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Assessment of the Deterioration of National Highways Geotechnical Assets and their Resilience to a Changing Climate

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Abstract

National Highways is responsible for the operation of the strategic road network in England, comprised of motorways and major trunk roads. On this network, there are nearly 50,000 geotechnical assets (cuttings, embankments, bunds and at-grade sections) formed in, or from, the wide variety of geological materials that exist around the country. Whilst these assets are relatively young compared to those of other transportation networks, they are approaching 20-60 years old in most cases and do show signs of defects and deterioration. The impact of this deterioration can be significant if the assets are not managed and reach a state of failure. Recognising this, research work has been undertaken to produce quantitative deterioration models of the geotechnical assets, based on both observed condition changes through time and an assessment of the potential impact of future climate change. This paper will explain how the condition of the assets has been tracked through time from analysis of inspection records and will present deterioration curves that demonstrate the influence of asset types and geological material types. It will also demonstrate how the potential impact of future climate change has been modelled based on available leading-edge research and use of engineering expertise. The paper will also discuss the potential future use of the deterioration models produced and their place in a wider decision support framework for resilient geotechnical asset management.

Keywords: Earthworks, condition, performance, deterioration, climate change

1. Introduction

National Highways is responsible for the management and operation of the strategic road network of motorways and major trunk roads in England, a network of 4,300 miles (6,900 km) carrying 34% of the road traffic in the country and 68% of all freight (National Highways, 2019). This transportation network runs through, and is supported by, nearly 50,000 geotechnical assets, which are managed in accordance with a standard called CS641: Managing the maintenance of highway geotechnical assets (National Highways, 2020). These geotechnical assets are relatively young in comparison to the canal and railway networks elsewhere in England, having been largely constructed in the period from 1960 to 2000 (see Figure 1) and hence benefitting from the greater understanding of geotechnical engineering (particularly slope stability analysis for design) available by that time. For the most part, the geotechnical assets perform well, but defects in the assets have developed over time, indicative of deterioration of the assets. Failures have also occurred, varying in scale and impact, but occasionally of considerable significance (see, for example, the failure at Flint Hall Farm on the M25 orbital motorway around London, described in Davies et al. (2003)). As part of the strategic aims of National Highways relating to sound asset management and the assessment of the impact of climate change (National Highways, 2022), a research project was commissioned to assess this deterioration of assets and produce models for projected future deterioration to support decision making for the current and future management of this critical asset group. The work, described in this paper, was part of a wider programme of tasks relating to climate change resilience of geotechnical assets, all being undertaken to support the strategic aims of the organisation (Codd, 2023).

2. National Highways geotechnical assets

2.1 Asset characteristics

National Highways defines a geotechnical asset as "The man-made or natural earthworks below the highway pavement layers, structures and the adjacent land within the Overseeing Organisation boundary". The assets

are defined by a series of asset types: cuttings, embankments, bunds (for visual and acoustic screening) and at-grade sections (which includes minor earthworks below 2.5m in height). Given the broad range of natural geological units occurring in England, these assets are composed of many different *in situ* and placed materials, though unlike older transportation networks there has been a much greater degree of informed engineering design in their construction, including the avoidance of unsuitable materials and reinforcement of assets by a range of construction techniques (referred to as Special Geotechnical Measures, SGMs). Recent work undertaken for National Highways has examined the performance of some of these SGMs over time (Duffy-Turner et al. 2023). Much of the performance of geotechnical assets is determined by the presence and performance of drainage within them (see Lane et al. 2019, which demonstrated that for the National Highways network, 74% of observed geotechnical asset failures can be attributed to drainage in some way). The geotechnical assets have drainage provisions in almost all cases, and its impact on deterioration was considered in the work undertaken.

