Geotechnical Asset Management for Climate Change Risk

by

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Abstract

Geotechnical asset management is a process and tool which encourages robust data management, optimised programming and evidenced based decision-making. Although asset management has come a long way since becoming a more accepted practice in the highways sector , and has fundamentally changed the way that assets are maintained, there are aspects that are still evolving as clarity on asset and network need improves and extends into future years. However, in gaining more sight into the future of asset networks, unforeseen risks begin to appear. These risks may not have been known or well understood at the time the asset network was constructed, or may not have been an issue when the asset was originally designed, yet, over the years the changing use of the asset network by users has led to new risks becoming apparent. One of these historically unknown risks is climate change. While knowledge about how climate change is expected to impact assets is improving, the understanding of the scale and scope of assets that will be affected by climate change is less well developed.

The tool presented in this research is a risk assessment, which evaluates the risk profile of the effects of climate change on a geotechnical asset as the result of the critical condition impact factors. This risk profile is completed by a scoring the impacting factors on a scorecard, for subsequent inclusion in the final risk score. The likelihood element of the risk assessment uses probability scores taken from the medium emission scenarios presented by the UKCIP 2018. The resultant risk score can then be utilised as a forward planning tool for maintenance, or increased monitoring, where appropriate.

Three case studies were assessed to show the practical application of the system. The results of the case studies show that the process works and produces results which aid the planning of maintenance to mitigate for climate change.

This thesis is lovingly dedicated to my Grandfathers (Grandpop and Granddad), Nanny and Uncle Peter, who should be here to see this, but sadly are not.

We miss you, every day.

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Huge thanks must also be given to my friends, you know who you are, I'm sorry for all of the times that I haven't been around, I promise to be better. But after 30 years, you already know what you are getting. I'll make up for it in wine.

To my family, Mum and Dad, thank you for believing in me, encouraging me, pushing me and supporting everything that I do. You have been there from the very start, but I do think that the tank, dam-building and Lego made the biggest difference. There are never the right words to describe how much it means. Thank you.

To my Husband, I'm sorry that the house is a mess – let's get a cleaner! My rock, who knew that when I started this project, we'd have been married for nearly three years by the time I finished! You are the best part of my day. I love you.

Lex

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1 Introduction

The UK has an aging and complex transport infrastructure network. The Strategic Road Network (SRN) in the UK is divided amongst a number of devolved organisations, including Transport Scotland, the Welsh Assembly, and the Department for Regional Development, Northern Ireland. In England, the SRN is currently under the ownership of Highways England, a publicly owned company. As the network custodian, Highways England operates, maintains and improves England's motorways and major A roads. Highways England utilize a large range of contracts and engage many contractors to manage around 4,300 miles of motorways and trunk roads in the UK. This represents around 2 per cent of all roads in England by length, which carry a third of all traffic by mileage and two thirds of all heavy goods traffic. (Highways England, 2016).

In addition to the operation, management and upkeep of the English SRN, Highways England are also partially responsible, along with other UK Overseeing organisations, for the production and revision of the Design Manual for Roads and Bridges (DMRB) (www.StandardsforHighways.co.uk, accessed July 2020), a series of documents which inform design specification and give guidance to designers and maintenance contractors for the provision of assets to be included on the SRN. As outlined above, these documents are also used and approved by Transport Scotland, the Welsh Assembly and the Department for Regional Development Northern Ireland. The specifications are also used by local roads authorities in the UK as guidance and accepted best practice.

Highways England, like most other large-scale asset owners, are endeavouring to understand how their aging network will change in the future. Condition deterioration models, decision support tools and funding profile models are being used by senior management to determine not only how the network will deteriorate, but also how to demonstrate prudent, optimized decision making, to stakeholders and budget controllers. A robust evidence base to present funding needs to the Treasury is required, and strong business cases must be presented to gain the extra funding required to develop and support the network. It is also the responsibility of organizations like Highways England and Network Rail to provide a transportation network with capacity and durability to meet future needs, however uncertain future conditions may be. As such, Highways England is now investing in a wide range of solutions to support and provide clarity for future investment, particularly with respect to resilience, the needs of future users, and climate change. This research aims to become a part of that process.

There are several themes running throughout this presentation of research. Asset management, a now business-as-usual management concept for transportation networks; differentiation of asset types, as in a network as diverse as the SRN it must be very clear which assets fall within which remit; Future Planning, i.e., understanding the limitations of planning beyond current funding cycles; and finally Climate Change, as predicting how our climate will alter in future is not as straightforward as comparing historic data.

1.1 Asset Management

Asset Management is not a new concept to the UK infrastructure, especially within the highways sector. Whilst the terminology was initially developed for the financial sector, the term asset management was first used in a publication by the United States Department for Transportation to describe the management of their physical asset portfolio in 1983. In 1984 Dr Penny Burns (TRANSFORM,2003) adopted the terminology for the management of drainage assets by the Engineering and Water Supply Department in South Australia. Further, in 1998, Road Maintenance Management (Robinson et al, 1998) presented a framework for the management of road maintenance which included many of the concepts and intricacies of current infrastructure asset management systems. Even in these cases, the distinction and time bounds are based on terminology; however, in practice highways asset managers have been managing their assets through operational maintenance for many years.

The principle aim of an asset management approach is to shift the understanding of an asset's performance and needs from a financial basis to a more holistic methodology that considers longevity and durability, and implements evidence-based risk management for decision making to meet the strategic goals of an organisation (ISO55000, 2018). It is now commonplace for UK SRN highway authorities and most other major infrastructure asset owners and operators to focus on developing long-term maintenance programmes to ensure that optimization for both spend and condition is undertaken across asset portfolios and measured through output performance, (ORR, 2019, ORR, 2018). Statutory obligations ensure a level of regulation with respect to inspections, and have a strong emphasis on safety (UKRLG, 2018).

1.2 Asset Types

Whilst asset groups will vary between organisations, there are four key groupings for most road and rail sectors: pavements/track, structures, drainage, and geotechnical assets. The work undertaken within this project will largely focus on geotechnical assets forming part of the strategic road network (SRN), managed by Highways England. From experience, the datasets available for geotechnical assets are often thought to be some of the most highly populated for both inventory data and condition data within the organisation. Highways England have a been recording asset data for many of years, and for some asset types have significant (>75%) inventory and/or condition coverage in their existing data, meaning little extrapolation is required to provide a profile of condition across the business. In addition, significant work has been undertaken by the both asset owner and within the academic community to understand the long-term deterioration profiles for infrastructure geotechnical assets (Mian et al 2011, Power, 2012).

In principle, all Infrastructure assets are founded directly or indirectly on a geotechnical base. Focusing the adoption of an asset management approach to address only a small number of asset types within the portfolio can therefore lead to a significant level of non-quantified risk that is associated with excluded asset types. Clayton (2000) highlights that, from ‘cradle to grave’ the construction industry itself has a high-risk potential, and that no construction project is risk free, and geotechnical costs often form a majority portion of unexpected costs incurred on building projects (Tyrell et al., 1983).

1.3 Future Planning

Future planning is an essential element of managing a highway network asset portfolio. By understanding the potential impacts, or ‘Drivers for Change’, on the network (for example, funding fluctuations, environmental factors including climate change, demographics, and political or technological changes) we can give greater confidence in the decisions that are being made now with the understanding that they will continue to be beneficial in the future. At the very least, we should be as certain as possible that short-term decisions made now do not create long-term issues in the future. Current techniques for understanding and modelling these factors include future scenario modelling, condition projections and risk assessments.

1.4 Climate Change

Our climate is changing at a rapid rate. The UKCIP 2018 is the latest iteration in a series of models which predict how our climate in the UK will change between now and 2080, considering all element of weather within our climate, and gives indications of likely regional variation. In addition, it presents a series of scenarios that estimate the probability of exposure to different levels of climate change, i.e. at the highest level of change, 90% of the area of the UK will not experience the most severe increase effects of climate change.

1.5 The research

This research aims to answer the problem of defining the scale and scope of geotechnical assets on the Highways England SRN which will be adversely affected by the impact of climate change effects. The researcher will address this problem by evaluating existing asset management climate change strategies, tools, and industry practice with respect to highway transport networks holistically, and with respect to geotechnical assets in particular. The research has identified a gap in tools and methods for the support of geotechnical assets and proposes a methodology to fill that gap.

An asset management process should consider not just events in the short-term future, but those in the longer-term as well; climate change will affect assets by affecting both the long-term deterioration of the asset, but also the likelihood and severity of severe weather events which may lead to a catastrophic failure. Asset owners should consider identifying assets at most risk to ensure that the transportation network remains functional and serviceable by maintaining network availability, even in changing conditions, whilst continuing to undertake maintenance, operational and upgrade activities in a systematic way to provide the desired level of service. This definition therefore ties in with the definition of asset management and resilience provided earlier in the thesis.

1.6 Aim

The key aim of this project is to develop a tool that assesses the risk to Geotechnical assets against the potential effects of climate change, for the purpose of prioritising future maintenance activities.

1.7 Objectives

- To review the state-of-the-art asset management systems and practices for highways networks in England and around the world including geotechnical asset types
- To examine the long-term approach to monitoring geotechnical asset condition and consider the impacts of climate change on support requirements when planning needs within the highways network.
- To study the geotechnical asset failure modes to determine the hierarchy of factors affecting the performance of the geotechnical assets including ground water fluctuations, seepage, soil properties, geology and hydrogeology.

- To develop an approach to quantify the long-term geotechnical asset management climate change risk for use in the planning stage of an asset management life cycle, by developing a tool to support engineering experts to make an assessment to determine if further maintenance work is required to support the asset against climate change effects.
- To test the approach through case studies and validate the tool.

1.8 Research Road Map

The outputs of the research is shown in Table 1 below.

Table 1 - Research Roadmap of Objectives

Objective No.	Objectives of the Research	Methodology to achieve the Objectives	Research Output
1	To review the state-of-the-art asset management systems and practices for highways networks in UK and around the world including geotechnical assets	Review of current literature for highways asset management including geotechnical assets adopted in UK and across the world	Literature Review
2	To examine the long-term approach to monitoring geotechnical asset condition and consider the impacts of climate change on support requirements when planning needs within the highways network (with focus on geotechnical) industry.	Review of literature on Risk-based approaches to asset management and long-term planning needs of road transportation network.	Literature Review
3	To study the geotechnical asset failure modes to determine the hierarchy of factors affecting the performance of the geotechnical assets including ground water fluctuations, seepage, soil properties, geology and hydrogeology.	Determining the impacting factors affecting the performance of geotechnical assets and their inter relationships and considered link to climate change	A list of critical factors and the interrelation between the same.

4	To develop a geotechnical asset management climate change risk mapping approach for use in the planning stage of an asset management life cycle and to develop a tool to support these assessments.	Develop a risk matrix to assign a risk level, according to the scored severity and the anticipated level of climate change. And boundary set thresholds for risk impacts and likelihood	Climate Change Needs Risk Assessment Tool
5	To test the approach through case studies and validate the tool.	Validate the decision support tool and the methodology; using pilot projects i.e. case studies and structured interviews with industry experts. Integrate feedback from the validation stage and develop the framework as a finished tool.	Case Studies demonstrating use and outcomes of the Climate Change Needs Risk Assessment Tool

1.9 Thesis Layout

This thesis is organised into six chapters, structured as follows:

Chapter 1 – Provides an introduction to the research, and lists the aims and objectives, background and demonstrates the need for to the research.

Chapter 2 – Reviews current and previous literature related to the research topic. This Chapter contains an exploration into the detailed aspects of asset management and risk and resilience, along with detailing approaches to geotechnical asset management.

Chapter 3 – Describes in detail the methodological approach adopted for this research.

Chapter 4 – Provides a detailed breakdown of the design phases for the development of the Risk Assessment Tool, including the various iterations undertaken to develop the approach are included.

Chapter 5 – discusses the research findings and provides detailed description of the tool and its approach. This is supported with the help of examples from Case Studies undertaken as part of the methodology. It also showcases the outputs of 3 case studies that have been used, in combination with Industry expert validation, to ‘verify’ the usefulness of the tool, and confirm that as designed it meets business needs. This chapter contains the discussion of the research and the limitations of the tool.

Chapter 6 – This chapter includes conclusions and a summary of the research undertaken and provides insights into future development work that might be considered within the context of current industry practice.

1.9.1 Outcomes

The successful outcome of this project is the demonstration of an operational asset management tool to assess the risk of climate change-related impacts on geotechnical asset condition.

This tool is an original contribution to knowledge.

2 Literature Review

2.1 Asset Management

2.1.1 Introduction to asset management practice

In this chapter the researcher will introduce asset management, definitions, processes, history and tools for delivery. Asset management has a broad scope in defining how the whole lifecycle of assets should be managed. The term asset management is believed to describe and has been used to document the process of managing a variety of infrastructure assets since 1984 (TRANSFORM, 1984), beginning predominantly in the water and utilities industries and moving the into the UK rail industry in the early 2000's following the Potter's Bar rail disaster (NAO, 2003). It has subsequently moved into use in the roads sector and is used in both the Strategic and Local roads sectors for the delivery of Highways-related activities. However, the activities falling under the 'umbrella' of Asset Management have been undertaken by asset owners in many forms, often under the premise of maintenance (IAM, 2017) however, activities that would now be described as Asset Management have long been undertaken by asset owners as maintenance activities, see next section.

2.1.2 Managing Assets vs Asset Management

Although the practice of managing assets has a long history within the industry, the discipline of Asset Management for infrastructure assets -particularly highways- is a relatively new and evolving area (ISO, 2017; Spink, 2020, Van Der Lei *et al.*, 2012; Zuashkiani *et al.*, 2014). Although sounding similar, it is important to understand that the two terms are distinct and should be considered independently from each other. 'Managing assets' can be considered as the things that are done to support the asset lifecycle and carry out maintenance. In most cases this is undertaken without a supporting framework, and without a systematic approach that adopted by the whole organisation. By comparison, asset management has a broader focus across many organisational levels and applies to all functions and departments, reducing silo-ing of assets and promoting consideration of the network as a whole (ISO, 2017). The following table (Table 2), reproduced from TC 251 (ISO, 217), shows how the two terms differ from each other.

Table 2 shows that where managing assets is simplistic and short term in its thinking, asset management provides a holistic framework which focuses the efforts of the organisation on deriving long-term value and supporting organisational objectives through management of asset lifecycles and collaborative working. (Lattanzio, 2018)

Table 2 - Managing Assets versus Asset Management (ISO 2017)

Managing Assets	Asset Management
Your colleagues are focussed on: • Asset data, location and condition • Current KPIs • Department budget	Your colleagues are focussed on: • Information supported decisions (strategic context and related to customer needs) • Strategies to select and exploit assets over their lifecycle to support business aims • Collaboration across departments to optimise resources allocated to activities
Your stakeholders are focussed on: • Costs • Current performance • Response to failure	Your stakeholders are focussed on: • Triple bottom line • Clarity of purpose of the organisation • Focus on impact of activities on organisation's objectives

Your top management is focussed on: • Short term gain / loss • Departmental / individual performance • Savings, especially OPEX	Your top management is focussed on: • Long term value for the organisation • Developing competence and capability across workforce • Business risk understood and mitigated
Your suppliers are focussed on: • Short term contracts and performance • Service level agreements are focussed on contract specifications	Your suppliers are focussed on: • Long term contracts and/or partnering relationships in support of client value and objectives. • Understanding client strategy and needs in 5-10 years.

2.1.3 What is Asset Management?

Given the wide range of industries and asset that Infrastructure Asset Management is associated with, it is important to define the scope and nature of the activities associated with the adoption of an asset management process. Numerous definitions exist, provided through guidance documentation produced by a range of learned organisations, all aiming to guide the user towards understanding of the extents and purpose of Asset Management. For example, The Institute of Asset Management (IAM) defines asset management as **"*management of (primarily) physical assets (their selection, maintenance, inspection and renewal) in determining the operational performance and profitability of industries that operate assets as part of their core business*".** Many organisations choose to focus their asset management outcome/priorities on the minimising of the whole life cost (WLC) of assets. However, other objectives may include reducing exposure to risk, delivering a resilient network, or reducing customer delay, (Institute of Asset Management, 2014, https://theiam.org/what-asset-management). More broadly, ISO 55000 (ISO, 2018), the internationally recognised standard for Asset Management, defines the process as ***"activities of an organisation to realise value from assets in the achievement of organisational objectives"***.

Whilst numerous definitions exist for asset management; It is important to review these within the context of the industry that the organisation operates within. As this research focuses on Asset Management for Motorway and Trunk road operations, the definitions provided by County Surveyors Society (CSS) and Organisation of Economic Co-operation and Development (OECD) and the Institute of Civil Engineers (ICE) are considered most applicable to road asset management systems (Table 3):

Table 3 - Asset Management Definitions

Organisation	Asset Management Definition
County Surveyors Society (CSS, 2004)	"a strategic approach that identifies the optimal allocation of resources for the management, operation, preservation and enhancement of the highways infrastructure to meet the needs of the current and future customers."
Organisation of Economic Co-operation and Development (OECD, 2001)	"systematic process of maintaining upgrading and operating assets, combining engineering principles with sound business practice and economic rationale and providing tools to facilitate a more organised and flexible approach to

	making the decisions necessary to achieve the public expectations”.
Institute of Civil Engineers (ICE, 2011)	“fundamental to the way in which we design, specify and replace”, but also … “including strategic links to the customer.”

Whilst all the above definitions are true and seek to outline the scope of asset management activities, the definitions also assert asset management’s existence in a wider context than simply dismissing it as maintenance approaches or managing assets in the way that ‘we have always done’, see Table 2. The definitions show that asset management considers existing strategy and policy, aspired levels of service, option feasibility and financial impacts. In order for asset management to be a robust approach, the implementing organisation must base it’s approach on current, accurate asset knowledge which requires the implementation, management and upkeep of adequate and reliable asset records that can be utilised and queried as the basis an effective asset management process, IAM, (2014).

For many Highway authorities, both national and international, infrastructure asset management operates across 3 distinct levels within the organisation- Strategic, Tactical, and Operational (Robinson, 1998). Further, for many highway maintenance authorities, infrastructure asset management has been a key area of focus and development for the last 10 years. Across organisations, the level of asset management maturity as measured by ISO5500 compliance and the methodology adopted will differ vastly; with approaches varying from sophisticated data warehouses with incorporated condition modelling and decision support tools to basic spreadsheets containing local maintenance and renewal programmes. In both instances, the approach methodology selected should support the requirements of the authority, usually based on maturity and network size. The requirements of the organisation must be set by senior managers as part of the defined asset management policy, business strategy, and have measurable objectives. The limitation to this development is the requirement of knowledgeable asset management professionals with appropriate domain expertise to oversee the process and undertake the relevant organisational change to support the asset management activities.

Asset management activities are focused on using high-level organisational objectives to define more detailed asset management strategy and policy in order to support maintenance activities and reduce whole life cost, whilst ensuring the delivery of the business objectives (ISO 55000, 2014). Where asset management is undertaken to deliver an asset management approach to long-term maintenance in a structured, process in accordance with best-practice, it is found that the strategy and policies are clearly defined, that they are underpinned by supporting asset and organisational data, and led by a suitably qualified team. (ISO 55000, IAM 2014, ICE 2001 and OECD 2001).

As such, the Author's definition of Highways asset management for the purpose of this research is:

'*An approach for evidence based, long-term decision making and forward planning for the construction, maintenance and operation of highway assets on the motorway and trunk road network through effective deployment of resources in order to meet organisational objectives, manage risks, meet levels of service or condition and encourage network resilience'.*

2.1.4 How is Asset Management undertaken?

Asset management focuses on supporting an asset-owning organisation to achieve its defined business objectives by providing an optimised schedule of activities. The most widely used asset management approach adopted is based upon six simple questions (IAM, 2014, UKRLG, 2018):

- What assets form the network? (**Inventory**)

- Where are our assets located? (**Geography**)
- What condition are our assets in? (**Condition**)
- How do our assets help us to achieve our business objectives? (**Targets**)
- What are the risks posed by our assets that may prevent us from meeting our business objectives? (**Risks**)
- What are the optimum mitigating actions we should take to address these risks (e.g. maintenance, refurbishment, replacement, and disposal)? (**Optimised Programming**)

The answers to these questions provide the organisation with insight into the geometry, geography and condition of their assets and the needs of those assets which are to be fulfilled. However, the answers to these questions do not provide an approach or directive to the organisation regarding the steps the organisation should take in order to meet the needs of their asset network. This task is, in the researcher's experience, very vast, but the process of asset management can be broken down into the following 6 areas, which align to the IAM requirements (IAM, 2014):

1) *Asset Policy and Strategy*
   - Understanding factors that drive organisational policy including legislation, stakeholder goals, service delivery, market forces, compliance drivers and climate change
   - Development of cost models for impacts and response
2) *Asset Information and Data*
   - Development of condition modelling and assessment strategies
   - Development of treatments to optimise performance
   - Understand current/setting new data standards
3) *Asset Systems*

- Development of tools and techniques for data acquisition, analysis and management to support data strategy
- Provision of Geographic Information System based communication tools to support planning, assessment, analysis and response

4) *Change Management – Stakeholder Engagement and Communications*

- Defining the communicative messages throughout the business
- Identifying key asset management stakeholders and the knowledge and process input, output, and ongoing requirements of the asset management approach

5) *Change Management – Capability Review and Training*

- Defined Asset Management Capability within teams at all levels of employment
- Ensuring that objective setting for individuals is directly tied to the strategic asset management objectives and focuses on how the individual's contribution helps to meet these organisational goals

6) *Performance, Audit and Assurance*

- Assessment of asset performance and identification of key risks (to include Data auditing and addressing data performance issues)
- Technical analysis of specific events in support or defence of claims

Both the initial 6 question and 6 focus areas gather details to understand the nature of the assets and the scope of the network, as well as considering the organisational requirements- including (but not limited to) personnel responsibilities and methods for improvement as required.

2.1.5 The Three levels of Asset Management

When considering an approach to asset management, many of the activities that are required to be undertaken, particularly for roads, can be seen to operate at three levels (Robinson, 2008):

i. Strategic (planning)

ii. Tactical (programming) and,

iii. Operational (preparation and operations management).

2.1.5.1 Strategic Asset Management

At the top level of asset management, there are organisational inputs from the corporate plan and the defined business objectives (ISO55000, 2018). It is at this level that levels of service may be determined, along with priorities for regions or priority improvement areas (i.e. network resilience or climate change). These strategies are often supported geographically at a network or regional level (depending on the size and geography of the asset network) by asset management tools including condition projection and decision support models. It is at this level that decisions for internal funding allocations or external funding applications may be made, and where evidence-based ‘state of the network’ reports are issued.

2.1.5.2 Tactical Asset Management

Tactical asset management focuses on turning the overarching strategies into plans, high-level long-term programmes, and key performance Indicators (KPIs) to measure delivery against the service level determined at the strategy level. At this stage, project programming and decision support tools are used to determine the operational needs of each project and outlining a provisional works programme. (ISO,55000, 2018).

2.1.5.3 Operational Asset Management

In terms of policy, operational management is associated with defining standards and intervention levels for road asset condition. Strategies are developed, by using these to assess road asset condition at the project level via an operational plan supported by project level management tools which make use of detailed comprehensive data sets to plan physical maintenance, renewal and development work activities. (ISO55000, 2018, UKRLG, 2017).

More recently, Spink (2020) presented further definition to the levels of Asset Management when presenting their keynote covering the "newly developing area of engineering geology, of strategic geotechnical asset management". (Table 4)

Table 4 - Asset Management Levels, (Spink, 2020)

Level	**Coverage**	**Purpose**
Strategic	Whole Organisation	AM Policy Development
		High level, long term corporate investment planning
		Target setting and corporate Key Performance Indicator reporting
Tactical	Sub-area of organisation	Detailed medium-term works planning
		Works prioritisation
Operational	Individual Scheme of Works	Optimisation of Scheme Design

2.1.6 Frameworks for Asset Management

Adopting asset management within an organisation requires a fundamental framework to support the delivery of activities within the organisation (ISO, 2017). A number of differing frameworks are currently in use within organisations using asset management methodologies. However, the most popular framework formats have consistent content. The figure below (Figure 1), taken from Burrow et al., 2016 shows a detailed breakdown of the activities undertaken by a highways' authority, with respect to the three levels of asset management. The diagram incorporates information on the interactions between activities, data and systems that are required for undertaking the activities and detail on the physical works at an operational level.

