* discusses the complexities of the business case of timely intervention and mitigation.

Key references

[1] Helm, P.R., Morsy, A., Postill, H., El-Hamalawi, A., Stirling, R.A., Rouainia, M., Briggs, K.M. (2023). **ACHILLES Reading Guide 3: Asset scale deterioration.** The ACHILLES Programme Grant Consortium, Newcastle University, UK, 8p

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[7] Armstrong, J., Loveridge, F., Helm, P.R. (2023). **ACHILLES Reading Guide 7: Intervention strategies and business case.** The ACHILLES Programme Grant Consortium, Newcastle University, UK, 8p

[8] Armstrong, J., Helm, P., Preston, J., Loveridge, F. (submitted). **Economics of geotechnical asset deterioration, maintenance and renewal.** *Transportation Geotechnics.*

[9] Armstrong, J., Preston, J. (2023). **ACHILLES: handling uncertainty in railway earthworks maintenance and renewals.** Accepted for presentation in: 4th International Railway Symposium Aachen (IRSA2023). Aachen, Germany.

Non-ACHILLES references

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[B] Mellor, R., Parry, L., Power, C., Spink, T. (2017). CP6 Earthworks Asset Policy Development Task 36 – Global Stability and Resilience Appraisal Interim Report. Network Rail, Milton Keynes, UK.

[C] Winston, W.L., 2004. Operations Research: Applications and Algorithms (4th ed.), Belmont: Brooks/Cole – Thomson Learning

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The ACHILLES Reading Guide Series

1. The ACHILLES concept
2. A deeper understanding of deterioration of engineered soils
3. Asset scale deterioration
4. Asset condition assessment
5. Design considerations for clay earthworks
6. **The role of data analytics in decision-making**
7. Intervention strategies and business case

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First Published in November 2023.

Version 2 (13/12/2023)