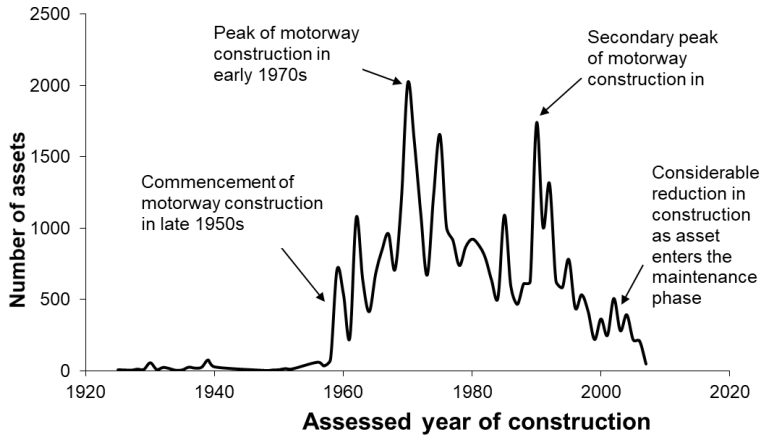

Figure 1: Age profile of the geotechnical assets on the strategic road network in England. Also shown in the period over which formalised principal inspections of the assets have been undertaken. (Adapted from Power et al., 2012).

All data and associated technical information relating to geotechnical assets are held in the Geotechnical and Drainage Management Service (GDMS), a secure online web-based GIS system with associated databases, that has been in operation continuously since 2002. This system provides an excellent source of quantitative data for the assessment of deterioration. At the time of writing, within GDMS there are 49,986 geotechnical assets recorded (13,332 cuttings, 15,153 embankments, 1,427 bunds and 20,074 at-grade sections)

2.2 Asset condition

The condition of National Highways geotechnical assets are almost exclusively assessed by Principal Inspections: physical, mostly foot-based surveys of the assets undertaken by qualified and trained inspectors, although investigation of remote methods is being undertaken (Pritchard et al., 2023). Data captured from these inspections is entered into software called TabletGAD, using ruggedised, GPS-enabled tablets. The captured data is synced directly to GDMS from TabletGAD, creating a history of condition of the assets through their period of inspection. By the end of 2020, almost all assets had been inspected at least twice, with the majority having been inspected three or more times.

Asset condition is determined through use of a formalised Feature Grade assessment methodology set out in CS 641, which classifies the severity of features seen in the assets (which may be classed as defects) and the local proximity of the feature to either the carriageway or critical highway infrastructure (known as the Location Index). Through guidance and training of inspectors, organisational oversight and regular reviews, this assessment methodology ensures that condition assessment of the assets is standardised across the network.

2.3 Asset failure

National Highways geotechnical assets are relatively young, well-constructed, regularly inspected and subject to ongoing maintenance regimes. As a result of this, asset failures that impact on the operation of the network are thankfully rare. Within CS 641, such failures are termed Geotechnical Events, which are defined as "A geotechnical defect that poses a threat to the safety of users, workers or other parties such that immediate

action is to be taken". At the time of writing, 39 Geotechnical Events are recorded in GDMS, with dates ranging from March 2011 to October 2022 (the recording of such events commenced in 2011). Whilst these events are rare, their impact can be significant, hence they pose a considerable risk to National Highways that must be addressed through sound asset management.

For the assessment of deterioration described here, a separate means of determining when an asset has undergone failure was derived (considered from a geotechnical perspective, i.e. where a slope has failed, no matter what size and irrespective of the impact it has on the operation of the network).

3. Geotechnical asset deterioration assessment

3.1 Review of previous work and setting the business requirements

The published body of previous work relating to the assessment of deterioration of geotechnical assets is limited, but good examples do exist, and the early part of this research work involved a literature review and critical appraisal of methods suitable for use by National Highways. 71 available documents were reviewed, and the following conclusions drawn:

- More than 75% of the documents reviewed were from UK industry practice or academic organisations. International publications were mostly from academia,
- Almost all the publications were from 2010 onwards, reflecting the fact that geotechnical asset management is a relatively new area of practice,
- Publications could be crudely related to the various recognised scales of asset management practice, ranging from operational (i.e. the physical behaviour of single assets) through tactical (i.e. the behaviour of groups of similar assets, with a level of abstraction or simplification of physical behaviour) to strategic (i.e. behaviour of entire portfolios of assets). The greatest number of publications reviewed related to the tactical and strategic level