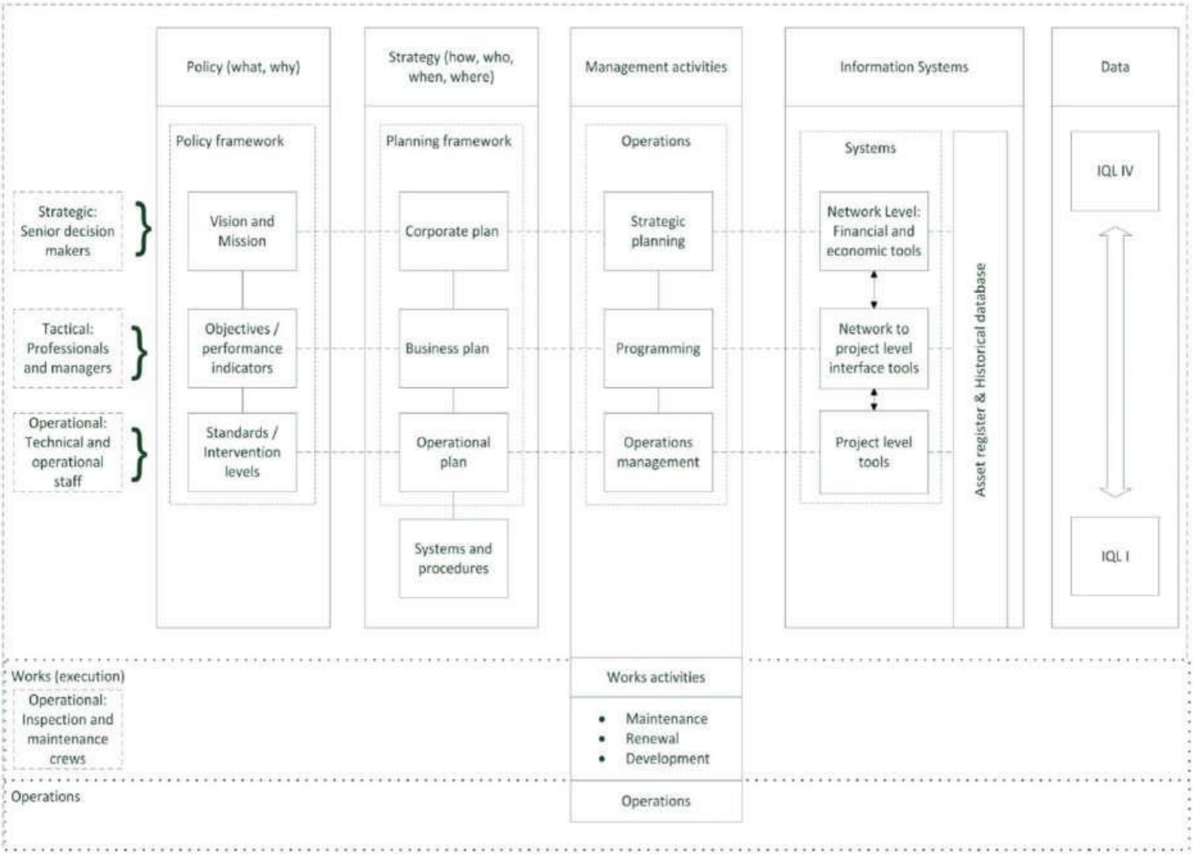


Figure 2: Road asset management framework (adapted from Robinson, 2008)

Figure 1 - Road Asset Management Framework (Burrow, et al., 2016, adapted from Robinson, 2008)

Burrow et al also categorises of the activities undertaken as both ‘basic’ and ‘advanced’ asset management (Figure 2)

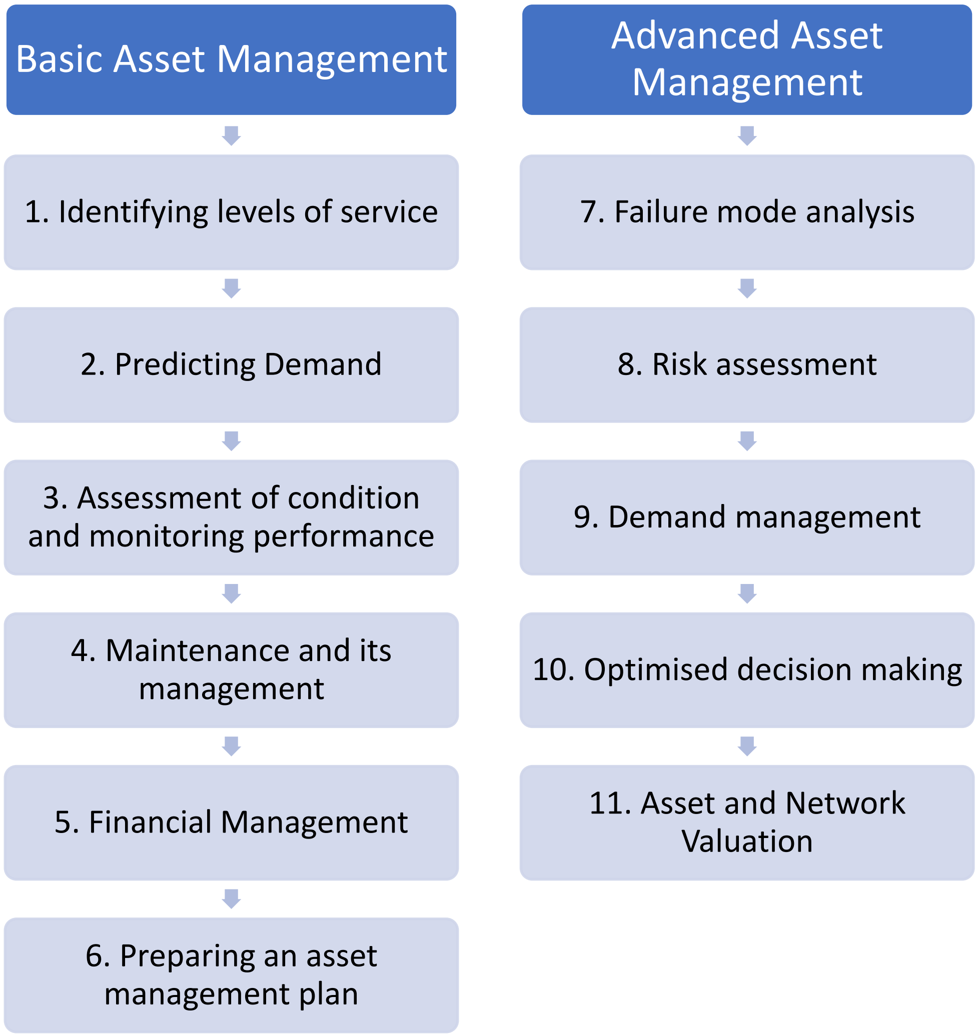


Figure 2 - Basic and Advance Asset Management Activities (Burrow, et al., 2016)

Whilst Burrow et al. observes that for much rural asset management or in countries where asset management adoption is in its infancy, a basic asset management regime may be sufficient. It is also important to note that many of these advanced activities can be classified within any of the three levels of asset management, thereby reiterating the importance of strategy, policy and defined objectives as the fundamental building blocks that support the Asset Management process. It is also important to note that both basic and advance asset management must be underpinned by accurate, relevant and current data.

Further, in order to meet the requirements of ISO55000, it is paramount to understand the various components and inherent implications that an asset management system or approach demands. Historically, there has been an amount of separation within organisations between the approach to asset management, and the most appropriate way to reap the greatest benefits. For example, County Surveyors Society 'Framework for Highway Asset Management' (CSS, 2004) suggests that the asset management approach should focus on extending the vision of the management of assets to consider a 10-year approach, with a minimum requirement to review a whole life span/cycle for all assets. Elsewhere, the Institute of Civil Engineer's 'Manual of Highways Design and Management' (ICE, 2011) compares asset management systems to a 'jigsaw' that that links together a wide range of activities in a logical manner that aims to enhance and improve the long-term management of asset systems. More recently, and as discussed above, the Institute of asset management produced an anatomy of an asset management system to be comprised of 39 components, highlighting the 6 key areas of focus. This approach is mirrored by the ISO55000 framework for an asset management system, however in this instance there is a clear shift towards the incorporation objectives and strategic vision from the very highest levels of an organisation leading to a more nuanced view of risk pertaining to these high-level business objectives. In the researcher's experience, the move toward a more focused approach to risk as it pertains to the meeting of objectives is becoming a much more widely held view of best practice. The figure below (

Figure 3) shows the various components for whole life cycle management of highways assets, as outlined by the Institute of Civil Engineers (ICE, 2011). Of note, these components are very similar in nature to those discussed by Snaith et al (1998), suggesting that there is a consensus in the approach requirements for asset management implementation.

Figure 3 - Components of Asset Management (ICE, 2011) (Adapted from Shah, 2016)

By comparison, the Institute of Asset Management provides a model (Figure 4) for asset management which uses 6 key topics to outline sets from the 39 requirements of an asset management system, as provided by their Asset Management Anatomy (IAM, v3, 2014):

1. Strategy and Planning (defined in Yellow)
2. Asset Management Decision Making (defined in Green)
3. Lifecycle Delivery (defined in Blue)
4. Asset Information (defined in Purple)
5. Organisation and People (defined in Red)
6. Risk and Review (defined in Orange)

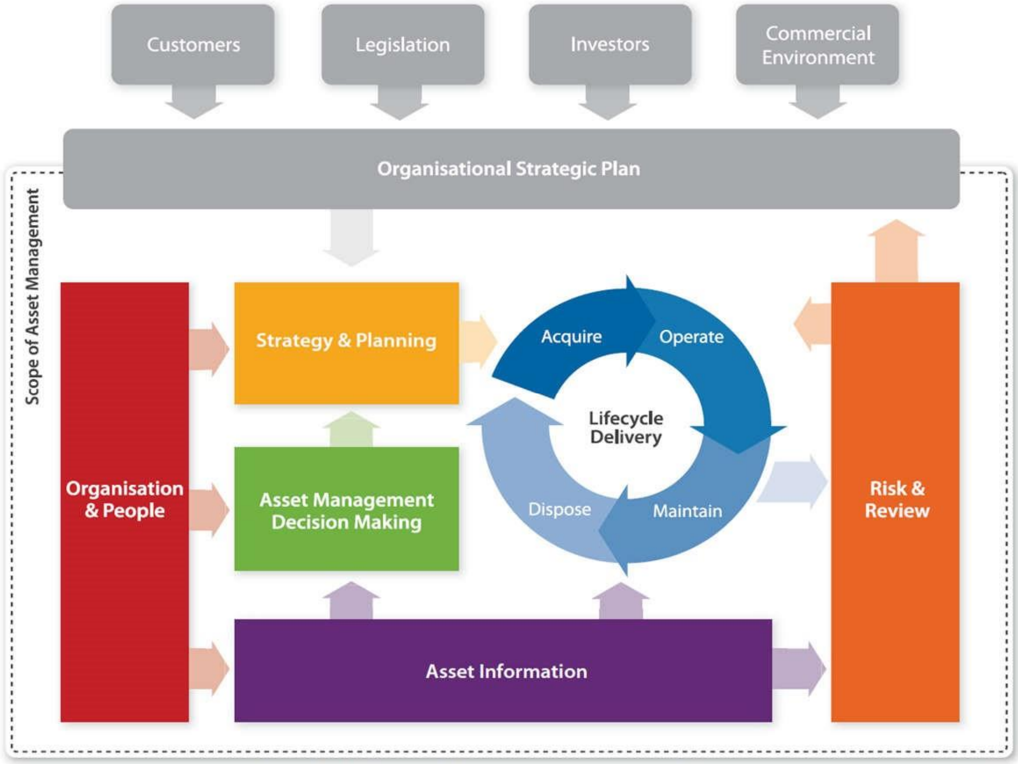


Figure 4 - Asset Management 6-box Model (IAM, 2018)

This model, whilst supporting the tasks found within the wider asset management process, does not define the three levels of asset management. It suggests instead that the 6 areas form a series of interlinked activities, rather than a distinct hierarchy of events.

In practical terms, both models presented are valid, and in practice the researcher has found through industry experience that the process of asset management adoption often forms a hybrid of the two models. At each of the 3 levels presented by Robinson (2008), all of the key areas outlined in the IAM 39 subject anatomy are undertaken, with many reaching across multiple levels; Table 5 outlines the 39 IAM anatomy subjects and categorises them against the 3 levels presented based upon the researchers industry experience in developing asset management system, in accordance with ISO 55000 and in line with the IAM anatomy.

Table 5 - High-level mapping of IAM 39 Subject Areas to 3 Asset Management levels outlined by Robinson et al (1998)

Subject Number	**Subject Title**	**Subject Definition**	**Asset Management level**
9	**Resourcing Strategy**	Determining and documenting the activities and processes to be undertaken by an organization in order to procure and use people, plant, tools and materials to deliver the Asset Management objectives and Asset Management Plan(s).	All
11	**Technical Standards & Legislation**	The processes used by an organisation to ensure its asset management activities are compliant with the relevant technical standards and legislation.	All
12	**Asset Creation & Acquisition**	An organisation's processes for the acquisition, installation and commissioning of assets.	All
17	**Asset Operation**	The processes used by an organisation to operate its assets to achieve the business objectives.	All
18	**Resource Management**	Implementing the Resourcing Strategy to manage the use of funds, people, plant, tools and materials in delivering asset management activities.	All
21	**Asset Decommissioning & Disposal**	The processes used by an organisation to decommission and dispose of assets due to ageing or changes in performance and capacity requirements.	All
22	**Asset Information Strategy**	The strategic approach to the definition, collection, management, reporting and overall governance of asset information necessary to support the implementation of an organisation's asset management strategy and objectives.	All
23	**Asset Information Standards**	The specification of a consistent structure and format for collecting and storing asset information and for reporting on the quality and accuracy of asset information.	All
25	**Data & Information**	The data and information held within an organization's asset information systems and the processes for the management and governance of that data and information.	All
28	**Organisational Structure**	The structure of an organisation in terms of its ability to deliver the organizational and asset management objectives.	All

Subject Number	**Subject Title**	**Subject Definition**	**Asset Management level**
29	**Organizational Culture**	The culture of an organization in terms of its ability to deliver the organizational and asset management objectives	All
30	**Competence Management**	The processes used by an organisation to systematically develop and maintain an adequate supply of competent and motivated people to fulfil its asset management objectives including arrangements for managing competence in the boardroom and the workplace.	All
34	**Management of Change**	An organization’s processes for the identification, assessment, implementation and communication of changes to people, processes and assets.	All
37	**Management Review, Audit and Assurance**	An organization’s processes for reviewing and auditing the effectiveness of its asset management processes and asset management system.	All
39	**Stakeholder Engagement**	The methods an organization uses to engage with stakeholders.	All
1	**Asset Management Policy**	The principles and mandated requirements derived from and consistent with the organizational strategic plan, providing a framework for the development and implementation of the asset management strategy and the setting of the asset management objectives.	All
2	**Asset Management Strategy & Objectives**	The strategic plan for the management of assets of an organisation that will be used to achieve the organizational / corporate objectives.	All
4	**Strategic Planning**	The processes an organization uses to undertake strategic asset management planning.	Strategic
27	**Asset Management Leadership**	The leadership of an organisation required to promote a whole life asset management approach to deliver the organisational and asset management objectives of the organisation	Strategic
38	**Asset Costing and Valuation**	An organization’s processes for defining and capturing ‘as built’, maintenance and renewal unit costs and the methods used by an organization for the valuation and depreciation of its assets.	Strategic

Subject Number	Subject Title	Subject Definition	Asset Management level
3	**Demand Analysis**	The processes an organization uses to both assess and influence the demand for, and level of service from, an organization's assets.	Tactical
5	**Asset Management Planning**	The activities to develop the Asset Management plans that specify the detailed activities and resources, responsibilities and timescales and risks for the achievement of the asset management objectives.	Tactical
6	**Capital Investment Decision-Making**	The processes and decisions to evaluate and analyse scenarios for decisions related to capital investments of an organization. These processes and decisions may relate to new assets for the organization (e.g. Greenfield projects) and/or replacements of assets at end of life (CAPEX sustaining programs).	Tactical
8	**Life Cycle Value Realisation**	The activities undertaken by an organization to balance the costs and benefits of different renewal, maintenance, overhaul and disposal interventions.	Tactical
10	**Shutdowns & Outage Strategy**	The activities taken by an organisation to develop a strategy for shutdown and outages.	Tactical
13	**Systems Engineering**	An interdisciplinary, collaborative approach to derive, evolve and verify a life-cycle balanced system solution which satisfies customer expectations and meets public acceptability.	Tactical
24	**Asset Information Systems**	The asset information systems an organization has in place to support the asset management activities and decision-making processes in accordance with the Asset Information Strategy.	Tactical
26	**Procurement and supply chain management**	The processes used by an organisation to ensure that all outsourced asset management activities are aligned with the asset management objectives of the organisation and to monitor the outcomes of these activities against these objectives	Tactical
31	**Risk Assessment and Management**	The policies and processes for identifying, quantifying and mitigating risk and exploiting opportunities.	Tactical

Subject Number	**Subject Title**	**Subject Definition**	**Asset Management level**
32	**Contingency Planning & Resilience Analysis**	The processes and systems put in place by an organization to ensure it is able to continue to either operate its assets to deliver the required level of service in the event of an adverse impact or maintain the safety and integrity of the assets (whether or not they operate).	Tactical
35	**Assets Performance & Health Monitoring**	The processes and measures used by an organization to assess the performance and health of its assets using performance indicators.	Tactical
36	**Asset Management System Monitoring**	The processes and measures used by an organization to assess the performance and health of its Asset Management System.	Tactical
7	**Operations & Maintenance Decision-Making**	The management activities and processes involved in determining the Operations and Maintenance requirements in support of the Asset Management objectives and goals.	Operational
14	**Configuration Management**	A management process for establishing and maintaining consistency of a product's physical and functional attributes with its design and operational information throughout its life.	Operational
15	**Maintenance Delivery**	The management of maintenance activities including both preventive and corrective maintenance management methodologies.	Operational
16	**Reliability Engineering**	The processes for ensuring that an item shall operate to a defined standard for a defined period of time in a defined environment.	Operational
19	**Shutdown & Outage Management**	An organisation’s processes for identification, planning, scheduling, execution and control of work related to shutdowns or outages	Operational
20	**Fault & Incident Response**	Responding to failures and incidents in a systematic manner, including incident detection and identification, fault analysis, use of standard responses, temporary and permanent repairs as well as the taking over and handing back of sites.	Operational
33	**Sustainable Development**	The interdisciplinary, collaborative processes used by an organisation to ensure an enduring, balanced approach to economic activity, environmental	Operational

Subject Number	**Subject Title**	**Subject Definition**	**Asset Management level**
		responsibility and social progress to ensure all activities are sustainable in perpetuity.	

However, this is largely a function of network scale, the competency of the staff undertaking the work, and the delivery set up and maturity of asset management within the organisation. Further information on the link between these high-level frameworks and the specifics regarding the management of geotechnical assets can be found in Section 2.2.

2.1.6.1 Management for Public Sector Assets

In 2001, the Organisation of Economic Co-operation and Development (OECD, 2001) released 'Asset Management for Road Sector'. The report highlights effectively that in most countries the road network is often the largest component of public assets. Most roads are owned by the government, and it is their responsibility to operate, maintain, and improve them. Kendrick and Taggart, 2006 remarks that the value of road networks has much wider importance since their role is central to the economic, social and environmental development of the nation.

2.1.6.2 Asset Management Practices in the UK Rail Sector

For the UK rail sector, improvements in the implementation of asset management came in 2003, following serious safety concerns highlighted by the Hatfield and Potter's Bar rail crash investigations. Both Health and Safety Executive (HSE) investigations highlighted that following privatisation in 1996, there had been a pattern of decreasing asset knowledge, safety breaches, and breakdowns in client/contractor relationships. As results of the investigation showed, significant improvements were required in order to meet customer and safety requirements. This was further emphasized by the Periodic Reviews (PR2000 and PR2003) undertaken by the Office of Rail Regulation in 2000 and 2003 respectively. As a result of these investigations and reviews, during the five-year period from 2005 to 2009, Network Rail were able to achieve efficiency savings of 34.1% through the implementation of formal Asset Management strategies and policies. (Network Rail, 2011)

2.1.6.3 Using Asset Management to define Objectives and Level of Service

In 2004, the County Surveyors Society (CSS, 2004) defined levels of service as the quality framework measure of service for the asset to the benefit of the customer. The level of service required is governed by the asset and network type, along with use levels, safety, accessibility, reliability, and availability of the assets (CSS, 2004 and ICE, 2011). The Institute of Civil Engineers 'Manual of Highways Design and Management' (ICE, 2011) highlights factors that influence the effective level of service; including, at an organisational level, having a clear understanding of customer expectations, development and usage of appropriate 'best practice' guidance or specifications, abiding by legislation, meeting organisational objectives and factors which can be used as a benchmark measure to assess customer satisfaction. These ICE recommendations are mirrored by the ISO5000 requirements and their focus on strong organisational leadership and asset management culture. (ISO55000)

2.1.6.4 Organisational Behaviour

In the Author's experience the implementation of Asset management systems is more effective when the focus of the development prioritises the development of the organisational approach and performance through successful change management, and lifecycle management aspects, which are often found to be functioning well, albeit with many of the aspects of the asset management approach lacking, for instance, limited access to asset data or a proactive management process. Further, by developing appropriate levels of competency at all levels of the business is key to driving the adoption of asset management and the capability of the organisation to undertake it as part of their business-as-usual tasks. Asset management competency allows employees of the to properly manage the assets within their remit and actively take responsibility for them (ICE, 2011), however, as noted by Kellick (2010) there is a recognition that this is a challenge put to organisations to drive asset management leadership from the top of the organisation down. Where this organisational culture does not exist, it often results in a lack of ownership of actions and non-uniformity in approach. Both the Institute of Civil Engineers 'Manual of Highways Design and Management' (ICE, 2011) and Kellick (2010) assert that commitment from the senior management is essential for the adoption of asset management from the earliest stages. Similarly, both The Institute of Civil Engineers 'Manual of Highways Design and Management' (ICE, 2011) and Kellick (2010) agree that a governance framework in the form of a steering or working group, which supports the focus of a prioritised adoption of the asset management approach, necessary to support the communication of activities through the organisation. Kellick (2010) further notes that if development and initiation of implementing asset management systems in an organisation becomes a responsibility of all, it ends up being a responsibility of none, which means that without ownership of the actions and there is no uniformity of approach. Ownership, accountability and responsibility remain key factors of the successful implementation of asset management for any organisation.

2.1.7 Data, Tools and systems for delivering Highway Asset Management

A key element of the asset management approaches outlined above is data. Engineers and highways management teams use data to support decision-making and undertake day-today activities involved in managing the network. In order to use the data effectively and to support evidence collection, many organisations use tool and systems to help them collect, store and use their data. The highway asset management sector operates with numerous tools to support service delivery, including Data Management systems, Decision Support Tools, Programme Optimisation and Whole life costing tools (UKRLG, 2018, Highways England, 2017). Many of them are based on the outcomes of literature on asset management and use 'live' asset data to apply a process to some common asset management activities, including making predictions, optimisations and decisions. Numerous models, tools and asset management systems (some IT-centric, others focused on process) have been devised to enable and support asset management activities. Most of the 'tools' available contain guidance and tutelage on the undertaking of asset management activities that are relevant for specific project issues, or at a higher level of asset management activity, support the management of asset type of groups.

2.1.7.1 Asset Data and Information supporting the Asset Management Approach

There is an emphasis in the cited guidance documentation that data must have an organisational process that lends itself to the practices of asset management (ISO55000, 2018; IAM, 2014; Robinson 1998). This includes: the amount of data, methods of data storage, who has access, and best practice for data management. ICE (2011) considers that the challenges for data in Asset Management are as follows:

- Inventory: Questions like location, level of condition, value, performance, significance and Impact on Network are important.
- Impacts: Short term, long term and medium term? Are the objectives deliverables cost effective?
- Utilisation: An important element to assess and evaluate current state of the asset. Questions such as 'are the assets over utilised, under-utilised or is the utilisation at an optimum level?' 'Is its utilisation significant enough to be justified as profitable asset?'

Data sets are critical to the maintenance of Infrastructure assets, accurate and up-to-date information should be required to undertake any asset management programme; however, data is not a cheap commodity, it takes time and money to collect, and may have timeliness considerations that require upkeep. At the Institute of Asset Management Conference in 2017, and in a subsequent publication (IAM, 2017), the importance of data and having a data management strategy with stringent rules on the type, quality and collection schedule of data, as part of AM system, was identified as being of critical importance to the success of the asset management approach adoption.

Efficient contract management can be an important tool in ensuring that suppliers provide the required documentation. A data-specific audit can also be used to monitor performance. Authorities working with contractors to manage and maintain geotechnical assets must face the continuing requirement to update the data inventory (Beckstrand and Mines, 2017). Historically, the data inventory available for geotechnical assets is incoherent across various types of infrastructure networks. For example, historically, Network Rail did not have a uniform data recording and upkeep system (NAO, 2003). Traditionally, Network Rail procured approximately 20 different contracts, with around 14 different suppliers, undertaking civil examinations, structural and building assessments, and earthworks inspections around the whole country. As a result, Network Rail collected asset data regionally, which led to inconsistent data capture. More recently, Network Rail procured the Civil Examination and Framework Agreement (CEFA) Contract which consists of regular inspections and monitoring of the geotechnical and other assets on the rail network and records the same on a common database system (ORR, 2009). This aims to remove the inconsistencies in the data inventory and enable a more standardised and integrated approach of data management across the rail network.

Data sets may be housed in several different ways; however, all should be managed with a similar set of policies which address how the following data sets should be collected, stored and updated, (IAM, 2017):

- Network Location Data – with GPS mapping and extents, where appropriate
- Inventory Data
- Condition Data
- Inspection Data – Last undertaken/next due
- Maintenance Records
- Reporting – for engineering and business performance
- Quality Assurance

By ensuring that datasets are adequately maintained and kept up-to-date, confidence in the methods chosen to allocate maintenance provision can be assured. ICE (2011) highlights one of the biggest challenges in asset management can often be found in the availability of basic information about the assets, inventory, location, extent, condition, value and function and most crucially, the quality and accuracy of the data recorded.

2.1.7.2 Data Quality for Asset Management

The World Bank have outlined requirements in terms of data quality (World Bank, http://opendatatoolkit.worldbank.org/en/supply.html, accessed October 2020). The organisation makes reference to what quality means in the context of data. Using EuroStat's definition of quality in statistics they provide a set of six data quality dimensions that originally defined statistical data, but can also be applied to many other types of data:

- **Relevance –** the degree to which statistics meet current and potential users needs
- **Accuracy and Reliability** - The degree to which data are free of errors arising from various factors; in the context of statistics, accuracy means the closeness of the estimated value to that of the true (unknown) value in the population
- **Timeliness and Punctuality** - How soon the data are published relative to what they measure, and how closely data updates adhere to the intended publication schedule
- **Accessibility and Clarity** - The ease with which users can access the data and the degree to which they are explained through metadata
- **Comparability** - The degree to which data can be compared across time, regions or other domains
- **Coherence** - The degree to which data comport to recognized definitions and methodologies

(World Bank, 2020)

Lin et al (2006) state that data quality is seen as critical to effective business decision-making for asset management. However, maintaining quality is problematic and challenging. The researcher asserts that these challenges result in data quality being the key challenge for engineering organisations to face today. A study by Minnaar (2015) found that a data quality framework requires three components to be of value (1) a data pipeline reference model, (2) a methodology to guide asset managers in collecting the relevant data and (3) a tool to help asset managers populate their data pipeline model and identify data quality issues.

Lin (2006) proposed a framework for the management of asset data, derived from research focused on data improvement techniques and asset management data requirements (Figure 5).

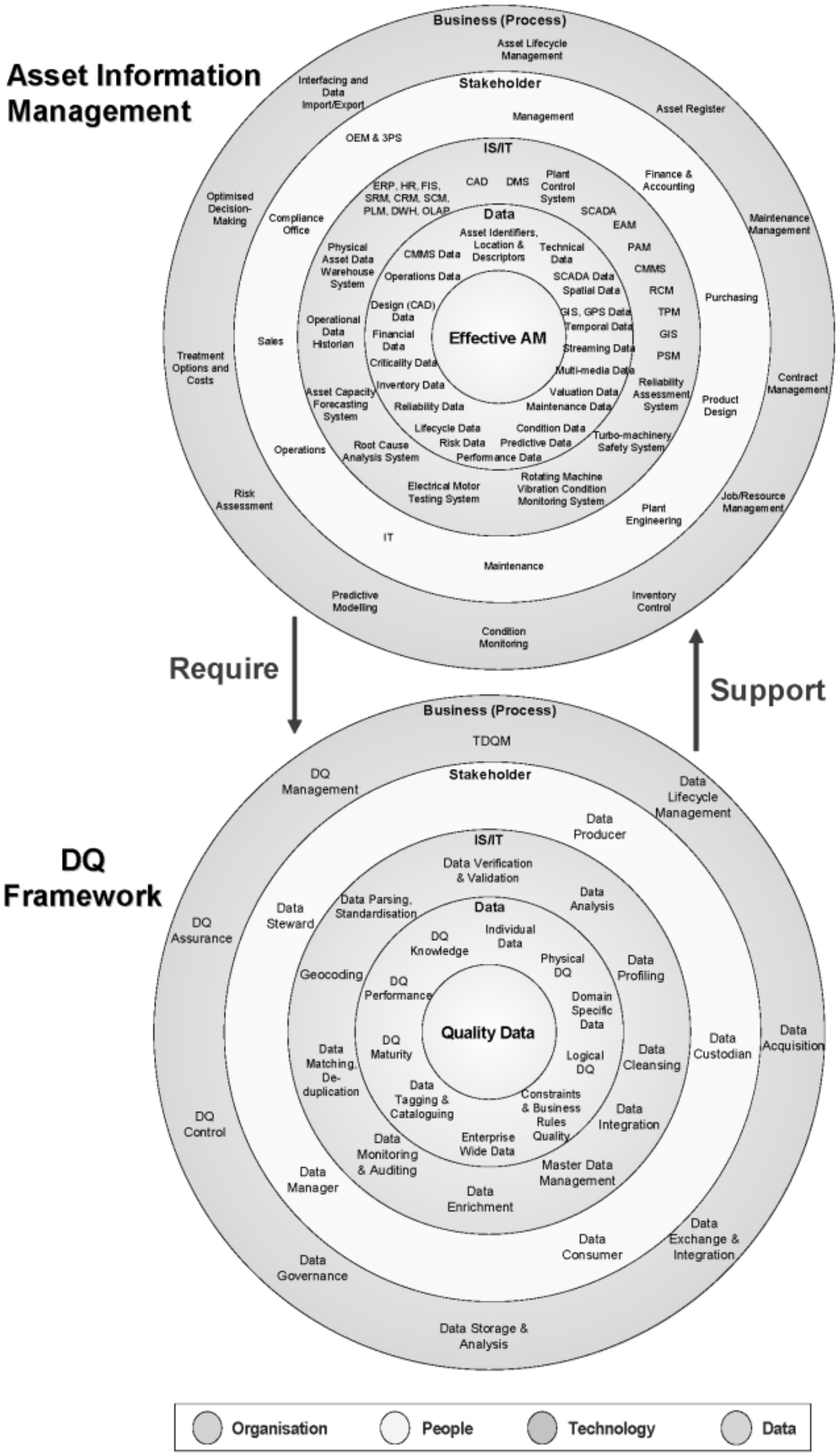


Figure 5 - Data Quality framework (reproduced from Lin et al. 2006)

2.1.7.3 *Tools and Systems providing Asset Management Support*

The tool developed in this work focuses on long-term risk assessment and planning for geotechnical assets. For comparison, several tools used in existing highway asset management systems are listed below. This list is not exhaustive, but representative of the tool functionality available in the marketplace.

2.1.7.3.1 Pavement Management System (PMS)

Pavement management systems, or PMS, are commonly adopted asset management tools for pavements (Haas, 1994 and Haas 1978). A variety of 'off the shelf', modular and bespoke systems are available on the market; examples include WDM, CONFIRM and HAPMS (UKRLG, 2020, Highways England, 2020). Most systems in use in the UK market are based upon the UK Pavement Management System (UKPMS), the national standard for management systems for the condition of local road network condition and for the planning of investment and maintenance on paved areas of roads, kerbs, footways and cycleways on local roads within the UK (UKRLG, 2011). The UKPMS plays a key role in the government guidance for Roads asset management, Well Maintained Highways Infrastructure (UKRLG, 2018). The PMS systems are often capable of undertaking tasks at a range of levels, and at the highest, most strategic level can be utilised for high-level deterioration modelling, budget/investment profiling or network targeting. At more operational levels the tools can be used to design and prioritise schemes and plan resource requirements. Most modern PMS systems are based around a central database or repository and have inputs in the form of performance metrics, objectives, deterioration models, analytical assessments and reporting applications (Dewan, 2004). Dependant of the level of the tool functionality the PMS may be used to cyclically evaluate the strategies adopted by senior managers to determine if they continue to act in the most optimal format. This process may often be undertaken on an annual basis, and usually considers performance metrics and condition measurements to determine an outcome (Dewan, 2004). For example, the UK government via the ORR (Office of Road and Rail, 2019) produce annual statistics about network size and condition, and use information contained within the Highways England PMS system, HAPMS, to determine the if their Key Performance Indicator (KPI) for Pavement Surface condition has been met, ORR, 2020 (www.orr.gov.uk, accessed September 2020).

2.1.7.3.1.1 The Components of a Pavement Management System (PMS)

Whilst within the UK a PMS system should align to the UKPMS standard, a number of defined components should be available in any off-the-shelf system in order to allow the tool to meet asset management requirements (Ausroads, 2019):

1. Evaluation of pavement performance (Condition of asset and rate of deterioration)
2. Evaluation of efficient allocation of resources, given budget constraints (Programme planning)
3. Analysis of data and resources (Modelling and decision support)
4. Database management tools (Data Management)

2.1.7.3.1.2 UKRLG Accredited PMS Tools

In order to meet UKPMS requirements the tools must consist of a representative road network model with uniquely referenced sections, contain inventory and condition data, and include functionality for defining specific business rules for treatment types and priorities as defined by organisational objectives (UKRLG, 2016).

As of 2016, there are only a small number of UKRLG accredited tools available to UK highway authorities. Non-accredited tools are also available in the marketplace. The UKRLG accredited tools are: (UKRLG, 2020 https://www.ciht.org.uk/ukrlg-home/guidance/road-condition-information/data-management/uk-pavement-management-system-ukpms/ accessed October 2020)

- Insight (Produced by Symology)

- MarchPMS (Produced by Yotta) [1]
- CONFIRM (Produced by Pitney Bowes)
- Bentley UKPMS (Produced by Bentley Systems)
- *WDM® Web PMS/UKPMS* (Produced by WDM)
- XA (Produced by XAIS Asset Management)

2.1.7.3.2 Highways Maintenance Efficiency Programme – Asset Management Guidance

To further support the management of assets within the UK, the Department for Transport created the Highways Maintenance Efficiency Programme (HMEP). The programme supports a range of tools and process documentations that outline the necessary steps for the successful management of UK road networks.

The documentation released by the HMEP includes high-level guidance presented in the Highway Infrastructure Asset Management Guidance Document (UK Road Liaison Group, 2013). This document supports highways asset owners with comprehensive advice on the requirements for successful management of their assets. Within this documentation, the HMEP recommend moving from a reactive 'worst-first' approach which leads to inefficient use of time and resources, to the undertaking of a long-term planning approach to asset management with preventive maintenance with timely intervention considered fundamental to successful long-term management. The guidance document supports:

- establish a framework to enable highway authorities to develop their asset management approach;
- provide context and advice for authorities on how to interpret the requirements of asset management;
- promote good practice through establishing a common framework approach highway infrastructure asset management;

[1] Yotta now produces an Asset Management Software System called Horizons; the author believes that this has now superseded the MarchPMS system, however the name has not changed in the latest UKRLG Annual Health Check Certificate (October 2020)

- support efficient delivery of highway maintenance through long term planning;
- provide highway authorities with practical examples of the application of asset management;

One output from this report is a series of recommendations that the group determine are the minimum requirements for achieving a substantive benefit from asset management. There are 14 recommendations that include:

1. selection/development of a robust asset management framework,
2. setting and assessing of performance measures,
3. the management of asset data,
4. lifecycle analysis, including planning to support decision making
5. whole life costing to justify allocation of funds,
6. risk assessment to anticipate and mitigate future threats to the asset, and
7. benchmarking to continuously evolve the asset management framework.

The report also provides recommendations across three themes- asset management context, asset management planning and asset management enablers- that establish a framework of support for users. The planning theme is central to the implementation of asset management, and unsurprisingly this is the focus of many of the recommendations outlined in that report. The report further focuses on establishing and developing asset management capability within the local authority highways sector, and as such the recommendations are proposed with this scale and scope in mind.

The asset management planning recommendations are vital for enabling the establishment of effective asset management planning. They include starting at the very highest levels of an organisation to outline a clear organisation-level policy and strategy towards asset planning. The strategy should encompass the long-term vision of the organisation, the strategic goals and objectives of the organisation along with and the permitted level of service (and therefore the organisation appetite for risk) anticipated from the highway network. At a more tactical level of asset management, the need for life cycle planning provides the rationale behind considering the long-term needs of the asset holdings while maintaining assets through their whole life cycle. The imperative requirements of effective asset management lifecycle analysis are current asset condition, the resulting analysis of areas of deterioration leading to diminished performance, and short and long-term operational and maintenance requirements including the organisation's intervention strategy. Long-term asset management planning provides stakeholders with evidence to support investment needs and provides insight on performance changes should investment level change. It also provides the platform for data-driven decision-support identifying the impact of funding changes and the impact of the resulting risk on the organisation.

Further, the HMEP framework establishes the role that asset management enablers play in the development and application of consistent asset management systems. The framework emphasises the importance of effective asset management leadership and culture, appropriate risk management strategies, training, benchmarking and performance monitoring. It is of note that these factors are also key cornerstones of the ISO55000 Asset management system guidance.

2.1.7.3.2.1 HMEP – Life Cycle Planning Toolkit

In 2007, the HMEP developed three toolkits that can serve as off-the-shelf decision support systems for highway asset managers. These include a carriageway toolkit and a footway toolkit, and in 2012 this was supplemented by the 'other assets' toolkit, referring to all other asset types not currently included within the carriageway or footway toolkits such as road markings, street lighting, traffic signals, traffic signs, utilities inspection covers, and earth retaining structures (FHWA, 2005; Li & Madanu, 2008; Hawkins & Smadi, 2013; Akofio-Sowah et al., 2014). Each asset-specific toolkit is available from the UKRLG website as a downloadable excel file. The purpose of these toolkits is to provide strategic decision making and to support asset management lifecycle planning in the local authority sector. It enables decision-makers to consider their approach to investment and understand the impacts that alternative scenarios may make to the network for the entire lifetime of an asset

The toolkit also supports authorities in establishing a structured intervention regime to deliver maintenance at the appropriate time to ensure long-term availability and performance of the asset in a way that is both affordable and achievable within the resource constraints in which the organisation is working. The HMEP express that using these toolkits will provide authorities with a process to facilitate long-term strategic planning by:

- Examining the impact of funding changes on asset performance and maintenance requirements
- Provide a forecasted estimate of the present and future funds needed
- Support authorities in the identification of costs required to perform an effective level of maintenance over the lifespan of the asset. (HMEP, 2014)

These toolkits provide the a ready-to-use function that support local authorities in basic asset management planning. They are relatively easy to use, and specific to the asset types encountered by local highway authorities. Conversely, the asset management support framework is quite generic and flexible in order to adjust to meeting the needs of a wide range of organisations. Since it has been delivered, the approach to asset management has moved on such that the author feels that there are other approaches now available that can provide a better level of support and more considered approach to the management of risk in the long term.

The HMEP toolkit can be used to further develop the outputs of the tool proposed within this research to support the forward programming of any maintenance works required to reduce the risk of climate change impact output by the proposed tool. Users would be required to determine the forward treatment strategy, budget and performance expectations to define the long-term approach and programme of intervention for the network, however it should be noted that the proposed tool currently supports individual project analysis, rather than operating at a network level.

2.1.7.3.2.2 UK Roads Liaison Group (UKRLG) Highways Infrastructure Asset Management Code of Practice

In 2014, the UK Roads Liaison Group issued guidance on the development of capability and functionality in asset management. Taggart et al (2014) discuss the Highways Infrastructure Asset Management code of practice (COP) documents for asset management, which offers three codes of practice to support and enable local authorities in UK on their asset management journey to adopt and become more capable in delivering asset management practices and make best possible use of available resources. In this first iteration the three codes of practice were 'Well Maintained Highways' for highways maintenance management, 'Well-Lit Highways' for maintaining highways lighting and 'Well-Maintained Highways Structures' for effectively maintaining highways structures. It is important to note that these Codes have no associated legal or statutory obligation, and as such there is no requirement for local authorities to adopt the approach laid out in the guidance. However, the guidance is considered to provide some of the best sector-specific practice available outlining the approach to developing asset management practices. The codes of practice provide guidance to highway authorities on the best approaches to achieve efficient, effective and economic delivery of highway maintenance services in the context of wider local authority objectives and pressures.

In 2018, an extensive edit to the UKRLG guidance was made leading to the Code of Practice being condensed down to a single volume and re-issued as 'Well-Maintained Highway Infrastructure'. This document extends guidance on litigation issues resulting from highways asset management and maintenance, along with suggesting a movie on maintenance intervention from prescriptive (i.e. replace every 10 years) to more 'Risk-based' (intervening when the risk profile becomes unacceptable). This change can lead to a deeper institutional understanding of how and when assets fail, however it also relies on strong policies regarding acceptable risk. This poses challenges for organisations where risk is not considered holistically, where asset management objectives are not directly related to corporate goals, where there is a fundamental disconnect in understanding of how asset deterioration relates to risk, or where asset management is in its infancy and staff do not possess suitable capability.

2.1.7.3.3 Decision support tools

The ISO 5500 (2018) suite of documents uses the term decision-support, but not the term decision support tool. Consequently, it cannot provide insight into what a DST is, or how it could be expected to operate. Despite no reference to decision-support tools, there is support for decision making that is focus and substantiated through pre-determined criteria (ISO 55000, 2018). The standard outlines a requirement for the organisation to possess a method and criteria for decision making, as part of the framework implementation. The Institute of Asset Management (IAM), uses the term DST in its anatomy publication (IAM, 2016) to outline common practices and terminology within the industry. Decision support tool is consequently a recognised terminology within modern Asset Management practices and is frequently found within articles and journals. Again, this guidance does not formally define what a DST is, or how it should operate. Within the anatomy, the extent of the reference made to DSTs confirms their use within strategic planning and investment modelling activities. Thus, they can be considered to support elements within an AM system, but that they are less critical parts of the framework. (Lattanzio, 2018)

The IAM provides guidance on developing DST functionality as part of the decision-making process. (IAM, 2015). Within this guidance, it states that the DST implemented should be proportional to the criticality and complexity of the problem. The most basic DSTs can be used to solve problems using simple, structured logic; whilst at their most complex they employ customised system/programme simulations. DSTs can therefore be seen to encompass both manual and computer-based tools. Lattanzio (2018) used the IAM (2015) has collated a series of DSTs across a range of asset management organisations and sector, Table 6 shows the range of their outputs, highlighting the breadth of tool functions that can be classified as DSTs.

Table 6 - Decision Support Tools used in Asset Management (Reproduced from Lattanzio, 2018 and IAM, 2015)

Organisation	*Severn Trent*	*Sasol*	*National Grid*		*Electricity North West*	*Citi-power*	*Network Rail*	*London Underground*		*Sellafield*
Sector	Waste-Water	Oil & Gas	Electricity		Electricity	Electricity	Rail	Rail		Nuclear
Lifecycle Costing	✓		✓			✓	✓	✓	✓	
Value Optimization		✓		✓	✓			✓		✓
Quantifying Risk			✓	✓		✓	✓		✓	✓
Value Opportunities		✓		✓	✓	✓				
Short-term benefits		✓					✓		✓	
Long-term benefits		✓	✓		✓		✓		✓	
Decision making tools		✓	✓	✓	✓	✓	✓	✓	✓	
Communication with stakeholders					✓					✓
Corporate data		✓		✓		✓				
Create / acquire							✓	✓		
Utilize							✓			
Maintain							✓			✓
Modify /Improve						✓	✓	✓	✓	✓
Renewal/Dispose		✓	✓			✓	✓	✓	✓	
Performance/ Reliability	✓		✓	✓			✓	✓	✓	
Life-cycle Activities		✓			✓	✓		✓	✓	

Auditable		✓	✓	✓						
Regulation	✓		✓			✓				
Business Planning	✓		✓	✓	✓	✓	✓	✓	✓	✓
Condition Assessment	✓		✓	✓		✓	✓	✓	✓	
Optimisation	✓	✓	✓	✓		✓	✓	✓	✓	
Life Extension				✓				✓		
Intangible Benefits		✓			✓			✓		

As described above, most asset management frameworks require the use of decision-support tools (DSTs) to provide evidence and aid the development of asset management techniques in the infrastructure environment, by running selected scenarios, will allow network condition to be predicted for given budget scenarios, or funding bids supported with evidence showing the necessary monetary input required to maintain current conditions (FHWA, 2009).

Further, the datasets can be used to understand condition and defect trends -for example, pothole or flooding clusters, taking place within a Network- and further extend the lifecycle of the asset by accurately predicting maintenance needs based on documented deterioration and condition information.

The tools available may act independently, or in combination, to address the following areas of asset management:

- lifecycle planning
- condition prediction models
- risk assessments
- business intelligence

These can take the form of an independent IT system or can even form a part of the functionality of more comprehensive tool, for example the PMS. The aim of the DST is to evidence the impact of the long-term maintenance demands on the deterioration of the network condition for a given maintenance budget (Lloyd, 2010). The decision support tools use a combination of algorithmic functions along with a data 'snapshot', to allow multi-attribute decision analysis to be undertaken, to give a profile of asset behaviour over the given time period.

In order to be effective, the process within the DST that supports decision-making requires consideration of a range of problem areas or issues and can require suitable iterative 'optioneering' processes to develop a solution that is effective and affordable (Shah, 2016).

A typical decision support tool comprises of 3 components,

- An information database,
- A pre-determined outcome action, which uses existing knowledge from the data using a tool that allows the user to interact with the data to determine the most appropriate outcome (Faiz et al, 2009).
- Identification of optimal maintenance strategies, which minimise risk of failure along with whole life costs. (Faiz et al., 2009)

However, decision support tools have their limitations. Many tools consider only a single asset type and are not able to consider decisions in a holistic, network-wide manner. This leads to the continued silo-ing of asset types that whilst providing convenient segregation for the allocation of funding, does not consider the network as a whole and can lead to an unintentional hierarchy within asset types. The key element in decision support, however, is setting defined business rules that support the meeting of asset management and wider business objectives (component 2 of the 3 listed above). The defined business logic within the tools is often driven by asset-specific requirements and maintenance needs, leading to the optimisation of only engineering needs (Faiz et al., 2009). This means that a tool can only consider how it should be prioritised against other similar assets, and in considering only historic maintenance needs and condition deterioration the tool generally lacks data and models to predict how the asset will behave in future should conditions change. In order to use decision support tools that consider wider context the tools should employ multi-criteria analysis and focus on a single set of defined organisational objectives that should apply to all asset types as the predominant business rules affecting delivery. This allows the organisation to provide detailed evidence of the decision-making timeline for how maintenance should be undertaken, and also (anecdotally more importantly) the decision to not undertake work. Both Lemer (1998) and Michele (2011) assert that the growing challenges in infrastructure management require the organisation to focus on wider aspects than simply the ‘need to maintain this asset at this time’ and concentrate on a balance of safe condition and long-term future resilience of the network. The following sections outline a range of different decision-support approaches

2.1.7.3.3.1 Factors used in decision support

A key outcome to this research is to investigate the following factors (Table 7) that are primarily used by Highways England to determine the impacts of climate change on the future condition of the geotechnical asset at an individual project level, and these include (Spink, 2020), for the purposes of this research, climate has been removed from this list, but is discussed in more detail in later sections :

Table 7 - Factors that may impact the condition, performance and maintenance need of a geotechnical asset

Factor	Comment
Location	Defining the location of the assets, both point and linear, against a single geo-referencing models that is used for all other asset types
Age	Knowing the asset age will give an indication as to the remaining lifespan, along with some idea of the durability of the asset
Interaction Between Different Asset Types	For example, an inadequate drainage profile may be a root cause for failure, in some cases
Asset Type	Differing assets will have different maintenance needs
Usage/Loading	Does heavy usage or more heavily trafficked routes mean more maintenance?
Underlying Geology	Do some geology types require more maintenance?
Previous Inspection/Maintenance History	Has the asset 'failed' in the past?
Design Safety Factor	Are current conditions now exceeding Factor of Safety?
Collision Trauma History	Has the asset been stuck as the result of a collision or incident?
Groundwater Fluctuations	

By understanding the impact each of these factors on condition and deterioration over time, as well as their likely relationship with asset failure, a hierarchy, or criticality list of data elements can be established and so define a list of key data elements that are required in future to support the gathering of knowledge, and as such become an attribute for future collection. However, in order to truly understand the interaction between condition factors, consideration must be given to the wider impacts from other asset groups.

'Earthworks Watch', used by Network Rail (Spink, 2020; Network Rail, 2018) as a condition monitoring system to determine an early warning of raised of geotechnical assets to vulnerability to adverse (dry and wet) weather, uses a similar series of criteria to determine where the most vulnerable assets areas per Figure 6.

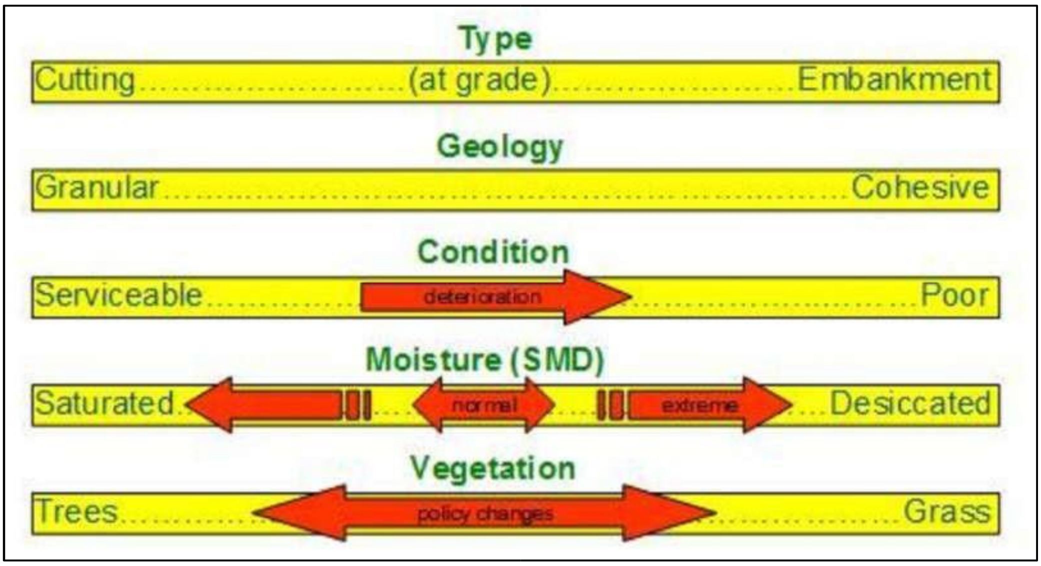


Figure 6 The five key variables considered by 'Earthworks Watch' to affect Earthwork performance.