In order to provide direction to the development of deterioration models, interviews of National Highways staff and key members of their supply chain were undertaken in an effort to understand the detailed business requirements. This interesting exercise was informative and garnered a range of views. There was general recognition that the geotechnical assets are currently well managed and that the use of Geotechnical Asset Management Plans (GeoAMPs), authored by geotechnical teams who understand the assets in their Area, is a robust and proven methodology. However, it was recognised that these plans only have a short time horizon (5 years) and that there is a need for a longer-term assessment of geotechnical asset deterioration. It was determined and agreed that the initial deterioration models should be based on whole portfolio assessment (i.e. at strategic asset management scale).

3.2 Deterioration assessment methods

Various methods for the assessment of deterioration of civil engineering assets (including geotechnical assets) exist that were potentially applicable to the task. An excellent summary of available methods is provided by McKibbins et al. (2019) from which the summary diagram shown in Figure 2 is taken.

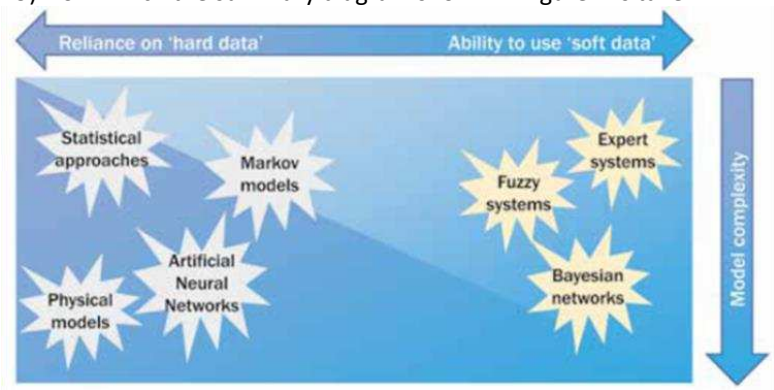

Figure 2: Methods of deterioration modelling applicable to civil engineering assets (from McKibbins et al., 2019).

Based on an assessment of the business requirements, knowledge of the available data and a need to avoid overly complex models in this initial stage of research, use of a Markov modelling technique was chosen from the potential methods that could be attempted. The Markov modelling technique has the added benefit of having a precedent case study of its use for geotechnical assets, as it was employed by Network Rail in the development of their funding business case for Control Period 5 (2014-2019), as described in Power et al., 2016 and as a case study in McKibbins et al., (op.cit.).

3.3 Adopted methodology

A Markov model (often referred to as a Markov chain) requires a finite number of condition states to be defined, and sufficient data to be available for the time that an asset sits in each condition state to be determined. These requirements could be met with available data from GDMS, but data preparation was required to produce an asset level measure of condition state, based on observed features within the asset extents. In order to normalise this condition measure for varying length, the geotechnical assets were divided into sub-assets of 100m sections (or as near as possible to 100m sections) and the observed features within the section extracted and given a weighted score, based on their Classification (a measure of severity), their Location Index (a measure of local proximity to the highway or critical infrastructure) and the longitudinal length of the feature. A measured change in each of these characteristics over time, increase in severity and/or local proximity, was considered to be an indication of asset deterioration (see Figure 3), resulting in a higher weighted score, and a potential change in overall condition state, should the boundary score between condition states be exceeded. Five condition states (called Asset Condition Ratings or ACRs) were defined from A (best condition) through to E (worst condition).

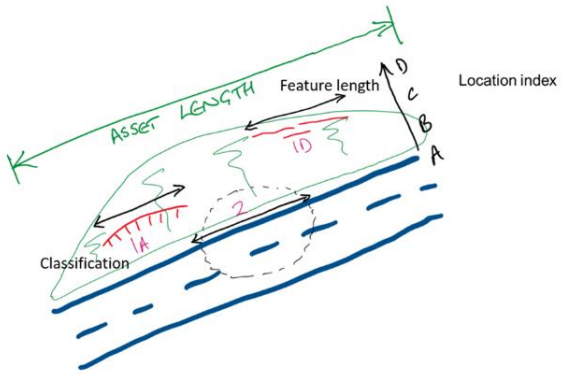

Figure 3: Indicators of deterioration used in the deterioration modelling, based on observations made during principal inspections of geotechnical assets.