Over time, decision-support tools can be used to assess the changes in the network, updating and further developing deterioration profiles, building a holistic picture of the strong and weak points within the network, and understanding the effects of customer usage, weather and maintenance spending, all of which will be specific to that network.

2.1.7.3.3.2 Highway Development and Management Tool (HDM-4)

The development of the Highway Development and Management Tool (HDM-4), on behalf of the World Bank is considered pivotal in the management of road infrastructure and digital data for road maintenance management. The tool has been designed to used forecast the condition and behaviour of a road pavement over its life span, (Kerali, 2000) and provide outputs focusing on the expected level of deterioration, impact of maintenance schemes and longer-term asset availability effect on users.

Initially developed from the theoretical approaches outlined by Robertson (1998) and the Highway Design and Maintenance Standards Model (HDM-III). The HDM-4 model is a key tool for Highway Asset management in many countries across the world, particularly in areas of the developing world, and for many countries is used as the primary tool to support the asset management planning system (HDM Global, www.HDMGlobal.com, assessed September 2020). The HDM tool uses a deterioration modelling approach to predict condition changes to a road pavement over the course of its design life and can be used to consider how changes in condition result in overall or sectional deterioration and the overall customer experience (Kerali, 2000).

The HDM-4 tool is consistent with the 4 key asset management categories outlined in Robinson, 1998 and delivers focused strategic analysis of forward works programming, scenario modelling, strategic planning and budgeting requirements.

Input data includes:

i. Route traffic loading,
ii. Pavement construction
iii. Pavement Inventory and condition information
iv. Environmental conditions/constraints.

Kerali (2004) asserts that the tool provides a decision-support capability which can predict the long-term changes to the network, and analyse the effects of the management policies over the lifecycle costs of a pavement asset; and finally the tool can be used to consider the impact of a variety of funding scenarios along with more crucially, estimating the overall impact on the value of the asset or network. (http://www.hdmglobal.com, accessed September 2017).

Odoki et al (2012) describes the development of the World Bank's highway development and management model HDM-4 for use by the UK Department for Transport at the strategic level. The adaption of the existing HDM-4 tool to accurately model pavement performance and road user effects in England, where it had previously not been applied; linking the tool with existing database systems used by the Department for Transport allowed the researcher was able use the tool to undertake strategic analysis of road investment decisions. The work was conducted a trial local authority road network to quantify long-term maintenance needs and assess different funding levels on the approach to maintenance and the resultant impact on condition of the network and costs to road users.

2.1.7.3.4 Using Asset Management for Network valuation

Highways England spend on asset, renewal, upkeep and winter maintenance for the year 2015-2016 was £2,972M of the total allocated budget from HM Treasury (ORR, 2017). Of this maintenance budget, £1,80M was invested in maintenance renewals schemes and major projects, leaving £1,072M to be spent on emergency, cyclic and winter maintenance. For an asset network valued at in excess of £80 Billion, this a substantial annual investment which, with increasing government scrutiny, must be invested in a consistent, optimized manner to provide maximum benefit for the customer (the taxpayer) whilst maintaining asset condition.

Snaith and Orr (2005) presented a model for the capital valuation of a road network based upon condition assessment. The author suggests that the trend for asset owners to evaluate against 'Current Capital Value' for all publicly owned and licenced assets should be undertaken. This implementation was imposed across the UK transportation sector by the National Audit Office (NAO) in 2005. This mirrored a practice pioneered in New Zealand beginning in the 1990s (TRANSIT, 2003). The principle behind Current Capital Value, or

Asset Valuation, maintains that if insufficient maintenance is undertaken on an asset, then the condition of that asset will reduce, thereby reducing the associated value of the asset. Given that the ability to maintain an asset is dependent on the funding available for maintenance, there is a cost associated with the failure to provide maintenance.

Snaith and Orr continue that some road assets may be conventionally valued by ascertaining the value of the land upon which they sit, e.g., Slopes or Embankments. However, given that the cost of small maintenance works can be significant, and given the safety requirements for daytime lane/road closures (which can be costly in terms of user delays), it could be considered that the requirement for Geotechnical Asset valuation goes beyond that of the land value.

Within the UK, all nations undertake road valuations of their Strategic Road Network on a quarterly basis as part of the Roads Authorities Asset Valuation System (RAAVS). The RAAVS valuation approach uses condition assessments and deterioration models for Pavement, Structures, Drainage and Geotechnical Assets plus Ancillary assets to undertake an annual update of the valuation of the SRN network in the UK. For UK local highway authorities, the CIPFA methodology and business rulesets are used to evaluate the change in condition of the road network in terms of monetary value. However, network valuation is not within the scope of the research and hence this is not discussed in further detail.

2.1.8 Risk-based asset management

Risk management and planning is an important function for asset owning organisations and forms an important part of the asset management framework when carried out effectively. ‘Moving Ahead for Progress in the 21st Century’, published by FHWA (2012) and Thompson et al (2017) both highlight the importance of developing risk-based asset management plan, the latter with a defined focus for geotechnical assets, to be deployed at all three levels of asset management.

The 2012 FHWA Transportation bill requires transportation departments to utilise a risk identification approach and management plan, where the main purpose is to minimise inherent risk while simultaneously making the most of available resources. The risk management plan should link directly to the organisation's objectives, to ensure that that they are adequately are met and used to communicate the identified risks and mitigation actions to be undertaken at all levels of operation. This demands that senior decision makers play a significant role in defining the level of risk appetite that is acceptable to the organisation. Options for the management of risk mitigations are often categorized as: treat, accept/tolerate, transfer, and terminate. Ignoring or not considering risk is a form of management by acceptance or tolerance (Vassely, 2018). Similarly, when considering onward mitigation actions, senior managers should consider how cost-effective solutions can be implemented, to ensure that consideration be given to the cost of the solution in relation to the level of risk the organisation is exposed to.

Risk management can be proactive or reactive, with not-yet materialised risks being proactively managed, and ongoing issues reactively remediated. Both approaches require collaborative working between engineers, planning managers and senior leadership teams. At an operational level of asset management, risks typically address project concerns including project duration, delayed completion, and cost overruns; In contrast, the strategic/tactical space senior leaders are focused on organisational, network or societal risks.

Risk identification and management requires data, process, and commitment from the whole organisation to be effective. Advances in technology have led to the development of sophisticated risk management systems; with good supporting data, these systems are often more accurate and consistent than even expert judgement. However, where data is crude, expert judgement may be the best tool available for decision making (Mian et al., 2011), despite incorporated biases and subjectivity.

Approaches and techniques for managing risk can incorporate a spectrum of qualitative methods and quantitative techniques (Hubbard, 2009). One set of quantitative risk management techniques is ‘actuarial risk management’, which combines statistics with data analytics (Boadi et al., 2009) and is used with historical data to estimate the likelihood of the occurrence of future events. This is approach is frequently used in the defence, energy and health sectors. For industries where such historic data are not readily or accurately available (which could be true for some highway networks), experienced judgment could be used, with support from qualitative techniques where appropriate. Amendola (2001) argues that where the emphasis for the organisation is in distinguishing between significant and non-significant risks in terms of scale and scope, probabilistic studies are not needed; an expert-based risk assessment can prove to be very informative.

All of the key technical asset management documents recommend the use of risk analysis and management as part asset management (ISO 55000, 2014, IAM, 2016, UKRLG, 2018, CSS, 2004 and ICE2011). Further, the County Surveyors Society (CSS, 2004) outlines that the undertaking of risk analysis is of paramount importance for successful implementation of asset management practice. Utilising risk assessment and risk management within an asset management process is necessary for the development of a long-term maintenance management solution. Risk management is listed as a step within the asset management process within three major guidance documents including:

- International Infrastructure Management Manual (IIMM, 2006)
- ISO 55000 and PAS-55: 2008 Asset Management (IAM, 2018, PAS, 2008)
- CIRIA C677 Whole-life infrastructure asset management: good practice guide for civil infrastructure (CIRIA, 2003)

The approach to measuring risk is often supported by the ISO31000 “Risk Management” (2018) technical standard that outlines the risk management framework, needs, dependencies and processes. Within ISO3100, ISO55000 and the IAM 39 Subject frameworks there is recommendation for asset-owning organisations to the use a corporate risk model to capture a range of different impacts and consequences to support effective decision-making (ISO 31000 (2018), ISO55000 (2018), and IAM (2016)). At a corporate level these models should focus on the risks that impact organisational objectives. Within the asset management system, asset performance and needs should be similarly aligned to the objectives of the business (ISO55000, 2014). Highways England supports this approach with their corporate risk matrix shown in Figure 7

ISO 33000 describes the framework requirement to support the management of short and long-term risks through:

- establishing the risk context, which includes recognising the risk scale and scope within the industry sector;
- identifying owners, stakeholders and those who are likely to be affected;
- identifying the risks, including scoring the risk to understand its impact and outlining possible mitigation actions and treatments for the risks.

Numerous authors have highlighted the importance of integrating risk management approaches within decision-making tools and frameworks to support effective decision-making and prioritisation of action, in order to make asset management more holistic. Using computational techniques and dynamic risk modelling techniques, including Markovian Chain and associated deterioration, models have been used to determine optimal portfolio strategies (Leccadito et al., 2007). Other methods that can be used for assessing dynamic risk measures include the policy iteration and value iterations methods and Newton's Method (Ruszczyn'ski, 2010).

Highways England Risk Dashboard MATRIX

IMPACT		£	Reputation	Asset	Delivery	Environment	Safety	People					
	Extreme (5)	Error or fraud or theft costing; £10m+; Overspend budget by 12.5%+	Media firestorm; Senior / ministerial jobs at stake;	Network Failure; Multiple routes unavailable for more than one day.	Major programme delays; Ministerial or public commitments not delivered;	Catastrophic or widespread environmental damage;	Multiple Staff or Contractor fatalities in a single incident; Multiple road user deaths in a single incident caused by acts or omissions of HA.	Calamity to, or resignation of management team;	5	10	15	20	25
	Major (4)	Error or fraud or theft costing; £5m-10m; Overspend budget by 10% +	National negative media attention CEO summoned to GMH, PAC, Select Committee, etc.	Multiple Asset Failure Route not available for a day or longer.	Severe (three months+) or multiple project delays Perf spec KPI missed/deferred	Widespread severe environmental impact	HA Staff fatality Contractor fatality Multiple road user fatality	Insufficient resource budget Can't afford to recruit/ acquire key skills	4	8	12	16	20
	Severe (3)	Error or fraud or theft costing £1m-5m Overspend budget by 7.5% +	Regional negative media attention Stakeholder, Monitor relationship breakdown Deteriorating NRUSS scores	A single asset failure for less than a day.	High profile project delayed Perf spec PI missed/deferred	Localised severe environmental impact	Road user fatality HA staff or contractor severely injured	Business critical personnel leave. Multiple key posts remain vacant Poor industrial relations	3	6	9	12	15
	Difficult (2)	Error or fraud or theft costing £¼m - 1m Overspend budget by 5% +	Shareholder /Stakeholder displeasure Complaint escalated to ombudsman	Critical component failure	High profile project delayed (less than one month) Local schemes delayed Internal targets missed	Widespread but moderate environmental impact	Multiple, severe road user injury	Key posts vacant Staff levels exceed control total Inappropriate skill set	2	4	6	8	10
	Undesirable (1)	Up to £¼m Overspend budget by 2.5% +	Some customers upset. Formal complaint	Component failure.	Local scheme delayed	Moderate, localised environmental	Harm to those who work or travel on the	High churn / staff turnover	1	2	3	4	5
	Opportunity (0)	Efficiency gains / Getting more for less Underspend budget by 2.5% +	Positive media events Winning awards	Innovative solutions add capacity or improve flow	Greater than planned benefits delivered	Environmental benefit, e.g. renewable energy, biodiversity gains	Accidents avoided or Reducing total road-user fatalities	Increasing engagement	0	0	0	0	0
									Very Unlikely (<5%)	**Unlikely (6% - 20%)**	**May Happen (21% - 50%)**	**Likely (51% - 75%)**	**Almost Certain (>75%)**
									Likelihood				

Figure 7 - Highways England Corporate Risk Matrix

In 2009, Highways England (2009) released the Climate Change Adaptation Strategy and Framework which was further developed into the Highway Agency's Adaptation Framework Model (HAAFM), outlines a seven-stage process that identifies activities that will be affected by climate change and determines associated risks and opportunities, as well as preferred options for mitigation. Within the framework, the researchers identified over 80 Highways England activities that may be affected by climate change. The study also found that over 60 percent of the risks identified against these activities are expected to be affected by current predicted levels of climate change (UKCIP, 2007) within their design life. A further finding from the same study showed that the approach to risk identification enabled the resulting outcomes to be prioritised based upon several criteria, including their potential to disrupt the operation or availability across all asset types forming the strategic road network, compared to previous investigations this provided important in opening up non-pavement or bridge assets to a consistent approach that can evaluate the network as a whole.

Highways England manage their risks across 7 key areas: cost, reputation, delivery, people, environment, safety and asset availability (Figure 7). All risks that are identified should fit within those 7 key areas. Spink 2020, states that geotechnical risk impact may be measured against five criteria; safety, performance, environment, reputation and infrastructure, and of these, safety and performance are the two categories most significant for the asset owners. In their presentation, safety risks relate to accidents and injuries not only to the travelling public, but also to asset operators and maintenance personnel. Performance risk impacts are considered to be more widely attributed to delays and asset availability, thus correlating with Highways England's approaches in the Safety and Asset Availability categories.

The process of identifying risks associated with assets, along with those posed to other adjacent assets forming part of an infrastructure network, are key to the development and adoption of an asset management approach. Whilst assessing the severity and likelihood of a risk is an important part of the risk identification process, without also indicating the subsequent maintenance requirement and priority and relating the risk to the meeting of organisational objectives, there is a limit to the usefulness of the approach. In the author's experience, many organisations are very capable of identifying the risks, however understanding of the importance of the next steps to ensure that the risk is appropriately mitigated and its impact on the organisation fully understood can be the limiting factor in the full adoption of a Risk-based approach. Controlling the impact of failure or addressing an increased maintenance risk can be achieved by adopting the following 3 steps:

i. Identifying potential risks associated with the assets and providing an estimate of the level of risk.
ii. Assigning a further assessment protocol to determine the priority of the risk
iii. Placing the score risk within a programme for remediating/mitigation actions.

However, geotechnical assets are diverse and complex in composition and as such this adds an additional layer of intricacy when considering the extent and level of uncertainty that the identified risk poses. The predictability normally associated with construction materials (e.g., pavement wear) does not apply to geotechnical assets, as there is often significant variability in the construction materials along the length of the asset (in the case of many highway network embankments for example) and in underlying ground conditions. In addition, many of the geotechnical assets currently in place on the SRN were constructed with limited records of their construction materials; work undertaken since construction has allowed Highways England to compile a database of information including this construction information in some cases. Even where construction materials are known, variation of underlying ground conditions remains a problem. Current risk assessment for geotechnical assets relies on judging the asset condition, both currently and looking forward to at least five years in the future, as this is the minimum requirement for a forward maintenance programme by Highways England. These risk assessment outputs are then used to calculate or predict the subsequent impact on the network.

As discussed below in Section 2.2, within HD41/15, the risk assessment categories range between unclassified (where no defect or feature is present) through low (Class 3) to severe (Class 1A) which relies on Asset inspector's experienced judgement to categorise defects and any potential risk appropriately and accurately. This approach lacks consistency and can show differences in categorisation between assets that are managed and operated under different contracts. As a result, many asset owners require more sophisticated risk models which include risk factors such as materials factors, earthwork condition, drainage, weather, vegetation and failure mechanisms including predicative and forecasted performance of the asset and their impact on safety and serviceability of the network (Spink, 2020). The risk models should also consider essential factors such as cost, user delays, lane closures, and associated environmental impacts.

2.1.8.1 Sources and types of risk

In the context of this project, risk can be defined as the calculated probability of reduction in geotechnical asset performance (in terms of safety, reliability, serviceability etc.) due to asset 'failure'. The event causing the 'failure' may be slope failure, a rock fall, settlement, or some other mode of ground movement; the loss of performance may range from full or partial closure of a trafficked carriageway to excessive tilting of a road sign. The reason these risks are defined in terms of their probability is that the occurrence of a failure event is not certain; in instances where a failure event is certain, the risk associated is limited to 'when' not 'if' (i.e. the severity is known, the likelihood is known, the exact timing is not). Reasons for the uncertain future behaviour of geotechnical assets come from two principal sources:

- **Natural variability** (aleatory uncertainty)

Non-engineered ground is innately variable. Bedrock strata, soil characteristics, and groundwater levels usually vary within an asset's geological environment, and this variation is a key reason that the factor of safety for geotechnical engineering design is typically much higher than for structural design. Asset owners can undertake expensive intensive survey work, such as GPR, to attempt to gather additional data to uncover where these variabilities lie, along with the type or magnitude of material variation. The inherent randomness of the occurrence of natural variability cannot, however, be predicted; the effect of the variabilities can be modelled.

- **Lack of knowledge** (epistemic uncertainty)

Ground conditions are never known with full certainty, and most of our understanding of the geotechnical behaviour of an asset is deduced from limited observation and information. The information gathered during an inspection forms only a snapshot of condition at any given time and must be correlated with historic and contextual data to provide a broader view and remove the effects of any outlying data that may unduly influence the output. This is then used to determine a condition profile for the asset.

Predicting future events such as climate change impacts cannot be done with certainty; the likelihood of impacts affecting stability can only be assumed using knowledge of the specific factors causing deterioration (e.g., loading or drainage issues), along with an understanding of the events associated with climate change and the profile of the network (e.g., geography, geology, traffic, construction, and deterioration profiles).

In these circumstances, we already know that an event affecting the stability of the asset will occur, given a long enough timeframe; we have no knowledge of the extent of the event, or the impact of the outcomes (likelihood and severity). More insight can be gained from utilising current knowledge of the network, along with experience, judgement, and knowledge of the outcomes of previous events to develop a true understanding of how the asset is likely to behave. Obviously, using current knowledge has limitations, especially when considering future climate change events given that the current predictions anticipate changes which are not measurable; however, understanding the potential affects means that priorities can be established and monitored in the future.

As mentioned above, the uncertainties faced by asset owners when trying to predict future conditions of an asset with respect to by both internal and external factors, are considered within the design by using a factor-of-safety approach. However, given the significant number of assets with a design and construction age falling before 1943, when Terzaghi (1943) first proposed the concepts of stability and elasticity (now known as Ultimate and Serviceability Limit States), many assets this age may be approaching these limits, or conversely, may have been over-designed to such an extent that they are unlikely to be affected by the future changes. In this instance, it is recommended that work be undertaken to determine the constructed factor of safety in order to understand if potential design limits are likely to be breached or have a breach impending. Within HD41/15 and the HAGDMS systems, assets with a construction date prior to 1950 are assigned a higher risk score and can be assumed to carry a greater risk, given that it was not until the early 1950s, over a century after peak railway construction in the 1840s, that the first formal standards in engineering geology and geotechnical engineering became available (Noakes et al, 2019; Orr, 2012).

Alternatively, utilising a reliability theory-based approach removes the uncertainty of the designed factor of safety and instead directly leads to the potential risk associated with the event. This allows for the effects of the uncertainty to be quantified. However, when considering application within the confines of this research, the lack of measurability of the outcome of future events means that a reliability approach would be challenging. The approach may be more suitable for other projects using a more deterministic approach to measuring changes in condition and deterioration over the long-term - for example work undertaken as part of the BIONICS (University of Bristol, 2016) and/or CLiFFS (University of Loughborough, 2005) projects.

2.1.8.2 Using Risk Assessment tools for managing long-term risk

Geotechnical infrastructure assets, much like pavements or bridges, are inherently variable along their length as a result of changing ground conditions and variations in construction materials from disparate suppliers. Unlike pavements and bridges however, geotechnical assets often have a significant number of less visible variables and vulnerabilities, often as a result of their interaction with other assets; for example, the impact of strength reduction on an embankment as a result of poor condition drainage assets (Lane et al, 2019). The uncertainty associated with the variability of geotechnical materials can impact the behaviour of geotechnical assets by affecting the failure of other assets; in particular, drainage failures in particular can have major adverse effects on geotechnical infrastructure. (Lane et al, 2020) A Risk-based approach is essential to understand and manage the variability of geotechnical assets, along with determining the limitations on actions to take place within an unknown future.

It is the additional information regarding likelihood and consequence of future events that provides the insight to inform and improve long-term understanding of issues affecting assets. In addition, these models support the organisation when communicating and evaluating these long-term risks by providing data, and the outputs are used both within the asset management decision-making process and when consulting stakeholders and financial controllers. Woodhouse (2001) states that decision-making for asset management requires understanding of the cost implications, risk and performance aspects to the solution posed for the asset. Whilst this is true in the short-term, the long–term requirements should be considered less certain and more subject to change. As such, a more fluid approach is required where options and scenarios are presented. By highlighting the potential impacts upon asset condition and tracking progress against them, the predictions for change and therefore the robustness of forward-thinking asset management processes can be improved.

Currently, the approach for managing condition and inspections of geotechnical assets, HD41/15, already assesses an asset's current risk of failure (See section 2.2). A risk rating for imminent failure or maintenance requirement is allocated to geotechnical assets during inspection based on observed condition and proximity to the running lanes or other significant assets. Therefore the proposed methodology developed within this thesis is not a fundamental change of approach; rather it is a way of making predictions of the future impact of climate change in a systematic and less subjective manner, taking into account the limitations of anticipated future climate scenarios, and the lack of an ability to validate the outcomes given the element of forecasting within the results. Putting the limitations this aside, the issues posed by climate change along with the need for a tool which highlights areas of weakness with asset to determine if preventative maintenance needs to be undertaken form the requirement for this approach. The proposed approach will take into account the following issues:

- The need for a practical aid to future decision making
- Decision making in asset management requires an understanding of the variability in future conditions to inform of cost, risk and performance.
- The inherent variability of geological materials and geotechnical asset performance.
- The ability to provide compare and group information between different assets and asset types for the purpose of building efficient maintenance programmes and working across asset-types to minimise disruption to the network.

2.1.8.3 Decision Support for Risk-Based Approaches in Asset Management, including Stochastic Modelling

In 2005, Costello et al., (2005) presented a planning methodology using Markovian processes targeted at the maintenance management staff responsible for pavement assets. The methodology used stochastic modelling techniques to make decisions and infer outcomes. The research was focused on the decision-making process through the 'development of long term, or strategic, estimates of road maintenance expenditure and road condition forecasts under various budgetary scenarios. The team used a range of Markovian processes to simulate uncertainty and generate pavement deterioration scenarios in order to consider the outcomes against regression models, which were the generally accepted method at the time of production. The team tested the model against a case study developed from data by highways authorities in held Central Europe. The model predicted changes in the future condition of the road network in response to changes to budget constraints. Further, the model used policy and funding inputs to support the estimation of the budget requirement for maintenance of the road network in coming years. Further work by Costello et al., (2011) notes that many of the existing stochastic or deterministic approaches cannot be applied to the lifecycle planning of many highway assets types (including those listed as 'other' within the HMEP framework) as a result of the lack of available data associated with determining the current condition of the asset, and thus determining reliable deterioration models. The team address this by noting that current condition and deterioration in these 'secondary' highway assets is established through the collection of data from video footage and walked surveys. As such, current opinion on the lifespan and expected deterioration approach has been gathered from industry experts and then developed into probability matrices using simplistic assumptions. The team (Costello et al. 2011) assert that visual condition data is suitably robust, and the assets sufficiently homogeneous that estimation of deterioration can be used for ancillary highway assets. The researcher's experience in the field finds this to be true with caveats. Secondary assets can be considered by a more simplistic approach, relative to pavement; however, a method that seeks to predict risk of failure or changes in asset performance over the life of the asset must also consider the risk profile of these assets against the corporate risk appetite. In a similar vein, Mian, et al., (2011) also presented an approach to risk prediction through a Risk-based framework for infrastructure asset management. The framework outlines a four-step process which can be used to define the criticality of the risks associated with asset deterioration through

1. Hazard identification,
2. Risk estimation,
3. Risk evaluation, and
4. Risk-based investment decision

The team outline the use of cross asset interaction, use of asset criticality, and asset vulnerability as key variables in the risk level through the risk-based framework. The authors suggest that asset management planning should be supported through the use of risk matrices, and that this approach can be considered simpler and a more suitable tool than sophisticated modelling tools when considering the level of information available on these asset groups and technical expertise within the asset management organisations. The team points out that the use of a risk-based approach is essential for timely asset maintenance interventions, and cultural changes to ensure that the lowest cost solution is not the default choice. This style of risk-based approach is reflected in the HMEP guidance discussed above.

Leviäkangas et al., (2014) similarly used a Cost Benefit Analysis (CBA) to predict and forecast the impact of extreme weather and climate risks on infrastructure assets in Europe. While the study is largely focussed on the financial impacts of the weather risks imposed by climate change, it also highlights the role played by other factors in the maintenance of an asset such as the impact of local or regional differences in asset maintenance practices and differing budget priorities. The paper acknowledges the inconsistent approaches and systems used to measure and record weather risk and explains that weather conditions/risks vary substantially between and even within countries; as such, they should be considered in any long-term approach to asset planning.

2.1.8.3.1.1 Failure Mode, Effect and Criticality Analysis

Further to the techniques described in the previous section, other risk management approaches that are widely used in the asset management industry include the Monte Carlo Simulation and Failure Mode and Effects Analysis (FMEA).

For Monte Carlo Simulations, a risk assessment is undertaken using probabilistic modelling, where the type and extent of uncertainty is determined using statistical models. It can allow the decision makers to anticipate a range of uncertainties and their probabilities along with the possible outcomes (Schuhmacher, 2001; Cohen et al., 1996). They can be simple or complex in nature and can provide an accurate picture of resulting uncertainty. However, these are often not used by engineers, unless part of a wider package of support tools.

Failure Mode Effect and Criticality Analysis (FMECA) is a systematic method of identifying potential causes of failure before they occur. Working at the operational level of asset management tool, the FMECA is most often used at a project level, throughout the asset lifecycle.

FMECA is a simple and useful technique for identifying potential component failures within a system and the effect of these failures on the overall operation of the system. Vassie & Ricketts (1997) present an example application of FMECA to bridge inspections and assessments, and Vick (2002) presents some examples of FMECA within a geotechnical framework. It is a risk-based approach that uses qualitative ratings of likelihood (OCC) and consequence (SEV). An advantage of this methodology is the ability to consider the entire system and all of its components in terms of the same ratings of likelihood and consequence.

FMECA works best where the failure of a single component is the source of the system failure, rather than considering interaction of two or more components (Vassie & Rickets, 1997). The assumption of independence between different components is therefore required. An important part of FMECAs is the consideration of the 'ease of detection' of a failure, which contributes to the resulting risk. FMECA is a 'bottom up' analysis, like an event tree, in that the occurrence of an event is extrapolated up to all possible consequences.

FMECA considers the severity of the effects as well as the probability of occurrence by implementing a criticality analysis to the FMECA, FMECA analyses different failure modes and their effects on the system, while criticality analysis classifies or prioritises their level of importance based on failure rate and severity of effect of failure. Criticality is a function of seriousness and frequency. The FMECA assigns a risk priority number (RPN) by multiplying severity, occurrence and probability. Each of these three parameters is then determined using linguistic expressions and a rating scale from 1 (lowest) to 10 (highest). The resulting RPN quantifies the risk of failure in a tangible manner: the higher the value of RPN, the higher is the risk and consequently the lower the reliability of the asset performance (Carmignani, 2008 and Braglia, 2000). Studies (Montgomery, 1997 and Xu et al., 2002) have discussed both the merits and limitations of using this technique and have even modified the technique to best fit their risk assessments, applying weightages where appropriate.

Failure Mode and Effect Critical Analysis is more typically used in mechanical/systems engineering problems but has useful applications to both geotechnical and cross asset management. The key steps of an FMECA are defined below, Figure 8:

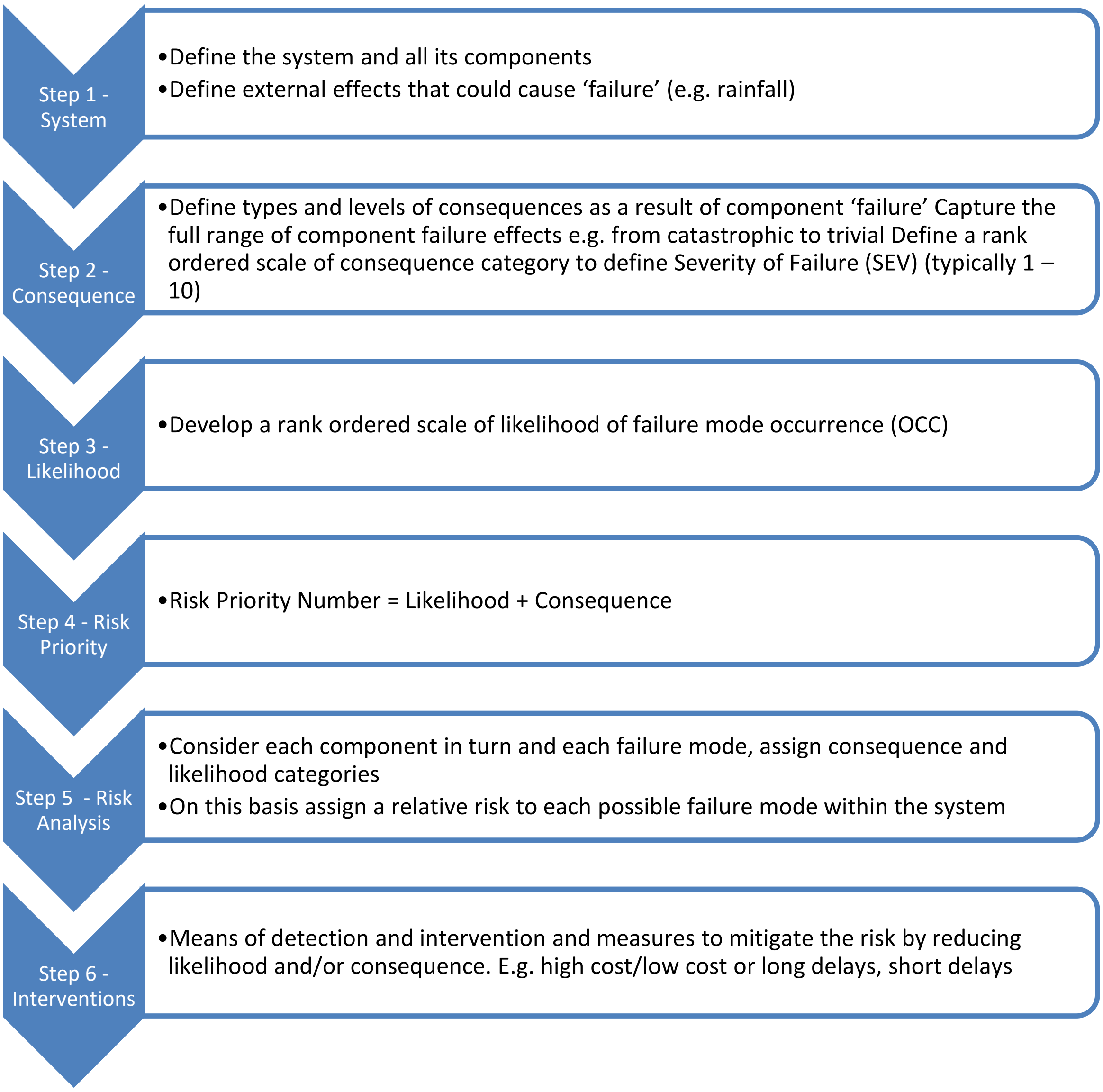


Figure 8 - FMECA Analysis

The possible applications of a FMECA for a geotechnical asset risk assessment are wide ranging and could include the evaluation of risk trade-offs where the highest ranked severity and occurrence scores are assessed, and then adopting an independent solution which will cause other consequences to become more highly ranked. In some instances, undertaking a FMECA can allow for specific items to be rejected without considering risk, components, or failure modes under the premise that the outcomes are unsatisfactory to the organisation- for example, safety impacts; increasing environmental impacts; excessive solution time, or cost. For other situations, a FMECA may suggest that the most beneficial approach is to undertake multi-layer, multi-tooled risk analysis, i.e. different projects will require individual, specific analysis to determine the risk that is posed to a particular asset.

The ranking output of the FMECA can be applied to any set of criteria or objectives, and this is a significant advantage when considering the prioritisation of risks. This is especially useful for evaluations where the assessment must be multi-disciplinary (i.e. considering multiple asset types) to demonstrate optimisation for systems components or performance. The output can also be limited in the case of more complex failure modes.

The first four stages of the FMECA analysis presented in

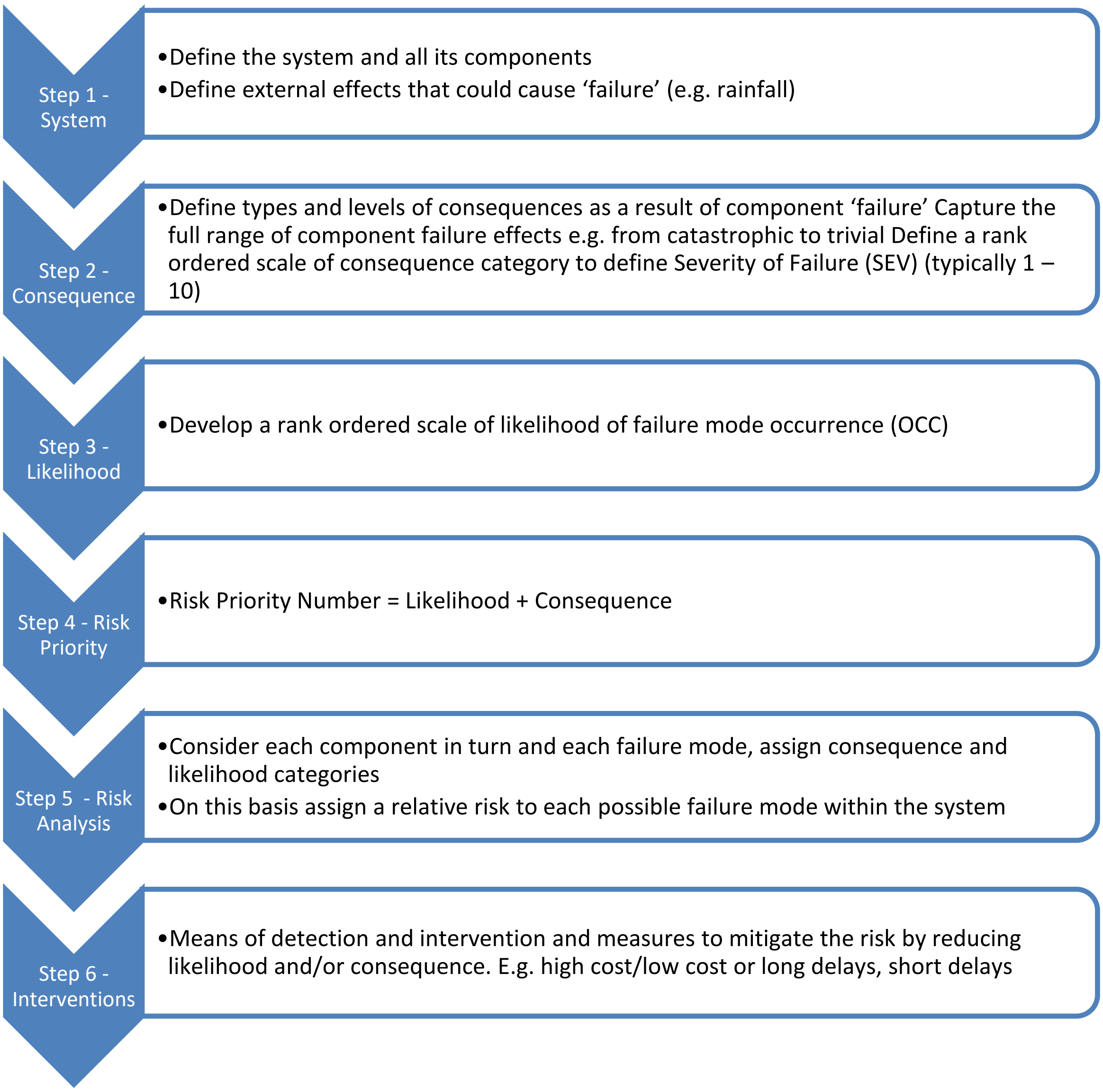


Figure 8 broadly define the four stages of the toolkit approach developed in this thesis.

Given Amendola's (2001) comments on the identification of significant versus non-significant risk being most appropriately delivered by expert risk assessment, the researcher asserts that a partial FMECA combined with a risk assessment approach should be used for this project i.e. an expert-led risk assessment should be undertaken for each asset and location to determine the presence and extent of climate change impacts. This can then be followed, using other tools as appropriate, with the project prioritisation occurring within the tactical asset management space to develop a modular programme of maintenance projects. Within this project, the nature of the items to be assessed, the long timeframe of assessment, and the levels of uncertainty combined with the crudity of the data available mean that a specific risk assessment tool must be developed to be used to assess the long-term impact of climate change.

2.1.8.4 Application of Risk-based approach techniques used in geotechnical context

Throughout the UK, there are several past and ongoing projects working to evaluate the impact of climate change; many of the projects are undertaken within the academic sector, and other work has been commissioned by asset owners to understand network-specific information.

Two of the projects approaching the issues raised within this project are Climate Impact Forecasting for Slopes (CLIFFS), led by Loughborough University and Biological and Engineering Impacts of Climate Change on Slopes (BIONICS), led by the University of Newcastle.

Both projects aim to investigate the long-term impacts of climate change effects on geotechnical assets. The current focus is predominantly for work to be undertaken on Slopes and Embankments, which form the majority of geotechnical assets forming the strategic road network.

Thirdly, the PhD thesis presented by Shah (2016) represents a current approach to measuring and managing resilience for geotechnical infrastructure assets. Scoring potential solutions, the process considers critical success factors against drivers for change and reviews the outcomes against four potential future scenarios.

2.1.8.4.1 CLIFFS project

Led by Loughborough university, the Engineering and Physical Sciences Research Council (EPSRC)-funded CLIFFS project was set up in early 2005 with the purpose of

"To stimulate an integrated research response to address the intricately linked problem of forecasting, monitoring, design, management and remediation of climate change induced variations in slope instability" (CLIFFS, 2005).

The project work was undertaken in a series of four 2-day workshops thematically linked and required to take learning and development to address issues of best practice and deliver information on future research programme approaches. The workshops concluded in mid-2007 (Dijkstra & Dixon, (2007); Dixon et al. (2006)). The workshops were undertaken biannually as follows Table 8Table 1:

Table 8 - CLIFFS Workshop Outcomes

CLIFFS Workshop	*Workshop Output*
1	• Use of climate change information in slope stability assessments including development of protocols for handling uncertainty and risk assessment • Validation of groundwater models incorporating climate forecast scenarios
2	• Impact of climate change on the magnitude and frequency of cutting and embankment slope failures • Impact of climate change on the magnitude and frequency of first-time failures and re-activated failures in natural slopes, both inland and coastal
3	• Influence of vegetation on slope stability • Monitoring techniques and applications • Development of appropriate remediation strategies
4	• Strategies for presenting and using information on future slope instability including: ○ landside hazard susceptibility maps ○ issues of land use/planning and ○ slope design implications

Fundamentally, this work has directed much of the climate change research for geotechnical assets within the UK. The project demonstrated an understanding of the future needs of the UK's infrastructure networks and was underway before much of the current work, which is considering condition deterioration for the purposes of long-term asset management.

Geotechnical assets are predisposed to deformation that varies by location and is influenced by a range of variables forming part of a hierarchy of processes and parameters that are largely interdependent and respond at different time scales to the effects of climate change. Dixon, (2010) the researchers group these variables at three levels:

(1) **material properties and processes**, including shear strength, plasticity, permeability, unsaturated conditions, etc;

(2) **site-specific conditions**, including stratigraphy and hydrogeology (e.g. bypass flow), vegetation cover, propensity for developing cracks, drainage provisions, topography (such as exposure, slope angle, micro-catchment), etc;

(3) **broad environmental context**: variation in climate influence, changes in infrastructure network use, etc.

The researcher notes that these three levels, and the factors found within them are in broad alignment with those found in section 2.7.1.3.3.1.

The specific elements of the work undertaken by the project have fed into complex models to predict the effects of climate change on the sector. The work outcomes are made using a previous set of climate change predictions (UKCIP 03) and predominately focus on the monitoring and modelling of deterioration and specific risks to slope and embankment structures such as the impact of vegetation on slope run-off (Glendinning, (2010).

2.1.8.4.2 BIONICS Embankment model

The BIONICS project began in the early 2000’s and aims to understand the impact that climate change will have on UK slopes and embankments by looking at the combined effect of changing rainfall patterns and changing vegetation on slopes. (Glendinning, 2006)

In order to understand the effects on UK infrastructure slopes and embankments, researchers constructed a large artificial embankment on a site at the University of Newcastle. The embankment is designed to mimic a range of common climate and vegetation conditions found within the UK. The embankment is equipped with a range of monitoring and sampling instrumentation for the purposes of gathering long-term data. The specific deliverables of the project are:

- Build and monitor an embankment representative of UK infrastructure subjected to different climates
- Plant and monitor representative vegetation subjected to different climates
- Create a controlled climate (using the specification provided by the BKCC project BETWIXT)
- Set up and run validated computer models under present and future climates to predict the embankment performance
- Develop a methodology to identify parts of the UK infrastructure that require further investigation (working in connection with other BKCC projects, in particular CRANIUM)
- Formulate a medium to long term research strategy, including some specific needs-based 'spin-off' projects

BIONICS (University of Bristol, 2016).

The project’s initial remit was to investigate the biological effects of climate change on slopes and embankments, considering how vegetation growth and removal can affect the stability of slopes. The project created a unique facility for engineering and biological research with the aim of improving fundamental understanding of the effects of climate change on slopes. Hughes et al (2009) describes the building and monitoring of a full-scale embankment representative of UK infrastructure, the planting and monitoring of representative vegetation, and the construction of a system of sprinklers and covers to control climate.

The researchers use the BIONICs facility to demonstrate that the research provides data concerning the long-term sustainability of slopes. Upon completion, this research can be used by engineers and infrastructure asset managers to design and maintain sustainable engineered infrastructure slopes through the selection of appropriate vegetation, drainage techniques and management systems.

Further findings from this work (Hughes et al, 2009) support the idea that climate change will affect the behaviour of slopes and vegetation growing on them, and further that there is a relationship between the slope and the vegetation that influences their long-term behaviour. The information that was collected as part of this work is providing data related to the failure modes anticipated as a result of climate change and hence on the sustainability of UK infrastructure slopes.

Since the completion of these project elements, work has been undertaken to understand the framework needs to support the data collected. Both the BIONICS and CLIFFS teams have invested time in the development of framework platforms to address the long-term implementation and management. This work has moved forward to become the iSMART project (Glendinning et al, 2018). As part of the iSMART work Briggs et al (2017) highlighted the following outcomes as part of a review outlining slope failures in highway and railway infrastructure embankments, with an emphasis on failure of the embankment fill

- Typical failure mechanisms differ for highway and railway embankments
- Pore water pressure increase affects both highway and railway embankments
- Some railway embankments are susceptible to deformation and progressive failure
- Embankment risk factors have been identified empirically but are poorly understood

2.1.8.4.3 Resilience Framework for Geotechnical Infrastructure Assets – Shah (2014)

Shah (2014) has proposed a resilience framework to understand how to best mediate for the social, environmental, and economic drivers for long-term change. The process provides a risk-based approach to resolving the long-term needs of a geotechnical asset network in order to facilitate a programme which ensures resilience and growth. The process does not account for the long-term effects of extreme weather, biodiversity, changes in standards or climate change.

Shah's approach scores each asset solution on seven factors for change (FC's), such as demographics, economic, governance, and technology against its critical success factors (CFS) e.g. Loading, Seepage, drainage etc. The resulting scores give an overview of the resilience of the solution which can then be reviewed to determine if the solution is suitable. In this instance, the solution could be 'do nothing' through to major re-construction or new works. This approach is very useful when considering the 'ease of use' for the user; an important aspect for the long-term usability of the tool in industry practice. The resulting tool must be simple to use and understand, give clear outputs, and not be onerous on the engineers using it. To this end, the researcher has adopted the approach of using Critical factors (Shah's critical success factors (CFS)) to determine the asset features that can be most affected by climate change effects; these banded groups characterise the main components of the geotechnical asset that can lead to reduce stability or increase likelihood of failure.

The project outlined in this thesis should consider the key factors that are affected by changes to our climate. It must identify what these factors are and outline a hierarchy of importance for the strategic road network. The critical deterioration factors that are assessed should be scored against the current inspection data collected in the industry environment. The resultant score can then be used as part of a wider risk matrix and can also be utilised to determine where current areas of weakness exist for the purpose of further investigation.

Ultimately, the assets are already designed and constructed and heading into a future unknown. Any tool designed by the researcher must be a useful operational tool to define where the critical impact factors are and support the engineer by determining the potential scale of the uncertain future climate change behaviour. As described above, the sources of unpredictable future behaviour of geotechnical assets is the reason that a risk-based approach is required, and that using a series of scenarios which can be applied independently is an appropriate means of describing future behaviour.

2.2 Geotechnical Asset Management

2.2.1 Introduction

Asset management is a relatively new concept for geotechnical professionals, requiring clear explanation of its relevance. Slopes, embankments and retaining walls usually do not carry traffic directly in the way that pavements and bridges do. However, these assets have a purpose and are costly to build. They require periodic maintenance and investment to maintain the functions for which they were originally built. (Thompson et al, 2016)

Many Geotechnical assets within the UK have reached or aged beyond their design life and thus need more challenging maintenance regimes and condition monitoring (Mian, 2011). As discussed in the next section 2.3, the process by which assets are managed and maintained is largely defined by the owning/operating organisation. Often, in the researcher's experience, organisational set-up may mean that the same team may administer, inspect and retain overall maintenance for several asset groups, including embankments and bridges; this may be especially true for smaller asset-operating organisations.

The focus of this work will be on the geotechnical assets found on major infrastructure networks, more specifically, those found on the UK Strategic Highway Network (Motorways and Major Trunk Routes), with reference to Network Rail infrastructure. Understanding what constitutes geotechnical asset is fundamental to developing knowledge of the nature, interdependence and criticality of the asset to the broader network.

2.2.2 Geotechnical Asset Management

Whilst asset groups vary between organisations, there are four key groups for most road and rail sectors: pavements/track, structures, drainage, and geotechnical assets. As such the researcher has chosen to focus the work within this project on geotechnical asset networks, however the co-dependency of these asset classes should be noted (to be discussed in section 2.3). The information held within datasets available for geotechnical assets is considered some of the most highly populated for both inventory and condition data within the Highways England Asset Databases (Power et al, 2012). The data provides a good degree of coverage for both asset inventory and condition, meaning that there is limited need for extrapolation. In addition, there has been ongoing work undertaken by asset owning agencies and within the academic community to understand the long-term deterioration profiles for infrastructure geotechnical assets i.e., BIONICS (Glendinning et al., 2006).

2.2.3 Asset Management for Geotechnical Assets

Principally, all Infrastructure assets are founded directly or indirectly on geotechnical assets (Bernhardt et al., 2003) - hence, limiting the adoption of an overall infrastructure asset management to just a few asset types can be quite risky. Clayton (2000) highlights that, from 'cradle to grave', the construction industry itself has a high-risk potential and that no construction project is risk free. From this it is easy to understand that ground-related risks render several ways of undermining the integrity of any construction project and beyond.

A geotechnical asset management approach will aid the designers in prioritising remediation of geotechnical assets, and will enable a whole life-cycle analysis which will determine the optimal choice of treating recurrent geotechnical defects over conventional one-off treatments, and will result in, the overall costs in choosing alternative treatment methods over conventional ones being the determining factor to maintain a working condition level, for the life of the asset. (Mian et al., 2010)

Bernhardt et al, (2003) argues that existing asset management systems are often used as hazard recording and management systems, which prioritise funding for those assets with the higher risk profile. This approach is somewhat justified (as safety is of utmost importance), and a risk-based approach is an effective method for comprehensive and holistic asset management. An asset management system which emphasizes giving the most cost-effective solution (whether the failure is disastrous or not) can support the organisation in promoting the movement of the maintenance cycle of the managed infrastructure from 'reactive' to 'proactive' – i.e., a move towards maintenance of a working asset, rather than later remediation of a failing one, as the provision of effective decision-making approach allows the engineers to choose the 'right' action more easily, often earlier.

The wider value of geotechnical assets is easy to underestimate, particularly where there is no direct acknowledgement of the role that these assets play. Thompson et al (2016) asserts that Geotechnical engineers should value geotechnical asset management in the same vain as pavements and bridges, for which asset management concepts and tools are becoming universally applied. As discussed in section 2.3, performance metrics of most asset-owning organisations reflects the primary asset (i.e., road and track availability) which is directly visible to users. Geotechnical assets are often literally 'part of the landscape', and the neglect of these features in turn leads to increases in the overall life cycle costs of the infrastructure assets (Bernhardt, 2003). For example, detailed records of pavement deterioration on road networks where the asset is showing the signs of failure long before the end of their expected design life can be argued to be obvious to the organisation, leading to a defined requirement for treatment within a short timeframe. In a further example, for Network Rail, the presence of 'wet beds' poses a significant impact to the organisation; The wet beds can be found in locations where the rail ballast has become saturated and exhibits condition deterioration. This presents an immediate capacity and safety issue as this can lead to track beginning to deflect beyond safe parameters. These issues could (and in the researcher's experience often do) result from a misunderstanding of the underlying cause of failure, which may well be of a geotechnical nature. Repeated re-surfacing treatments of the road pavement taking place at intervals less than every 3-5 years will be ineffective if the underlying subgrade is weak and is deteriorating. Likewise, remediating the carriageway which is showing cracks or other signs of failure will be ineffective if the supporting embankment has defects and is in a process of failure, effectively removing the support system for the carriageway. In order to successfully maintain and manage any asset within a road or rail infrastructure network, it is of paramount importance to inspect, maintain and manage geotechnical assets effectively and robustly (Robinson, 1998), and as part of this process, recording deterioration, defects, failures and associated repair costs effectively.