An addition Asset Condition Rating (F) was created to specifically define geotechnical assets that had experienced geotechnical failure. As previously described, this measure was not defined by the use of the small number of Geotechnical Events recorded in GDMS but was instead a selected subset of features classified in CS 641 as Class 1A (Major Defect), where additional recorded data showed this was a geotechnical failure of some kind (for example slope failure, subsidence, washout etc.).

In order to determine the change in sub-asset condition over time, data from GDMS was pre-processed to determine the ACR of sub-assets at each point in time that they underwent a Principal Inspection. The frequency of these inspections is determined based on a risk assessment process set out in CS 641, but on average geotechnical assets undergo an inspection every five years.

To enable the outputs of the deterioration modelling to be considered in terms of key characteristics of the geotechnical assets, the modelling also included tagging each 100m sub-asset with details of:

- The sub-asset type (cuttings, embankments and bunds (combined) or at grade)
- The geological materials of which the sub-asset is comprised
- The presence of any Special Geotechnical Measures
- The presence of earthwork drainage

4. Outputs of the analysis

The raw output of a Markov model is a matrix of probabilities that a sub-asset will transition from one ACR to another (or stay in the same ACR) within a given timeframe. The geotechnical assets of National Highways are overwhelmingly in good condition, and deterioration rates are slow, so in all analyses by far the greatest probabilities are that sub-assets stay in the same ACR in each time step. However, some deterioration is detectable, and is seen in the output matrices. The Markov modelling technique also determines where sub-assets have improved in ACR, which may be the result of interventions undertaken to address problems on the network, or corrections to the data through editing, or variability in the inspections undertaken. In order to ensure that the outputs relate to deterioration alone, such improvements are modified in the matrix to assign them to an un-changed ACR within the timestep. This assumption is reasonable but has been identified as a potential improvement for future modelling.

The raw transition matrices from the modelling are informative, but hard to interpret and compare between different groups of sub-assets with different characteristics (referred to hereafter as cohorts). In order to allow such a comparison, the matrices are further processed to produce two metrics that can be plotted against time into the future:

- The overall condition of all the sub-assets in a particular cohort is tracked through time using an Average Cohort Condition Score (ACCS). ACCS is a weighted average calculated by determining the number of sub-assets in each ACR in each time step and multiplying it by an arbitrary weighting, from 1 (for ACR of A, or best condition) to 6 (for ACR of F, or failed condition). These values are then summed and delivered by the total number of sub-assets in the cohort. If all sub-assets were in the best condition, the ACCS would be 1, and conversely if all sub-assets had failed, the ACCS would be 6,
- The number of sub-assets in the failed condition (ACR of F) is tracked through time, as this is a more tangible way of understanding the potential issues that may increase as deterioration of the geotechnical asset progresses. It is important to remember the definition of sub-asset failure described previously: whilst a number of sub-assets have been predicted to experience geotechnical failure, this does not necessarily mean that they would meet the threshold required for them to be considered a Geotechnical Event.

It is not possible to present all of the analysis outputs within this paper. A number of examples are presented to illustrate the insights gained from the modelling and to demonstrate the confidence that has been gained in the results following a review against engineering judgement provided by the experienced research team.

The analysis outputs for geotechnical asset type cohorts are shown in Figure 4. In terms of the ACCS, the portfolios of cutting and embankment sub-assets are predicted to deteriorate at the same rate, with at-grade sub-assets starting from a better condition and deteriorating at a slower rate. A similar prediction is seen in terms of number of annual expected sub-asset failures, albeit the starting position shows more failures for the embankment sub-assets than the cutting sub-assets. The expected number of annual failures for at-grade sub-assets is much lower than for the other cohorts, as would be expected.