In 1996, Turner and Schuster reported that the cost of repair for minor 'nuisance' sliding failures would go beyond $100 Million, exceeding that of the repair cost for more major landslides. Since then, increased costs, aging networks, and changing climate patterns have all caused the routine maintenance cycles of geotechnical assets to be reduced. However, the need for regular, pre-emptive maintenance has never been greater, whilst the experience of the researcher asserts that the primary organisational focus remains on defective and failing assets.

In 1983, Tyrell et al (1983) found from a study of ten highway projects that where the total project cost overran (just over 35% of the projects reviewed). More than half of the additional costs were as the result of geotechnical issues or unforeseen problems (Clayton, 2000). This result demonstrates that the nature of geotechnical assets differs from other asset types, where much of the construction material and processes are man-made and hence generally uniform and easy to modify and control. The inherent natural variability of the ground conditions and groundwater make the assessment and rectification of any issues complex, as the result of the variable properties in different regions and different depths (Spink 2020, Clayton, 2000). As such, the predictability normally associated with man-made construction cannot be applied to engineering ground conditions.

Bernhardt et al (2003) highlights that although the common understanding of 'transportation assets' includes facilities such as pavements, bridges and railways, all of which are founded on geotechnical assets, their performance and costs are directly or indirectly dependant on the performance of geotechnical assets. Asset Management is increasingly popular terminology in the infrastructure industry, however of the many large asset groups involved, the management of geotechnical assets has not yet found its niche and has not been fully developed. In addition, Bernhardt (2003) also throws light on the several challenges faced in management of geotechnical assets, which range from identifying and classifying infrastructure assets into geotechnical assets, to determining the priority of maintaining them within the constrained budgets in today's economic climate. For example, the author highlights that in the case of geotechnical assets, different remediation measures may have different 'shelf life' and can vary dramatically in their costs. Sometimes, use of alternative techniques may prove to be an economically and technically sound choice.

In the UK, HD 41/15 (2015) and HD22/08 (2008) are the guidance documents for inspection and maintenance of highway geotechnical assets for UK road network. In addition, the 2011 edition of the Institute of Civil Engineers (ICE) Manual of Highway Design and Management (ICE, 2011) contains a chapter devoted to the use of Asset Maintenance in long-term highways maintenance planning, breaking it down into four key areas, Highway Condition, Safety, Availability and Environmental considerations. It considers asset valuation, the use of collected data, levels of service and life cycle planning. However, it largely focuses on the asset management of pavements within a local authority setting, with significantly less consideration given to structures, and just a few comments specifically directed at Geotechnical assets. The picture is similar across the much of the infrastructure specific guidance available. Advice on the asset management of larger infrastructure networks is largely provided by the network owner or operator and advice is limited to only one asset type or is very generic advice for decisions at policy/strategy level. The UK Roads Liaison Group (UKRLG) published Code of Practice for Well Maintained Roads (2005) and only briefly mention embankments and cuttings, whilst its companion, the Code of Practice for Management of Highway Structures (2005) contains some information regarding the long-term maintenance of only culverts, retaining walls and approach embankments. This has been extended to a limited extent with the updated Code of Practice, "Well-managed Infrastructure", which is a combined version of the previous two codes, (UKRLG, 2016). CIRIA published "Whole-life infrastructure asset management: good practice guide for civil infrastructure" (CIRIA, 2033), however again this guidance is somewhat generic and limited to local authority use with very little specific information on the long-term maintenance of geotechnical assets.

The most recent UKRLG Code of Practice, ‘Well-managed Highway Infrastructure’ (2016) includes just two sections focused on the management of embankments and cuttings, recommending the adoption of a risk-based approach to managing these assets, focussing on the delivery of three core objectives:

- Safety
- Serviceability
- Sustainability

The guidance also recommends a ‘robust regime of inspection’ focusing on highspeed links and proximity to dwellings, where the impact of failure will be highest.

As this research provides a focus on the impact of climate change on geotechnical assets with a focus on the requirement for the UK trunk road network, it remains critical to define what constitutes a geotechnical asset to determine the extent, interdependence and criticality of the asset to the network as a whole.

2.2.3.1 Geotechnical assets definition

The definition of what constitutes a geotechnical asset is not clear cut, and it can often be argued that there are areas of overlap with other major asset groups. Bernhardt et al (2003) defines a list of geotechnical assets and their function, with rankings from exclusively geotechnical through to minimally geotechnical, as shown below in Table 9:

Table 9 - Geotechnical Asset Definition, reproduced from Bernhardt et al (2003)

Asset Type	***Asset Function Purpose Category***	
Embankments and Slopes	Exclusively Geotechnical	To provide for gradual changes in vertical alignment
Tunnels and Earth Retaining Structures	Partially Geotechnical	To retain earthen materials so that highway can be constructed in restricted right-of-way
Culverts and Drainage Channels		To provide control of surface waters
Foundations		To transmit structural loads to supporting ground
Pavement Subgrade	Minimally Geotechnical	To serve as foundation for pavement

This thesis will focus on the categories assigned as 'Exclusively Geotechnical' in Bernhardt et al (2003), with the understanding that some of the functionally lesser geotechnical assets will be assigned to other categories within the owning operation; for example, foundations are usually assigned to the Structures remit within the context of the trunk road network.

2.2.3.2 Owners of geotechnical assets in the UK

The majority of geotechnical assets in the UK are owned by either public offices or publicly owned companies. Their assets form networks, and as such require an integrated approach with other asset types. Others may be privately owned and are thought to be much smaller in number. Current members of the Geotechnical Asset Owners forum, set up by CIRIA, are (in alphabetical order) CIRIA (2015):

- ADEPT*
- Canal & River Trust
- Environment Agency
- Highways England
- London Underground
- National Roads Authority
- Network Rail
- Northern Ireland Roads Service
- Scottish Canals
- Translink (Northern Ireland)
- Transport for London
- Transport Scotland
- Welsh Government

* The Association of Directors of Environment, Economy, Planning & Transport

2.2.3.3 *Benefits of adopting Geotechnical Asset Management*

The range of geotechnical assets found on any given infrastructure network varies significantly, however the researcher argues that the differing way these assets are managed and maintained between organisations is potentially more important and has a greater effect on the condition and longevity of the asset. The approach that asset owners use for structuring their organisation may mean that asset groups, such as embankments, may be administered by the same team that has the responsibility to inspect and retain overall maintenance for bridges. This is especially true for smaller organisations such as local authorities. This can have significant impact, not only on the condition of the asset, but also on the level of service that can be achieved by the organisation.

Clayton (2000), like Bernhardt et al (2003) asserts that given all Infrastructure assets are founded directly or indirectly on geotechnical assets, these assets cannot be ignored as part of the overall infrastructure asset management process. The author also highlights that the nature of the construction industry is high-risk and that all construction projects maintain and aim to minimise any risk profile, where unforeseen geotechnically-related risks can often pose a significant threat to the completion of a project.

Ensuring that a geotechnical asset management approach is undertaken throughout a project will provide aid the designers and engineers with the tools to prioritise condition issues found within the geotechnical asset suite, along with an opportunity to undertake a Whole Lifecycle analysis of the asset suite to determine the scope and the nature of the treatments required for the purpose of assessing the potential cost and effectiveness.

Bernhardt et al., (2003) provides a very salient point in that there is often a deference to ‘traditional’ transportation assets (pavements, rail tracks, bridges, etc), in terms of financing and maintenance; the geotechnical asset underpins each of these asset types and thus their performance is often directly dependant on the performance of the geotechnical asset. Shah (2016) asserts that asset management has become a popular terminology in current infrastructure industry but managing geotechnical assets has not yet found its niche and is not developed fully; this is also the experience of the researcher.

2.2.3.4 Challenges for Geotechnical Asset Management

There are several challenges posed as a result of implementing a geotechnical asset management system. Bernhardt et al., (2003) defines a number of these challenges through defining the extent of the geotechnical assets within the organisation and effectively prioritising these assets against other asset types (pavements, etc) using the constraints of available budgets within the current economic climate, which can be seen to fluctuate over time. The authors also assert that there are challenges in mapping geotechnical assets to current asset management systems, given that many of the commercially available solutions are focussed on hazard management and a more reactive approach to high risk issues, including safety-related issues; for example, replacing damaged signage, or resurfacing and remediating cracked pavement. This reactive model of intervention ‘after the fact’, Bernhardt argues, is unsuitable for accurately capturing and managing compound geotechnical failures or suggesting cost effective solutions providing long-term improvement in the performance of the asset.

As addressed in section 2,1, when considering the costs and benefits of maintenance (proactive intervention) versus remediation (reactive intervention), the case for considered and holistic geotechnical management becomes more apparent.

2.2.4 Geotechnical Asset Management on the UK Trunk Road Network by Highways England

The underpinning document for The Highways Agency's Geotechnical Asset Management plan and process can be found within the Design Manual for Roads and Bridges (DMRB) as HD41/15, Maintenance of Highways Geotechnical Assets (Highways England, 2015). Originally published in 2003 and updated in 2015, this standard outlines the necessary processes and competencies required by engineers and designers for the completion of the geotechnical asset management process. This includes inspection planning, method and guidance for inspects on condition risk assessments, providing a risk assessment framework and process for geotechnical work planning and review (Power et al., 2012).

Other geotechnical standards of note include HD22/08 'Managing Geotechnical Risk' (Highways Agency, 2008). This standard provides further details on the geotechnical risk assessment process and how engineers and designers should review both locational and condition information for the current 'as is' condition and the predicted condition in 5 years' time. Power et al., 2012 outlines the standard as encouraging the adoption of a proactive approach to maintenance and includes key components to an asset management system, including data management processes, whole life costing tools and condition modelling guidance.

A rigorous programme of examination of the inventory and condition of the assets is critical to developing an understanding of the asset's behaviours and performance. As such, the skills and competencies at an appropriate level to provide accountability and responsibility for the inspection and management of the assets must be sought when appointing personnel to positions within these mixed teams (Power et al. 2012).

Infrastructure asset management can operate at a range of different levels, within both national and local networks (Spink, 2020). It is a key area of development for most infrastructure authorities. Methodologies differ vastly however, from sophisticated integrated data warehouses with incorporated condition modelling and decision support tools; to basic spreadsheets containing local maintenance and renewal programmes. Regardless of the implementation method chosen, tools and methodologies should support the level at which the authority is working and the size of the network and facilitate an asset management process focused on organisational strategy and policy (ISO 55000, 2014).

However, guidance for the development of such strategy and policies is limited and patchy. Whilst the recognised asset management standards, ISO 55000 (2014) and PAS 55(2008), provide some guidance on the broad range of activities required for a successful asset management approach, infrastructure-specific advice is inadequate. Where infrastructure asset guidance has been produced, it is often very generic and requires considerable engineering, network, and in some cases local knowledge of assets. This is especially true in the case of geotechnical assets, where the complex interaction of factors described in section 2.3 is understood by Subject Matter Experts within the business, but not necessarily supported directly by policy or guidance.

2.2.5 Data Management for Geotechnical Assets

Data collection and maintenance is essential to support asset management and track progress and performance. Whilst managing inventory and condition data is an ongoing and costly process, the benefits of undertaking this work day-to-day as a routine task ensure that asset management can deliver a programme of works which is a true reflection of the current and future condition of the network (Mian, 2011). Repeating the data collection process gives weight to deterioration/condition models, which may be used on larger networks to predict condition and expenditure profiles for 25-30 years.

Highways England currently operates a legacy geotechnical database system called as the Highways Agency Geotechnical Data Management System (HAGDMS) which is an inventory of the various geotechnical assets on the highways agency network. It contains information on the condition of the geotechnical assets and the associated severity of the risks associated with the asset. Highways England also has a database for structural assets called the Structures Management Information Systems (SMIS) and an inventory for the drainage assets on the road network, called the Highways Agency Drainage Database Management System (HADDMS) and Highways Agency Pavement Management Systems (HAPMS), respectively.

Until more recently, there had been an absence of a standard, integrated, uniform data management system that contains information about all the assets on the entire road network at any given location. The importance of an integrated approach is also stressed by Bernhardt et al (2003), who highlights that although a geotechnical asset management system is necessary, there should be the facility of 'cross referencing different assets at the same location on the road network. Hence, in order to implement an Integrated Asset Management System which facilitates and aims to provide a plan for managing the infrastructure system as whole (rather than individual assets) a coherent integrated data inventory is required to provide robust solutions that are economically and technically well optimised over the full life cycle of the asset (Beckstrand and Mines, 2017). Highways England is now in the process of procuring and transferring its data for its four key asset types (pavements, structures, geotechnics and drainage) into more integrated decision support tools, with each asset using appropriate reporting tools and links to a separate optimising decision support tool. This will be supported by asset management-centric contracts for Contractors and Consultants, giving rewards and benefits to support the provision of correct, accurate data in volume.

2.2.5.1 HAGDMS Highways Agency Geotechnical Data Management

Asset registers and inspection records require regular audit to ensure currency, compliance, accuracy and completeness. Many current 'off the shelf' asset management products have the scope for a range of free text fields, where data can be added without restriction on the metrics provided. This makes the review of the data provision due to the time/cost/technical challenges imposed by aggregating data inputs of this type.

The HAGDMS was developed in 2002 (Power et al., 2012). It provides a central system where geotechnical asset data is saved and can be accessed by Highways England or their contractor/design partners. The system provides a location for updating and storing information about all geotechnical assets. The HAGDMS platform is a GIS-enabled database, which stores information in layers appropriate to the asset requirement. Information contain within HAGDMS includes:

- Asset Locational Information
- Geotechnical asset type
- Asset geometry (e.g. slope height and slope angle).
- Age
- Asset history, including maintenance
- Condition information in terms of the current risk level, and predicted risk level in the next five years.
- Information of Geology (i.e. Drift and Solid)
- Information about structures, bridges, highway furniture and link to the drainage database.
- Information on Coal Mining and other historical information (i.e. subsidence, made ground locations)
- Environmental Information (e.g. Flood plains, likelihood of flooding etc.).

- Records of Historic data for example borehole data, site investigation reports, historic inspection records, desk studies and construction as-built record.

2.2.6 Geotechnical Asset Inspection Cycle

2.2.6.1 Assessing the Condition of Geotechnical Asset

As with all other highway assets, Geotechnical asset condition should be reviewed on a regular cycle, as part of the visual inspection process. The Highways England HD 41/15 (Highways England, 2015) process for geotechnical inspections reviews the asset in totality and considers all aspects of condition, including:

- presence of slips,
- cracks
- subsidence,
- rock falls,
- voids,
- terracing,
- ravelling
- vegetation extent and type,
- evidence of animal burrowing,
- observations of ground water behaviours e.g., ponding

(HD 22/08 and HD 41/15 – Highways England, 2008 and 2015).

As the asset owner, Highways England regularly review the current condition of all its assets in context of the maintenance history in order to model and effectively predict deterioration of the asset in future.

The deterioration models require a risk assessment to be carried out to determine both the safety and economic aspects of treating the deterioration found within the asset. Glendinning, (2009) notes that this form of assessment uses the outputs of the inspection process to determine the need to treat deterioration now, versus treating it in the future.

Considerations are given to the safety risk posed to travellers, limitations on availability of the network including impact of regional traffic flows and routes, and traffic management requirements. The risk assessment is used as evidence to develop the business case for funding of maintenance or remediation work.

This process is entirely dependent on a regular inspection process being undertaken and recorded by qualified personnel. Details of the Highways England Process are outlined in the following section.

2.2.6.2 HD41/15 definition of a geotechnical asset

2.2.6.2.1 <u>Geotechnical asset types</u>

Highways England, within HD41/15, categorises their geotechnical assets into two asset types:

- Minor earthworks
- Major earthworks

Minor earthworks are defined as those whose maximum vertical height is less than 2.5m within the longitudinal extent of the asset. Minor earthworks may comprise slopes, embankments and at-grade sections.

Major earthworks are defined as assets having a maximum vertical height within the longitudinal extent of the asset greater than or equal to 2.5m. In specific instances where an earthwork begins at-grade and extends to a vertical height equal to or greater than 2.5m within its longitudinal extent, it is considered to be a major earthwork from its start point (at-grade) to its end point. Major earthworks may comprise slopes cuttings, embankments and bunds. This meets the requirement set out in the geotechnical asset definition found in section 2.2.3.1, however, the limits of this will need to be tested through the approach to case study selection.

2.2.6.2.2 Geometry of the Geotechnical Asset: Point item vs. linear items

Broadly, the fundamental geometry of an asset on the transport network can be considered to either comprise a 'point' – a discrete item found along at a single location upon the road network, (for example, signage or traffic signals) or a linear section, such as pavement. The influence of point item on the network is generally limited to a single section of the network; in contrast, geotechnical assets can be considered as linear assets (Loveridge, 2010) due to their generally longitudinal nature and potential to impact several sections of network. Geotechnical assets often share characteristics with both pavement and structural assets; like pavements, geotechnical assets are generally linear. Unlike pavements, Geotechnical assets often have maintenance needs more in keeping with structural assets (for example gantries). Given the wide variability of the geotechnical asset, and the process by which it exhibits its properties, consideration must be given to the location referencing model in order to ensure that the data incorporated in any tool is appropriately georeferenced in line with both pavement and structures assets, as this will form the basis of the asset management system and will have significant impact on the outcomes from any decision support modelling taking place.

To this end, Highways England model their geotechnical asset by linear lengths of network carriageway that usually follow the centreline of the road, and as such the reality may differ from the mapped asset. In addition, it must be understood that due to the line nature of the asset, and the approach taken to sectioning at node points, Highways England may not own the asset in its entirety, due to the extension of the asset beyond the network limits and into those managed by another authority. (HD 41/15)

2.2.6.2.3 *Geometry of the Geotechnical Asset: Point Longitudinal definition of a geotechnical asset*

HD 41/15 (Highways England, 2015) defines the longitudinal extents (i.e. the start and end locations along the length) of a geotechnical asset as any of the following:

- points of zero height between geotechnical assets of different types

- bridges and underpasses
- Area/Regional (HE defined) area boundaries
- substantial changes in geology (as shown on the 1:50,000 BGS map, or observed)
- Significant variation in earthwork construction materials (either from as-built records or observed).

2.2.6.2.4 Geometry of the Geotechnical Asset: Lateral definition of a geotechnical asset

HD 41/15 (Highways England, 2015) also defines the lateral extents of a geotechnical asset as any of the following:

- the centre line of the carriageway immediately adjacent to the asset
- the ownership boundary of the Asset Owner, typically marked by a fence line

As the result of this, it should be noted that typically, each section of the motorway and trunk road network will have two geotechnical assets associated with it, one to each side of the carriageway centre line. Additionally, in some cases, geotechnical assets may also be found in other areas, e.g. split carriageways and slip roads.

2.2.7 Schedule of Inspections

HD 41/15 Outlines an inspection regime for the inspection of a geotechnical asset to meet the following objectives:

- Location and type of geotechnical assets
- Key characteristics for each geotechnical asset; e.g. construction material, age, bedrock geology, geometry etc.
- Condition of the geotechnical asset at the time of inspection.
- To evaluate the wider setting of the asset in order to assess any impacts on geotechnical asset performance

The inspection schedule for the assets may be subject to change during the length of the maintenance contract for several reasons:

- Acquisition of assets by the Asset Owner, e.g. adoption of a local authority road.
- Newly Constructed assets associated with new or modified (i.e. through widening) road sections.
- Loss of assets by the asset owner due to changes in administrative arrangements (such as de-trunking).
- Physical removal of the asset, such as in a junction re-modelling or similar.

2.2.7.1 Inspection frequency

The frequency of inspections is determined by the maintenance contractor or asset manager using an assessment of risk presented by the geotechnical asset to the wider road network, or other criteria as agreed with the asset owner.

The diagram below (Figure 9) sets out a framework for the inspection frequency of geotechnical assets, based upon the observed condition and network criticality.

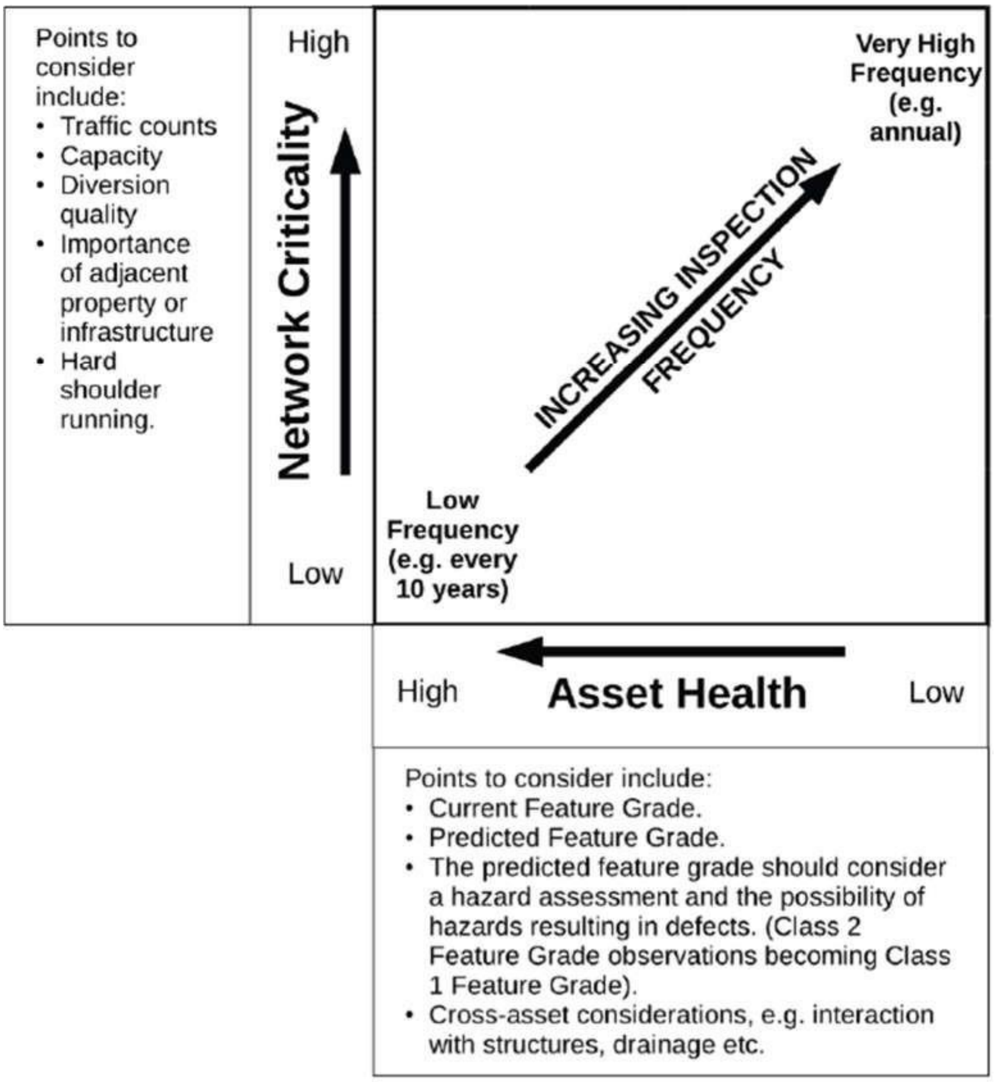


Figure 9 - Framework for Inspection Frequency of Geotechnical Assets. Reproduced from (HD41/15)

The inspections and risk assessments are carried out by the maintenance contractor on behalf of the asset owner, in this case Highways England. The results of the inspection and subsequent risk assessment, along with a proposed inspection schedule are then agreed with the asset owner and forms part of the maintenance contractor's contract. In most instances, principal inspections are undertaken every 6 years with general inspections undertaken every 3 years with the scheduled frequency of inspection recorded against each asset in the asset management information system by the maintenance contractor.

2.2.7.2 Geotechnical Asset Inspection types

Geotechnical assets are subjected to a hierarchy of different inspections that include:

- Detailed or Principal Inspections – these are the main type of inspection, providing inventory and condition data.
- Monitoring Inspections – these are inspections undertaken as a preintervention option to assess risks and requirements.
- Emergency inspections –inspections undertaken in response to a Geotechnical Event (see below).
- Inspections by non-geotechnical staff e.g. watchman inspections to recognise obvious geotechnical characteristics that are indicators of change.

2.2.7.3 Observations made during inspections

The inspection process reviews all characteristics of the asset and lists them as observations. These observations may be geotechnical events, features of the asset, defects requiring remedial works or hazards requiring ongoing monitoring. Relative changes in condition from previous inspections of the asset should be noted. The inspection should also consider the impact of the asset, not only on the asset network in which it sits, but also to encompass a wider understanding of the interactions it may have with assets owned by another party.