In order to assess the impact of geological material types on geotechnical asset deterioration, it is necessary to simplify the huge number of geological units that are seen on the strategic road network into groups of materials with similar geotechnical properties. With the kind permission of Network Rail, this was achieved in the task by using the methodology employed in the development of the Global Stability and Resilience Appraisal for the rail network of Great Britain (Mellor, 2017). An example of the impact of geological material types on predicted deterioration of embankment sub-assets is seen in Figure 5. Whilst the predicted future values of ACCS for each material group are similar, it can be seen that materials with the highest potential for progressive failure (generally higher plasticity, brittle materials such as Gault or Oxford Clay) are predicted to deteriorate faster than materials with medium to high, or medium potential (generally lower plasticity, more ductile materials, an example of the D3-S3 group being Charmouth Mudstone and the D1-S1 being Mercia Mudstone). This result accords well with engineering judgement and was also seen in the results of similar analysis undertaken for Network Rail earthworks (Spink, 2020).

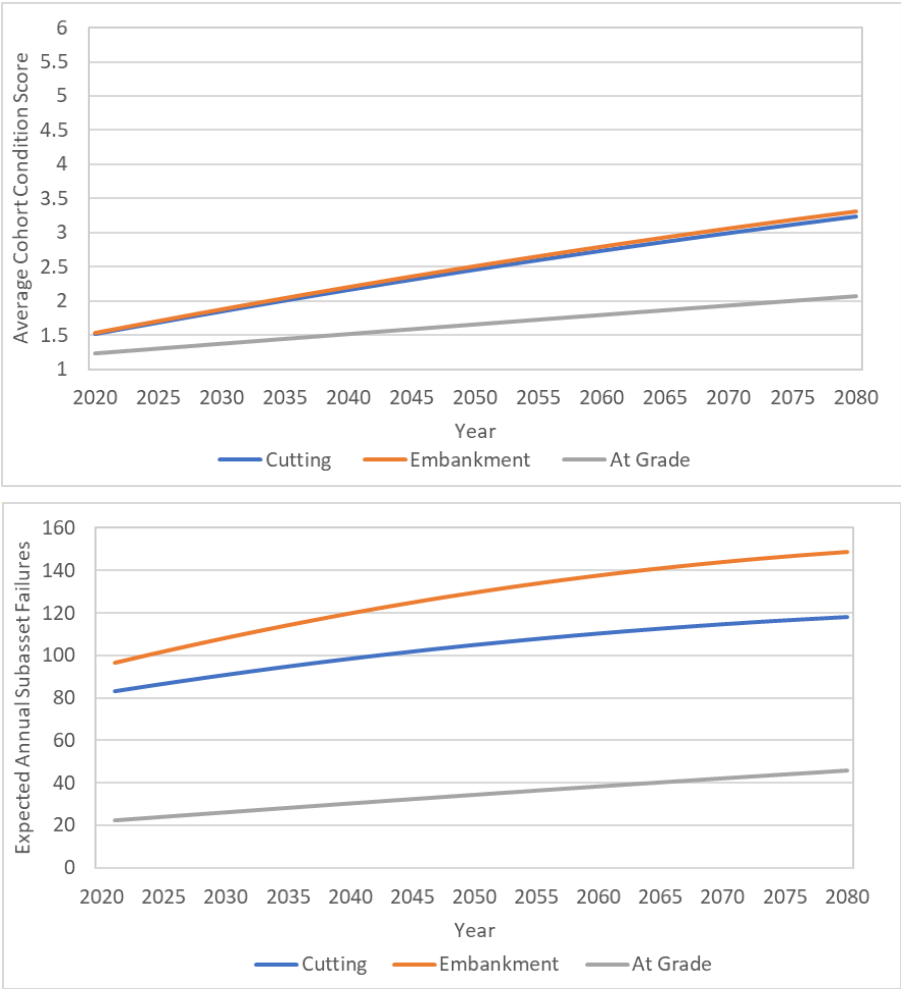

Figure 4: Predicted change in Average Cohort Condition Score (top) and expected annual sub-asset failures (bottom) for geotechnical asset type cohorts.