During inspections of geotechnical assets, characteristics of the asset are recorded over part or all of the asset length. These characteristics must be recorded in a documented, formalised and repeatable manner. The observations are required to focus on the changes in the condition of the asset relative to the previous inspection, and where appropriate the observations must record any arising geotechnical hazards that could impact the road network, including those that are visible outside of the occupancy boundary. For example, adjacent development, landfill operations, quarrying etc. Consideration should also be given to hazards imposed on the geotechnical asset by other assets (e.g. blocked drainage). The record of the observations should include quantitative data, photographs, maps and sketches, in order to validate the findings and aid audit functionality.

Where the asset is found to be defective, a defect must be recorded, as a general monitoring inspection, HD41/15 requires that each defect must have, recorded against it:

- at least one photograph
- an annotated sketch
- quantitative measurements

All defect records must be digitised and input into HAGDMS accordingly.

2.2.7.3.1 Geotechnical Events

A Geotechnical Event is a defect that poses a threat to the safety of users, workers or other parties or critical network assets. The presentation of a geotechnical asset requires emergency action from the asset owner and maintenance contractor to ensure the safety of both the network and those who use it. An example of a geotechnical event could be:

- A landslip causing a blockage of the carriageway by material. This is often the result of slope failure or debris flow.
- Active subsidence (or predicted subsidence) of the carriageway due to collapse, such as a mine shaft, or removal of material from the asset.
- Active subsidence (or predicted subsidence) of the carriageway due to scour of an embankment. This could be as the result of vegetation removal, excess run-off or wind-related activity.

As the result of a geotechnical event being declared, there is a requirement by HD41/15 for action to make safe, which may include one or more of the following:

- temporary signing
- traffic management
- temporary barriers
- debris clearance
- temporary asset support

- asset inspections

Following the initial report of a geotechnical event, the maintenance contractor with schedule an Emergency Inspection to be carried out. The inspection will investigate the details of the event, including date and time of occurrence, type pf event, scope of damage and resultant condition, along with a preliminary report of the required maintenance needs. This information is then presented to the asset owner, as per the process is shown in Figure 10.

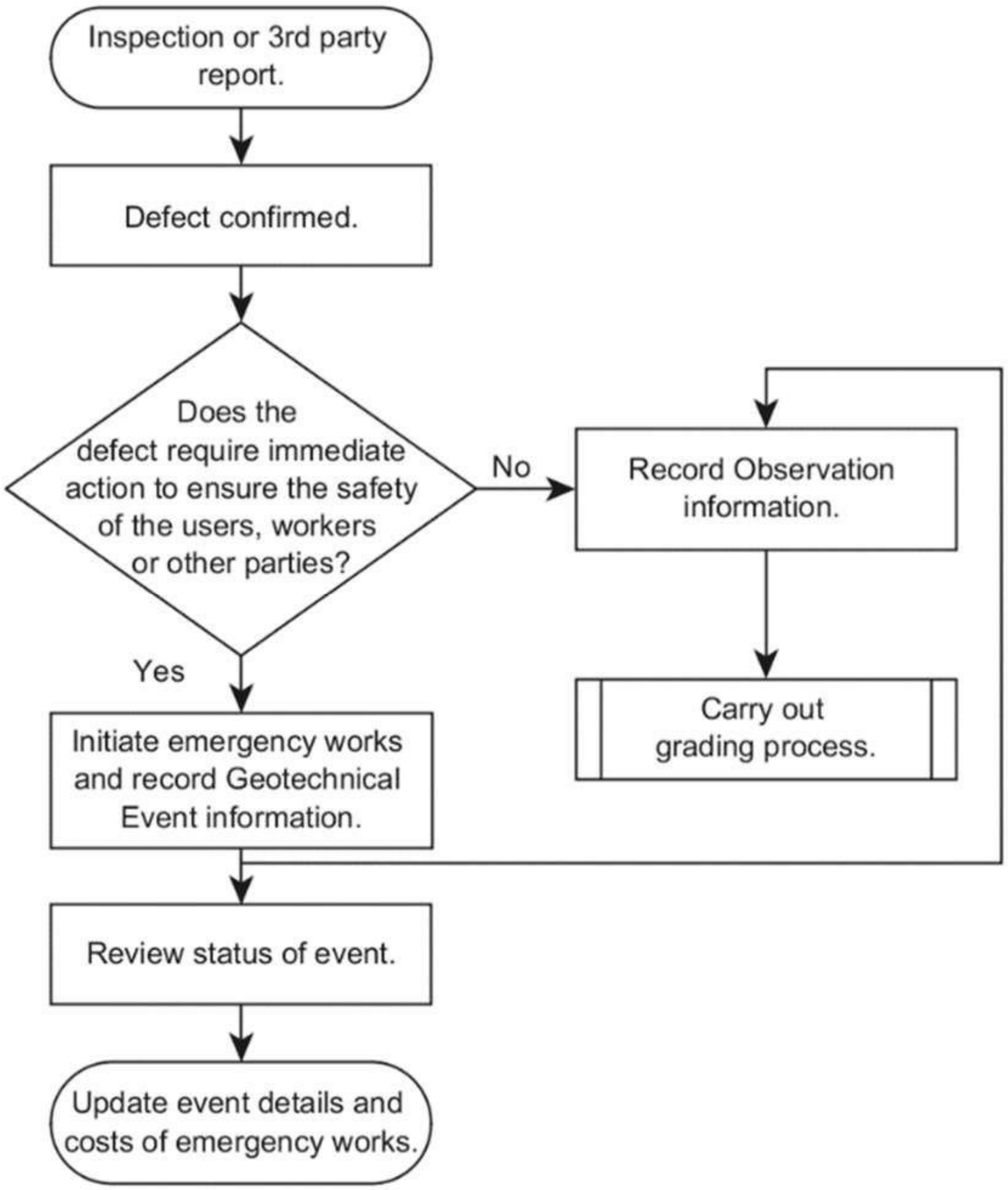


Figure 10 - Geotechnical Event Process (reproduced from HD 41/15)

2.2.7.4 Assessing Geotechnical Assets

2.2.7.4.1 <u>Assessment and grading of features</u>

The defects or features of a geotechnical asset are geo-referenced observations made and recorded during an inspection that have been assessed as requiring grading. The grading of geotechnical features provides an indicator of the relative condition of the asset at that location and is used as the basis for input into Risk-based assessments, considering current condition and intervention requirement.

The process of grading a geotechnical feature requires two inputs:

- Feature Class and
- Feature Location Index.

The process for Feature Grade Assessment is shown in below in Figure 11:

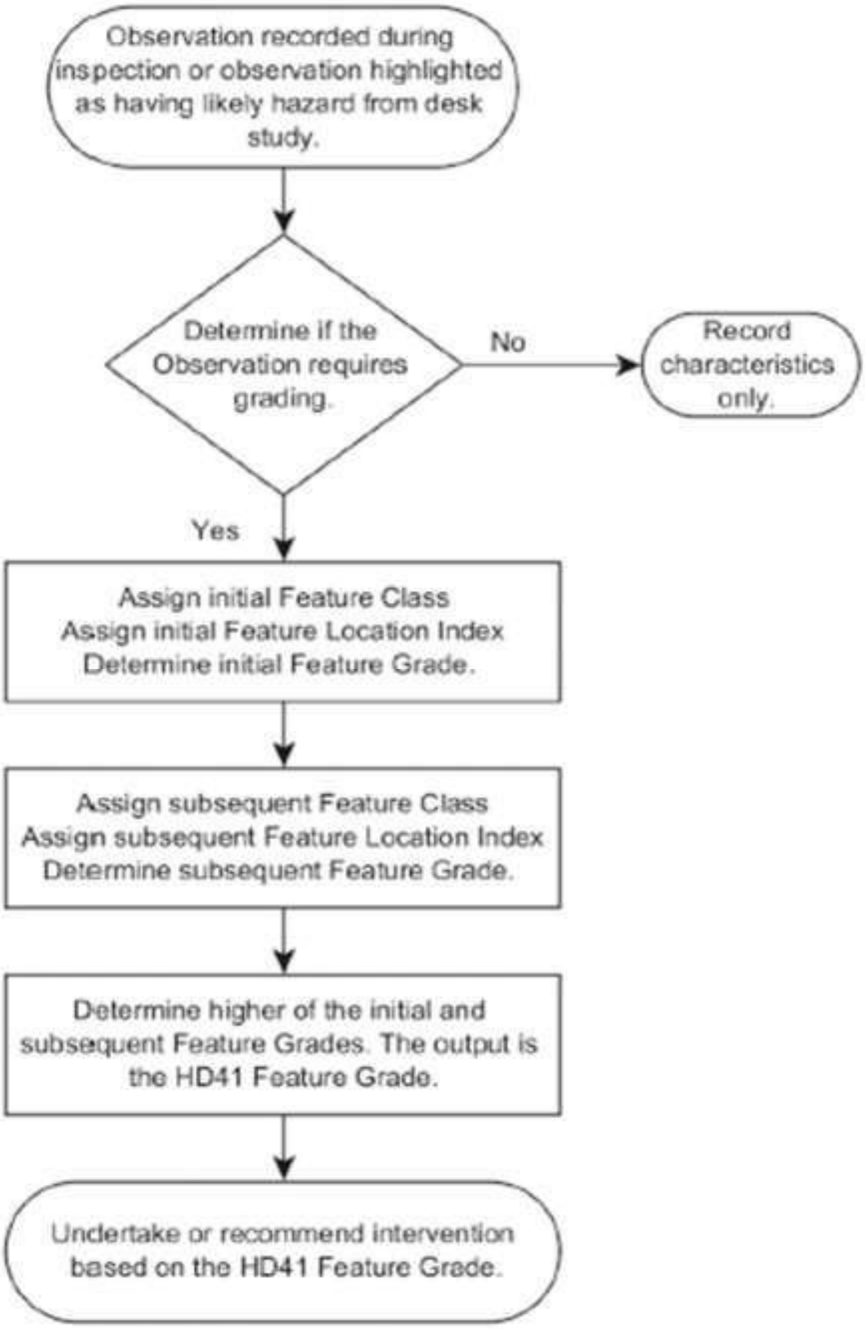


Figure 11 - Feature Grade Assessment, taken from HD 41/15

2.2.7.4.2 Assessment of Feature Class

Each geotechnical feature identified during an inspection of an asset should be assigned a Feature Class, based on the definitions given in the Table 10 below. HD 41/15 presents the examples provided as general guidance, intended to provide a repeatable assessment process. However, it is understood that there may be exceptions, wherein engineering judgement should be applied when determining the asset condition and, therefore the applied Feature Classes. The reasoning for allocating non-standard Feature Class should be recorded within the inspection details, in order to understand the justification and course of action chosen at a later date. However, the assessment of Feature Class must not consider the impact of the feature on the network or 3rd party property. It shall be confined to the size and type of feature only. The classification system presented below should be applied to all features identified across geotechnical asset types.

Table 10 - Classification of Geotechnical Asset Defects, reproduced from HD41/15

Class	Description of feature	Examples of features
Class 1: (visible defects)		
1A	Major defects	A slip greater than ½ height of a major earthwork. A rock fall involving boulder-size* blocks of rock or greater than 1m^3 volume of rock debris.
1D	Minor defects	Defects other than Major defects
Class 2: (likely defects)		
2	At Risk areas. Assessment may be based on available information (maps, historical reports, behaviour of similar assets, etc.) and/or visible inspection.	An asset overlying an area of mining activity where no mitigation measures were carried out during construction or where mitigation measures have deteriorated. An area of sidelong natural or made ground subject to historical slope movement. Animal burrows.
Class 3: Areas of repair		
3	At Risk Repaired areas. Sections of geotechnical assets where defects have been repaired or where preventative works have been undertaken to prevent deterioration of areas considered to be at risk. This class does not apply to areas that have been reinforced as part of a widening or improvement project.	Granular slope replacement of a failed cutting. Areas of remedial slope drains. Areas of remedial mine filling. Areas of remedial rock-bolting. Areas of bioengineering.
Notes: Class 1B and 1C as used in HD41/03 have been consolidated into Class 1A. Class 2A and 2B as used in HD41/03 have been consolidated into Class 2. Class 3A, 3B, and 3C as used in HD41/03 have been consolidated into Classes 2 and 3. *Large boulder is particle of diameter greater than 600mm. approx.		

2.2.7.4.3 *Assessment of Feature Location Index*

The maintenance contractor must assign a Feature Location Index for each feature, based on the definitions given in the Table 11 below:

Table 11 - Location Index Guide, reproduced from HD41/15

Location Index	Assets Affected
A	Assets that ensure the safety of users, workers or other parties, or safeguard the environment. Overseeing Organisation assets: e.g., the running lanes or hard shoulder used as a running lane. Emergency refuge areas, Vehicle restraint systems and motorway communications and structures etc. 3rd party assets: e.g., adjacent safety critical infrastructure or buildings, reservoirs or pylons etc.
B	Assets which are less critical to the safety of users, workers or other parties, or safeguard the environment but are required to ensure the reliable performance of the network. Overseeing organisation assets: e.g., hard shoulder or roadside, structures and communications etc. 3rd party assets: e.g., adjacent non-safety critical infrastructure or buildings etc.
C	Land occupied by the Overseeing Organisation and adjacent to the carriageway but not A or B.
D	Land occupied by the Overseeing Organisation and remote from the carriageway but not A or B. 3rd party assets: e.g., adjacent soft estate.

2.2.7.4.4 *Assessment of Feature Grade*

The maintenance contractor will use the results of the Feature Class and Feature Location Index assessments to determine HD41 Feature Grade as show in Table 12. The initial Feature Grade Assessment is then made using the following table:

Table 12 - Feature Grade Classification, taken from HD 41/15

Initial Feature Grade Assessment	
	Class

Location Index	1A	1D	2	3
A	5	4	3	1
B	5	3	3	1
C	4	3	2	1
D	3	2	1	1

The grading process is then completed by the maintenance contractor who will make a prediction of the potential deterioration that the asset condition is likely to be subjected to in the next 5 years using the final Table 13 below.

Table 13 - Subsequent Feature Grade Assessment, taken from HD 41/15

Subsequent Feature Grade Assessment				
Location Index	Assessed Class			
	1A	1D	2	3
A	4	3	1	1
B	4	2	1	1
C	3	2	1	1
D	2	1	1	1

The maintenance contractor will then record the highest value of the initial and subsequent assessments as the HD41 Feature Grade. This final risk assessment outcome will then be used to determine the geotechnical intervention requirements.

This process assesses the current and future (5 year) asset condition/deterioration. It gives an indicator to the likely requirement of the asset within that timeframe, in a quick and easy-to-use method.

2.2.8 Geotechnical Asset Management Plan (GeoAMP)

The Geotechnical Asset Management Plan (GeoAMP) found in HD 41/15 (Highways England, 2015) is a long-term management plan required by Highway's England as part of the DMRB Specification (HD41/15). It sets out how the geotechnical asset is to be managed for a specific area or route, in terms of condition, needs, risk and maintenance approach. The GeoAMP is prepared by the contractor and gives information on the anticipated programme of inspections and planned interventions. The GeoAMP aims to set out planned activities on the asset across a rolling five-year period and is reviewed and submitted to Highways England by the contractor on an annual basis.

The structure of the GeoAMP should include:

- A regional overview of the geotechnical asset, the number of assets, their length, and dates of last inspection.
- An overview of the historic, current and predicted condition of the geotechnical asset.
- An inventory of the potential geotechnical hazards that may affect the network.
- A record of the inspections, surveys (such as ground investigations) and monitoring carried out within the previous year.
- A summary of any Geotechnical Events that may have occurred within the previous year and their impact on the network.
- A schedule of inspections and monitoring to be carried out in the next year.
- Data from any detailed surveys/testing carried out (i.e. ground investigations/boreholes).
- A programme of the completed and proposed geotechnical works projects.

The GeoAMP is also used as a tool to record risk assessments for inspection and maintenance activities. Risk assessment should include the following:

- hazards,
- geotechnical asset information
- network criticality
- proximity to other asset groups
- mitigation methods/solutions

2.2.8.1 *Geotechnical Hazard Appraisal*

The GeoAMP is used to identify, in detail, the likelihood and impact of risk affecting the asset. The hazard risk assessment should include all types of risk and triggers (where known), including:

- Natural hazards, relating to the natural environment in which the road is located. These hazards may be due to the behaviour of geological materials (for example voids due to dissolution of limestone, or soft/compressible ground due to the presence of alluvium) or the behaviour of natural slopes within the landscape (for example largescale post-glacial slope instability).
- Man-made hazards, which are not related to the imposition of the road network on the landscape. Examples include hazards relating to mining and quarrying, or construction of landfill.
- Man-made hazards, which are related to the imposition of the road network on the landscape, for example over-steep slopes in earthworks. A more detailed catalogue of the hazards presented to geotechnical assets can be found in Annex A of HD41/15 (Table 14, below):

Table 14 Geotechnical Hazard Categories, taken from Annex A, HD 41/15

Key Category	**Sub-category**	**Geotechnical Event resulting from combination of hazard and trigger**
Natural Hazards	Dissolution features (Inc. cavities/voids) Note: the presence and hazard posed by natural cavities may not always be related to surface water or groundwater.	Subsidence Collapse
	Soft or compressible ground	Subsidence
	Natural landslides (soil)	Material on road
	Natural landslides (Rock)	Material on road
	Shrink/swell	Subsidence/heave
	Groundwater rise	Slope instability (as landslides) Surface flooding

Key Category	**Sub-category**	**Geotechnical Event resulting from combination of hazard and trigger**
	Soil or groundwater chemistry	Chemical damage (e.g., thaumasite), health and safety impacts (e.g., methane or radon)
Man-made hazards (non-road)	Abandoned mine workings and mine entries (coal and non-coal) Note: Includes deneholes	Subsidence Collapse Surface instability
	Backfilled opencast mines	Subsidence
	Current or future mining	Subsidence
	Quarries	Rock face instability (old quarries) Blast and vibration (active quarries) Stability
	Landfill sites	Subsidence Pollution (leachate & methane)
Man-made hazards (road)	Engineered slopes of marginal quality	Material on road or cracks/damage to assets
	Defective or inappropriate drainage	Slope instability Surface flooding Erosion Dissolution of soluble rocks
	Animal burrows Note: These are classified as 'man-made' as they tend to affect man-made earthworks.	Slope instability
	Loss of vegetation	Slope instability Erosion
Note: The hazards categorised in Columns 1 and 2 may require suitable triggers to cause the events listed in Column 3. Triggers may include natural occurrences such as heavy rainfall, high winds, or earthquakes.		

2.2.8.2 Example of a Risk-based Assessment for the Strategic Road Network

As described in the sections above, the risk assessment element of the visual inspection comprises of a grading made up of two elements, the feature class and the location class.

- Where the feature class is categorised as Class 1, Class 2 and Class 3, the asset is considered to be at risk, as these represent significant defects. Further investigation into the maintenance action is required
- The location class defines the proximity of the asset defect to the carriageway or other assets, for example Bridges, VRS or Lighting Columns. The location grade is categorised from A to D, where A is in the closest proximity to other assets.

The risk category determined by the assessment of the feature class and the location grade is assigned in both the current condition and the anticipated condition in 5 years' time.

Power et al., (2012) provides an example of how an asset exhibiting a tension crack which is assessed as a small or minor defect (1D), that is located largely away from other assets, including the carriageway (Location Index C) may be assessed to have an Initial Feature Grade or grade 3 or 'Moderate' risk currently, now but in five years' time, the risk may have increased to 4 to 'Severe' as a result of the defect transitioning to a slip failure, increasing the proximity of the defect to the carriage assets.

This process requires significant experience on the behalf of the inspector to effectively assess the risks and defects presented during the inspection. Through the completion of this process, the client should be provided with adequate confidence that the decisions have been made by persons with technically sound knowledge, in turn providing weight to the impact of any works programme presented as a result.

2.3 The Deterioration of Geotechnical Assets in the UK

2.3.1 Introduction

This research focuses on the geotechnical assets such as Embankments and Slopes (See Section 2.2). As such, this research considers the factors which are likely to have the highest impact on these asset types over a long term. This chapter explores the relationship between modes of failure, critical impact factors which can result in the instability of the asset, and finally drilling down into the relationship between the impact factors and the resulting input triggers and output effects on the asset (Figure 12) triggering events

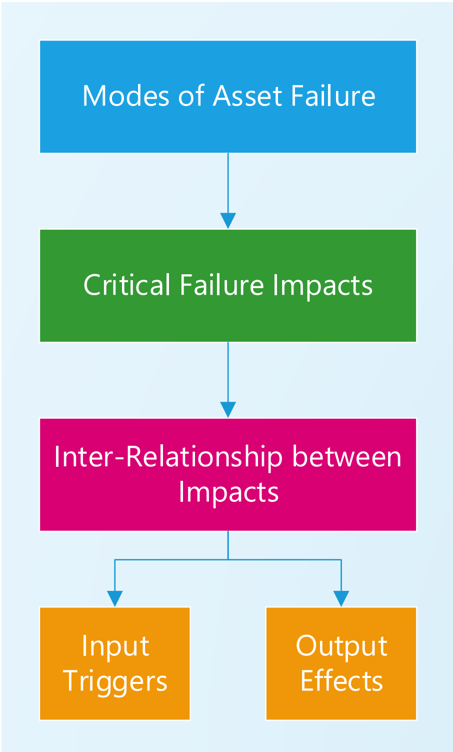


Figure 12 - The inter-relationships between modes of failure and their triggering events

2.3.2 Deterioration of assets (loss of performance)

Over time, geotechnical asset condition deteriorates due to both wear-and-tear and climate factors such as weathering and erosion (Glendinning et al, 2018, Spink 2020). The rate of the deterioration is affected by a range of critical factors that can accelerate of slow deterioration, along with the magnitude of the impact, and the current state of the asset-for example, an asset which is currently in good condition is usually better placed to withstand negative critical factors impacting on it when compared to a similar asset in poor condition. Poor condition often leads to expansion of defects and accelerated deterioration as failures compound, which can in turn, lead to failures.

Small scale defects and failures can be associated with high costs for both investigation and remediation. Geotechnical issues often have prohibitive cost and time implications (Clayton, 2000) such that even at small scale the need for 'make safe' activities, along with traffic management causes costs to mount up – particularly when loss or reduction of service, and public image damage, is factored in to the total cost of remediation. It is important to understand how assets fail in order to understand the hierarchy of critical impacting factors, and how these factors contribute to the organization risk profile, see section 2.1.13.

2.3.3 Failure Mechanisms of Geotechnical Assets

There are a range of failure mechanisms associated with geotechnical assets, which are dependent on a range of input trigger factors and corresponding consequences and effects.

2.3.3.1 Categories of Asset Failure

Failure of geotechnical assets broadly falls into two distinct categories:

- **Ultimate Limit State failure (ULS)** is the state of instability, collapse, or defect where the failure poses a significant risk to user safety and the functionality and availability of the infrastructure. ULS failure may be termed 'Catastrophic', resulting in near total asset loss, significant network closure, and major financial impact [Clayton, 2003]. ULS failure can also impact associated network assets, such as pavements, bridges, and retaining structures.
- **Serviceability Limit State failure (SLS)** is the state of instability, collapse, or defect where the failure limits the use and functionality of the asset to the extent

where immediate intervention or maintenance is required- for example a rockfall or landslide that does not affect the long-term availability or safety of users. Timescales for intervention to prevent further deterioration or asset damage are generally dependent on the degree of failure.

2.3.3.2 Failure Features

A consequence of most geotechnical failure – for both catastrophic, and more minor serviceability failures - is a change to the geometry or cross-sectional profile of the asset. For slopes, most failures occur because of direct erosion and weathering, settlement of slope material due to changes in loading, or as the result of groundwater fluctuation. Dixon et al, 2010). Less commonly, failures may be due to exceptional events such earthquakes, poorly planned excavation, or direct vandalism. In most instances, the eventual failure of a geotechnical asset is the result of slow deterioration from good to poor, with the rate at which this deterioration occurs dependent on the combination of factors impacting upon it.

Akhyami (2014) presented research which considered the factors impacting on asset condition deterioration. A summary of factors for the failure of embankments is seen below Figure 13:

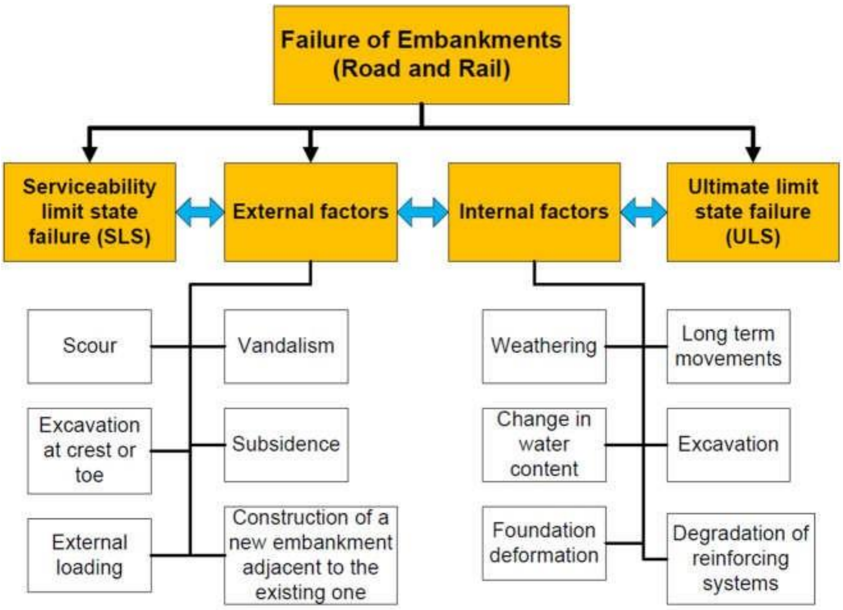


Figure 13 - Critical Factor Deterioration Mechanisms for road and railway embankment. Taken from Akhyani, 2014.