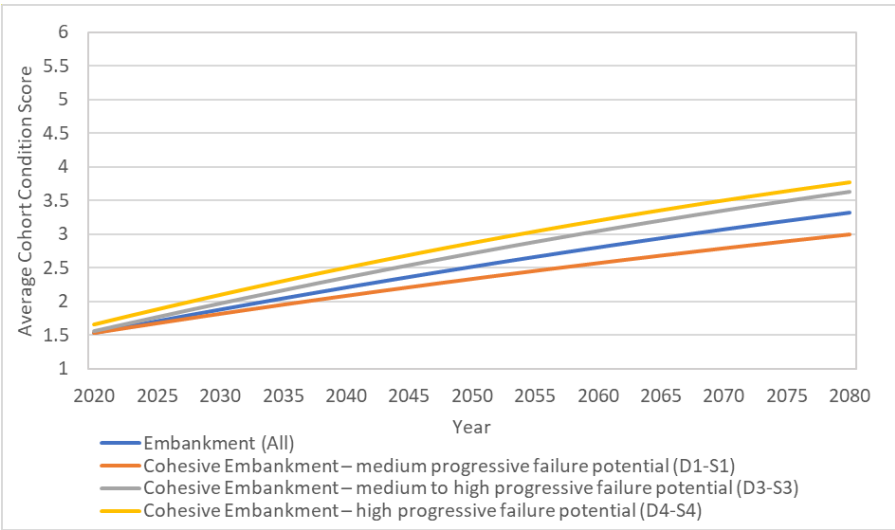

Figure 5: Predicted change in Average Cohort Condition Score for cohesive geological material groups in embankment sub-assets.

5. Impact of climate change on deterioration of geotechnical assets

All of the analysis results shown so far in this paper are based on observed deterioration over the period of inspection of the geotechnical assets (from 2002 to date), projected forward into the future. This observed deterioration occurred under the climate that the assets have experienced from their construction to the present day. If the future climate varies from this past climate, as is predicted in published climate change projections, this methodology, whilst useful to calibrate and understand the model outputs, is not a valid predictor for sound asset management decision making. The impact of predicted climate change on the performance of geotechnical assets is a complex and multi-faceted issue, and relatively little quantitative data is available to support deterioration modelling.

That said, some research work into this area is being undertaken and a particularly useful example is the ACHILLES research programme (ACHILLES, 2022). National Highways are a supporter of ACHILLES and through this link engaged with the research to help provide quantitative values for increased deterioration due to future climate change, based on the detailed, slope scale modelling that has been undertaken (see for example Postill, 2019). Whilst the ACHILLES research is currently focussed on high plasticity slopes, an understanding of the magnitude of potential climate change impact was invaluable to the deterioration modelling we have undertaken. By comparing deterioration of a cutting slope in high plasticity clay for a current climate model, with a synthetic future weather pattern based on a future climate from the UKCP18 predictions (Met. Office, 2018), the work of ACHILLES has demonstrated that the time to failure of a slope (defined by a calculated Factor of Safety of less than one being seen in the model) may be significantly shortened. Deterioration that is between approximately 1.4 and 2.9 times faster than currently seen might be expected.

Using this benchmark value as a guide, the research team used engineering judgement and prior experience to derive a series of deterioration uplift factors (with a plausible central value and a minimum to maximum range), which could be applied to the Markov model output matrices. In accordance with National Highways guidelines (National Highways, 2022), a range of multipliers were calculated for the present day to 2050, and from 2050 to 2080. Values were also derived for different geological material types, and the presence of types of Special Geotechnical Measures and drainage in the assets.

The output of one of the analyses is shown in Figure 6, for the expected number of annual failures in embankment sub-assets.

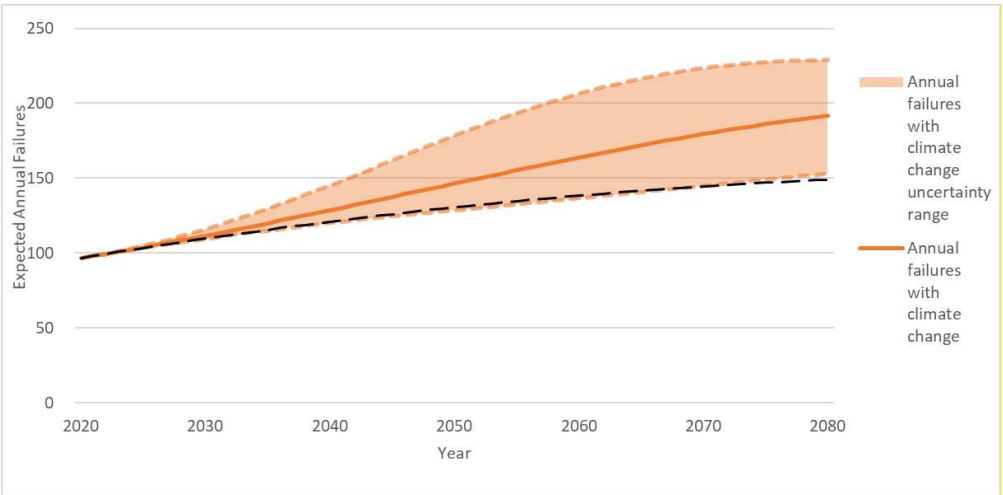

Figure 6: Predicted change in expected annual sub-asset failures for embankment sub-assets with consideration of future climate change.

The modelling shows that the prediction of expected annual failures with consideration of climate change is higher than without such consideration and also that a wide range of predictions are seen in the modelling. This is the result of the range of multipliers that the research team derived, that had a central value, and two plausible minimum and maximum values. Considering the prediction for expected annual failures by 2080, without consideration of climate change, a 55% increase in the number of failures compared to 2020 is seen in the modelling. When the climate change multipliers are applied, the increase in number of failures ranges from 57% to 136% with a central value of 97% increase compared to 2020.

6. Conclusions

The research undertaken has developed quantitative deterioration models for National Highways geotechnical assets and has demonstrated how key characteristics of the assets influences their observed and predicted future performance. Whilst not all of the outcomes of the modelling are able to be presented in this short paper, they can be summarised as follows:

- Whilst deterioration has been observed in all asset types, the rates of deterioration are slow, and in general the majority of the geotechnical assets on the strategic road network are in good condition
- Cuttings and embankments have been shown to be deteriorating at almost the same rate, both of which are faster than for at-grade assets,
- Relationships between geological material types comprising the assets and their deterioration rates are generally well aligned with engineering experience, although not as clearly as seen in the similar modelling undertaken for Network Rail (Spink, op. cit),
- The presence of SGMs within assets produces counterintuitive results in that the presence of an SGM seems to increase the rate of deterioration. This is believed to be due to the small size of the cohorts of assets with SGMs in them which may make the inspection data insufficient for representative modelling, and the fact that many of the SGMs are associated with slope repairs, indicating assets which have undergone a degradation of performance, or even failure. Further work is required in this area of the modelling,
- Similarly counterintuitive results are seen when considering assets with, or without, drainage, in that the presence of drainage suggests faster asset deterioration. The majority of assets on the strategic road network have drainage present, and it appears that the influence of other factors (such as asset type and geological materials) is more important in the modelling than drainage, which is almost ubiquitous in the asset portfolio. It is also possible that assets without drainage present perform better because they do not need drainage, due to their geometric configuration or perhaps permeable ground conditions,
- The quantitative influence of climate change on potential future deterioration of geotechnical assets has been clearly demonstrated, perhaps for the first time at such a significant scale (i.e, for an entire transportation network). It is recognised that the basis of the analysis is through extrapolation of a very limited set of high quality modelling data, through the use of expert judgement and engineering knowledge,
- The deterioration models produced provide National Highways with a sound base for future development of decision support tools for their geotechnical assets, and also provide immediate information for the development of asset management plans to ensure the resilience of their assets in future Road Investment Strategy periods.

Acknowledgements

The work presented here would not have been possible without the high-quality principal inspection data that has been collected for over 20 years by numerous geotechnical asset inspectors. Their hard work and diligence is acknowledged here. Thanks are also due to Network Rail, particularly Simon Abbott and Mike Edwards, who allowed the geological material groups used in the GSRA methodology to be used by National Highways for this work.

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