This is further developed in Table 15 which details the typical failure mechanisms that can be found as geotechnical assets fail. (Shah, 2016 and Glendinning et al., 2009).

Table 15 -: Typical Geotechnical Assets Failure features

Geotechnical Asset	Failure Mechanism
Slopes and Embankments	Slips • Shallow • Deep • Rotational • Translational • Wedge Failure • Rockfall Tension Cracks Backscars Ravelling Toe Erosion Bulging Settlement

Retaining Structures	Bearing Failure Sliding Seepage Failure • Scoring • Piping Settlement Structural Failure • Chemical Attack • Buckling
Foundations (Deep and Shallow)	Bearing Failure Sliding Overturning Settlement • Total • Differential Shear Failure Punching Failure Structural Failure • Chemical Attack • Buckling

2.3.3.2.1 *Slip/Slope Failure*

Slope failure is a category of geotechnical asset failure. Slope failures can be shallow or deep in nature, with shallow failures typically less than 2-3 metres deep and rarely passing through both the crest and the toe of the asset. Slope failures are usually translational in nature, where a section of material slides downslope away from the crest of the asset and with a failure plane near-parallel to the sloping face. Deep failures are greater than 2-3 metres in depth, and often pass through the crest or the toe (or both) of the asset profile. Deep failure planes generally form a circular or curved profile with respect to the slope face. (Perry et al 2003).

Leroueil (2001) uses 4 time-bound categories to describe slope failures:

- pre-failure,
- onset of failure
- post failure
- reactivation of failure

However, Leroueil advises that although base geology plays an important role in slope stability, a more holistic approach to slope analysis is required. Detailed understanding of how soil structure interactions take place, along with measuring the mechanical responses to loading and subsequent changes in slope geometry, boundary conditions, strength parameters and pore water pressure with time also provides an important knowledge base, and more complete picture of the potential impacts causing failure.

2.3.3.2.2 Other failure Mechanisms of geotechnical assets

2.3.3.2.2.1 Soil Creep Movement

High plasticity soils (e.g., Bentonite) are prone to slow creep movement, often associated with high levels of natural soil movement such as water induced shrink/swell (Hughes et al, 2009). These soil types are typically clay, organic, or soils in which a combination of these materials forms a large component. The movement of these soils may be triggered by seasonal fluctuation in groundwater level, soil moisture content and temperature; movement may be exacerbated by external weathering factors and increased soil exposure.

2.3.3.2.2.2 Deformation of the Asset Foundations

Change in soil properties can cause deformation and stress on the foundations of an asset– for example, swelling due to groundwater change may cause lateral compression of the foundation, or shrinkage may lead to voids and insufficient support. The consequence of these changes (where potential for ground change has not been accommodated in the foundation design) is often subsidence. Other types of failure mechanism include:

- Bearing Failure
- Punching Failure
- Sliding
- Structural Failure
- Overturning
- Chemical Attack
- Settlement - Total
- Buckling
- Settlement - Differential
- Seepage Failure - Scoring
- Shear Failure
- Seepage Failure - Piping
- Tension Cracks
- Backscars
- Ravelling
- Toe Erosion

2.4 Drivers for Change to Long-term maintenance

2.4.1 The need for long-term asset management

Identifying the drivers and challenges to long-term asset management is critical to the determination of 'need' for long-term strategy and solutions. Forward planning and development of 'treatment plans' to identify how the most common issues should be dealt with, ensures that the focus remains with the long-term behaviour of the asset.

The following PESTLE (Political, Economic, Social, Technological, Legal and Environmental) analysis, taken from Akhyami (2014) and refined by the researcher (Figure 14) outlines the key drivers for change to long-term asset Management. The PESTLE analysis focuses on outlining the relevant business needs within an organisation's operating environment in a helpful way when planning for change.

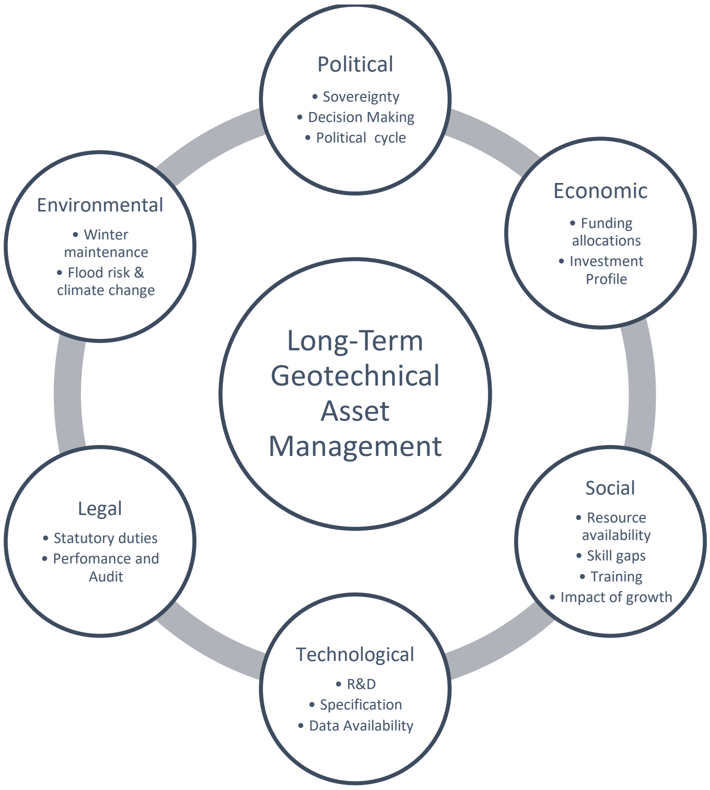


Figure 14 - PESTLE analysis of the Drivers and Challenges for Long-Term Geotechnical Asset Management

2.4.1.1 Political Drivers and Challenges

2.4.1.1.1 <u>Sovereignty</u>

Asset Owners want to retain sovereignty over decisions on schemes or investment within their network (Issues requiring remediation on highway networks are often very emotive and roads are used by most residents on a daily basis). The importance of strong leadership, clear objectives and effective communication within collaborative arrangements is well understood.

2.4.1.1.2 <u>Decision-making</u>

Investment decisions made on a network basis will inevitably lead to inequality across the network regions. Interventions will be focused in areas where the maximum economic benefit will be felt (For example prioritising high volume routes over more 'local' trunk roads). This is further compounded due to the variability of asset condition across the network, often as a result of significant investment in previous years' works being focused on economically important corridors.

Decision-making must be undertaken at a local, as well as at a national programming level. However, the challenge in this instance, is to align local and national priorities for the benefit of the network as a whole.

Proposals for works on the SRN will inevitably have an impact on the surrounding networks, including local authority routes. Such impacts may well be negative, and most will need mitigation of some description. Impact on adjacent roads may be far reaching.

2.4.1.1.3 Political Cycles - Funding

The cycle of political elections will provide a tension even with multi-year funding agreements. Currently, UK infrastructure networks work to a four-year spending review period, largely in line with the general election cycle. However, to get the most benefit from asset management, organisations need to think longer-term, i.e. longer than four-year cycles. Most asset owners are becoming increasingly accountable to the higher levels of government, and ultimately to the taxpayer to provide evidence-based bids for funding to ensure that the network will be maintained at a suitably safe level, with improvements to be made to reduce congestion, increase availability and limit the environmental impact.

Political Cycles - Objectives

Over the course of the last ten years, there has been an increased accountability of government bodies to UK taxpayers, as public perceptions of “value for money” and “service delivery” have become ongoing political themes. In the HM Treasury Autumn Statement (2011) there is a clear focus for the government and its service providers to improve infrastructure network performance, whilst ensuring value for money. It highlights making smarter use of existing infrastructure by improving capacity and connectivity. The 2013 Autumn Statement, and National Infrastructure Plan (2013) propose a programme of targeted investments to alleviate congestion at ‘pinch’ points, supported by a strong programme of asset management across the rest of the network.

The concern for long-term asset management is that whilst extending whole-life cost, ‘sweating the asset’ and looking at long-term investment are hot topics within current governments, this may not always be the case. Historic lack of funding and prioritisation has been directly responsible for the significant deterioration of infrastructure assets. A cross-party agreement could help to deliver a more concerted effort and give confidence in funding streams and thus ensure condition remains static. However, in order to improve our road infrastructure, more is needed.

2.4.1.1.4 Economic Drivers and Challenges

2.4.1.1.4.1 Funding Allocations and Investment Profiles

In 2010-11 the Highways England's budget allocation was £7,869M (HE Business Plan, 2010), of which 29% (£2,282M) was spent on maintenance (defined as 'upkeep of assets and winter maintenance'). Of this maintenance budget, £1,608M was invested in over 900 maintenance schemes and 50 major projects, leaving £674M to be spent on emergency, cyclic and winter maintenance. Since such a large proportion of the agency's government funding is spent on maintenance, it is only right that HM treasury demand an amount of evidence for works to be carried out with certainty that the 'right' interventions are being taken at the 'right' time. Work to understand how the maintenance pot is to be split between regions and areas is still being undertaken.

The primary consideration with funding allocation is how to best allocate monies to get best value for the network as a whole. Investment profiles can be a minefield, for example, where investment is split equally, some regions may struggle to meet deteriorating condition profiles, given the size and complexity of their area. Likewise, promoting 'good behaviour', where data sets are complete and accurate, condition is maintained, if not improved and targets for work's related user delays are met; would result in areas whose performance does not meet standards falling even further behind, offering poor lifecycle potential to the assets and poor customer satisfaction.

2.4.1.1.5 Social Drivers and Challenges

2.4.1.1.5.1 Skills Gaps and Retention of Staff

The availability of the necessary technical skills to manage, design and implement assets and schemes as well as administer any long-term commitments is a key challenge. This is an issue for each asset owner within the UK and low availability of key contacts or loss of key individuals going forward will impact on long-term asset condition and network resilience. (Unison, 2010)

This skills gap is reflected across the board and affects all levels from senior technical staff, through to on-the-ground operatives. Comprehensive education of personnel is key. Asset management, like safety, is something for which everyone is responsible in some way or another. Developing a whole organisational understanding to drive long-term asset management is a critical function of the asset management team. It must be clear and understood by every member of the team, from inception through to maintenance and beyond. (IAM, 2014)

2.4.1.1.5.2 User Perceptions

Whilst many average road users are oblivious to the need for asset management, they are very sensitive to the impacts of maintenance, both in terms of delays due to road works and also where they believe that their local area or routes that they travel regularly are low in a list of prioritisation. As climate change impacts increase, the requirement for maintenance across all assets is also likely to increase, this will become increasingly apparent to the general public as a more comprehensive approach to strategic prioritisation is applied, as this may result in quite marked differences in levels of investment across both regions and assets, however this is not necessarily going to cause a marked difference in condition (Spink, 2020). At a local level, this will impact directly on the political leadership, placing strain on the relationship between political requirement and technical need.

2.4.1.1.6 Technological Drivers and Challenges

2.4.1.1.6.1 Data Availability

Availability of comprehensive and accurate data on the asset and on road conditions is essential to enable effective strategic prioritisation and planning. Most current data sets include unknown levels inaccurate, incomplete or out of date information.

Utilising a single asset management database can have significant benefits for integrated asset management, however 'off the shelf' systems are often expensive, and of little value, if implemented incorrectly.

2.4.1.1.6.2 Asset Standards

A lack of comprehensive data undermines the ability to make the case for investment. The setting of consistent standards for maintenance, availability or other performance criteria across Asset networks limits progression and the understanding of how deterioration of network-specific condition is happening. Most directly, where asset condition allowed to consistently fall below current intervention levels then overall the asset will become more costly to maintain going forward. (Power et al, 2019)

However, the implication of an introduction of further consistent asset condition/performance standards will potentially result in additional training needs or up-skilling in areas such as inspections or broader asset management skills.

Once asset performance standards are established, the challenge is not only to maintain condition to meet them, but to drive forward improvement to the residual life of the network, often with decreasing budgets.

2.4.1.1.6.3 Research and Development

The adoption and acceptance of new technologies/materials/processes is notoriously complex and introduces a number of potential challenges such as those around non-proprietary specification requirements and more practical issues such as affordability, long-term maintenance requirements and the necessary education of user groups. However, innovation can reap wide benefits in terms of cost-saving, maintenance benefits and extend residual life.

2.4.1.1.6.4 Specification

Statutory specification requirements, i.e. DMRB or MCHW (www.standardsforhighways.co.uk, accessed December 2017) for the UK trunk road network are designed to deliver a network built and maintained to a set of specific criteria. The DMRB is a tool used by designers and contractors to deliver the requirements of Highway's England. However, the specifications can often limit the use of more innovative materials or techniques due to the limitations imparted. The line between innovation and specification is small. Specification must be used to police the use on materials and techniques in order to moderate the variability within and ensure a safe, and useable network with a minimum baseline for quality expectations. Innovation will drive change, getting more for less and being SMARTer (Specific, Manageable, Achievable, Realistic and Time-bound) with maintenance will ensure that the aging network is fit to meet future challenges.

Policy makers must ensure that standards are revised at regular intervals to keep pace with innovative change, whilst at the same time, moderating to limit inappropriate applications.

2.4.1.1.7 Legal Drivers and Challenges

2.4.1.1.7.1 Statutory Duties

Most transportation assets are owned by bodies with statutory obligations that they are required to fulfil. These often form elements such as User Safety and network availability. As a result, the asset owners will pass these and other requirements on to maintenance contractors as part of their contract. Failure to meet the statutory requirement may result on fines, investigation and even suspension of duties. Highways England are currently under licence with the Office of Road and Rail who monitor performance of the organisation, with respect to the continued meeting of licence framework obligations (ORR, https://www.orr.gov.uk/monitoring-regulation/road/highways-england/what-we-do-on-roads , accessed September 2020)

2.4.1.1.7.2 Performance and Audit

Most asset owners are subject to a remit of audit and performance management to ensure that they are meeting their statutory obligations, along with the maintenance contractors. The audit process can also be used to monitor contactors against the clause in their contract and assign scores against their Key Performance Indicator (KPIs). Audit function can also be used to vet the asset data collated, in terms of currency, accuracy and correctness.

2.4.1.1.8 Environmental Drivers and Challenges

2.4.1.1.8.1 Winter Maintenance

Winter maintenance is a key issue for most infrastructure asset owners. Poor conditions lead to safety issue and can endanger users. Ensuring that an asset owning organisation has and uses processes and inspection schedules to determine the needs of the network in order to maintain availability and safety are critical business objectives.

2.4.1.1.8.2 Climate Change

Climate change is happening and is continuing to make significant and irreversible change to our planet and the way that we live. This means that past greenhouse gas emissions will lead to the major changes to the UK's weather and environment, with the greatest changes to be seen over the next 40 years (UKCCP, 2009). Changes beyond the 40-year models are largely governed by changes made to CO2 emissions at the current time. The iSMART research project (Glendinning et al. 2018), a continuation of works undertaken as part of the CLIFFS and BIONICS projects, has confirmed through extensive field testing that rates of deterioration will worsen with the current UK climate change predictions of drier summers, wetter winters and an increase in the intensity and frequency of extreme events (Met Office 2018). Currently at least 74% of earthwork failures been found to have an issue in the inventory or condition of the drainage asset as the cause (Lane et al. 2019). However, in addition to this issue, many existing geotechnical assets are not designed to manage the predicted increasing rate of extreme weather events. As a result, the is likely to be an increase in the number of failures of the geotechnical assets due to inadequate drainage asset provision on the network (Spink, 2020). It is clear that the presence of appropriate earthworks management strategies to support ongoing maintenance of the geotechnical asset will become more pressing in the future (Loveridge et al. 2010). Further work resulting from Boadi (2015) suggests future research to focus on (1) the evaluation of the effects of climate change on ancillary assets (of which geotechnical assets form part),(2) assessing asset vulnerability, to show how this impacts the risk assessment process and how it can offer great information in the risk-informed decision process.

2.4.1.1.8.3 UK Profile for climate change

The UK Climate Impacts Programme 2009 (UKCIP, 2009) has developed a series of models to predict future trends in climate change based around four future climate change scenarios; ‘Low’, ‘Medium-Low’, ‘Medium-High’ and ‘High’. The scenarios consider the uncertainties that exist about future trends and behaviours.

In summary, UKCIP average predictions for climate change in the UK are (UKCIP, 2009):

- Temperature: for all scenarios, average annual temperature will rise by between 0.5°C and 1.5°C by 2020, and by an average of 2.5°C and 3.0°C by 2080.
- Precipitation: on average, Annual rainfall shows little change, however, Winter rainfall is predicted to increase by up to 30% by 2080. Summer rainfall is predicted to decrease by up to 50% by 2080
- Soil Moisture Content: Relatively small predicted changes in annual, winter and spring soil moisture content by 2020. Predicted soil moisture content decreases of up to 30% and 50% in summer and autumn respectively by the 2080s. Predicted soil moisture content increases of up to 30% and 50% in spring and winter respectively by the 2080s

- Wind speed: Possible increase of up to 10% in the winter months
- Snowfall: Predicted 60% to 90% decrease by the 2080s

Historically, UK construction and maintenance policies have been based on past climate data, but since the climate is expected to change more rapidly over the next 40-60 years with increasing frequency of severe weather events, attention must be paid to the outcomes of future predictions instead. Changes to policies and current maintenance methodologies are needed to ensure that the UK's trunk road network can cope with future variations to the climate and can avoid the negative effects of these changes. In particular, the effects of hot and dry summers, wetter winters with more extreme rainfall events, and warmer winters must be accommodated.

There has been an increasing trend towards more very hot days (i.e. with temperatures over 25°C) in the UK over the last 40 years. In addition, the number of extremely hot summers (where high temperatures were sustained over a number of days) has increased (Capps and Lugg, 2005). For example, the summers of 1976, 1983, 1990, 1995, 2003 and 2006 all showed lengthy periods of very hot, dry weather. In the London School of Economic Policy briefing (Ward and Hicks 2013), they outlined that of the UK's 10 warmest years, 7 of them have taken place since 2002. Typically, hotter, drier summers will lead to increased incidences of geotechnical asset deterioration through cracking and desiccation as a result of a prolonged hot and dry period leading to severe reduction in soil moisture content and therefore and increase in soil shrinkage (Glendinning et al, 2018). The concern is that incidences like this are expected to increase in frequency and severity as climate change continues.

Wetter winters and more extreme rainfall events will lead to increased occurrences of flooding, as seen in the summer of 2007, and throughout 2012 and 2013 (Clarke and Smethurst, 2012). This will particularly be a problem in low-lying areas and floodplains and will increase the risk of landslips and embankment erosion.

Flooding will also have implications on geotechnical asset maintenance as rising water tables, along with increased water ingress can lead to structural instability and premature deterioration and failure of the asset. More intense rainfall, increased storminess and more severe winds will have impacts on geotechnical asset resilience (Shah, 2014), along with associated impacts on drainage capacity and condition, utilities and highways structures (such as; bridges, culverts, road signs, street lighting) which all may affect the wider network function and availability.

Warmer winters may lead to fewer instances of snowfall and ice which may in turn reduce the need for winter maintenance activities (salting etc). Warmer winters and more intense rainfall events will also lead to a lengthened growing season. This will result in an increased demand and need for maintenance of the soft estate and new plant species may begin to thrive. However, the removal of vegetation may also result in embankment and slope weakening. This in turn will have additional potential impacts such as;

- drainage blockages
- impaired 'sight-line' vision of road signs
- vegetation growth onto the highway
- reduction of water uptake through roots and decrease in evapotranspiration levels.
- soil exposure increase, leading to increased capacity for external weathering

Adaptation and mitigation techniques are already being implemented across the UK to deal with the effects of climate change on the highway network. Some examples of these are shown below. (Roads Liaison Group, 2005)

a) Undertake a risk assessment to determine vulnerable areas of the network (**Maintenance Planning**)

b) Define alternative routes and ensure they are adequate, well signposted and well maintained (**Contingency Planning**)

c) Work with external agencies to improve flood protection/defences in areas of multiple flooding events (**Groundwater Fluctuations – Flooding**)

d) Implement a targeted programme of improvement (**Maintenance**)

e) Ensure drainage inspection and maintenance programme is suitable and reviewed on a regular basis (**Groundwater Fluctuations – Drainage**)

f) Encourage and adopt innovations in more permeable assets to control surface run-off and prevent flooding (**Groundwater Fluctuations – Flooding**)

g) Capture and store water to be released gradually (**Groundwater Fluctuations - Drainage**)

h) Consider tree felling to reduce soil moisture deficits, where appropriate (trees remove moisture from the soil and can cause subsidence). (**Vegetation Removal)**

i) Develop an Emergency Plan with the emergency services and local communities (**Contingency Planning**)

j) Increase the use of warning signs on major roads. Provide advice and warnings to drivers on the dangers of high winds (Minimised vehicular damage) (**Trauma Collisions**)

k) Undertake a structural appraisal and considered programmes of strengthening and/or removal (**Pre-emptive Maintenance**)

There are a number of clear implications for the UK trunk road network as a result of current and future climate change. These effects should form part of the basis for any decision-making carried out when assessing network policies and standards, and include:

- Increased risk of deterioration due to flooding from rivers;
- Increased risk of deterioration due to flooding from inadequate drainage;
- Increased risk of landslides;
- Damage to bridges, signs and other structures from increased wind speeds and scour from both intense rainfall and high temperatures;

- Increased road safety problems due to adverse driving conditions
- Increased number of routes unavailable therefore, increased level of user delay experienced.

Catastrophic asset failures as a result of climate change or severe weather events is often as a result of excessive movement in the soil caused by increase in pore water pressures and a resulting decrease in the total stress and thus strength of the soil, Loveridge (2010). The long-term effects of climate change leading to hotter drier summers and wetter winters that are associated with more frequent intense rainfalls can be considered to have a significant impact on the integrity of embankments, cuttings and slopes, Kilsby (2009). Further, Clarke and Smethurst (2012) suggest that the warmer and drier summers along with wetter winters associated with climate change will result in significantly increased “soil moisture cycles”. These cycles will impact the long-term serviceability and stability of slopes on the UK transportation network.

These impacts will have a significant effect on the UK highway network over the next 40 – 60 years, of which some are already being experienced. Not all of these impacts will directly affect the geotechnical assets; however, some may have a small ‘knock-on’ effect, such as damage from a vehicle collision as the result of skidding on a wet road. The implications of these events must be taken into account, even if both the risk impact and likelihood are both small.

It is important that the design, construction and maintenance of the highway network assets consider the impact of these factors and take action from the inception of the asset to apply policies, standards and practices to cope with predicted future climate change. However, ensuring that the asset owners and operators, government and the general public understand the need for these adaptations, in order to address the issues already undergoing and forthcoming by way of appropriate policies, standards, practices and strategies is a significant and ongoing challenge.

2.4.1.1.8.4 Regionalisation

The UKCIP 2009 present a series of scenarios with significant regional differences. The most significant events of long-term climate change, where less than 10% of the geographical area of the UK is likely to be exposed, are predicted to take place in the South-East regions of the UK. The Figure 15 below, taken from UKCIP, 2009 show evidence of this:

Variable		Mean temperature, winter			Mean temperature, summer			Mean daily maximum temperature, winter			Mean daily maximum temperature, summer			Mean daily minimum temperature, winter			Mean daily minimum temperature, summer		
Probability level		10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%
High emissions	Highest change in UK	2.2	3.8	5.8	2.9	5.3	8.4	1.6	3.4	6.1	3.0	6.8	11.7	2.0	4.2	7.0	2.8	5.3	8.8
	Lowest change in UK	1.0	2.1	3.5	1.6	3.1	5.0	1.1	2.3	3.9	1.2	3.5	6.3	0.8	2.4	4.3	1.7	3.3	5.6
Medium emissions	Highest change in UK	1.7	3.1	4.8	2.2	4.2	6.8	1.3	2.9	5.1	2.2	5.4	9.5	1.5	3.5	5.9	2.0	4.1	7.1
	Lowest change in UK	0.8	1.8	3.1	1.2	2.5	4.1	0.8	2.0	3.4	1.1	2.8	5.0	0.6	2.1	3.7	1.3	2.7	4.5
Low emissions	Highest change in UK	1.5	2.7	4.1	1.4	3.1	5.3	1.3	2.6	4.3	1.4	4.1	7.5	1.4	2.9	4.8	1.4	3.2	5.6
	Lowest change in UK	0.8	1.7	2.7	0.8	1.9	3.2	0.9	1.8	3.0	0.7	2.1	3.9	0.7	2.0	3.3	0.9	2.1	3.5

Figure 15 - Highest and lowest changes in annual-, winter- and summer-mean daily precipitation, and in precipitation on the wettest day of the season (%) in winter and summer, by the 2080s, relative to 1961–1990.

A geographical representation of this shown in Figure 16, again taken from UKCIP, 2009 shows the regional probability mapped out for mean temperature change.

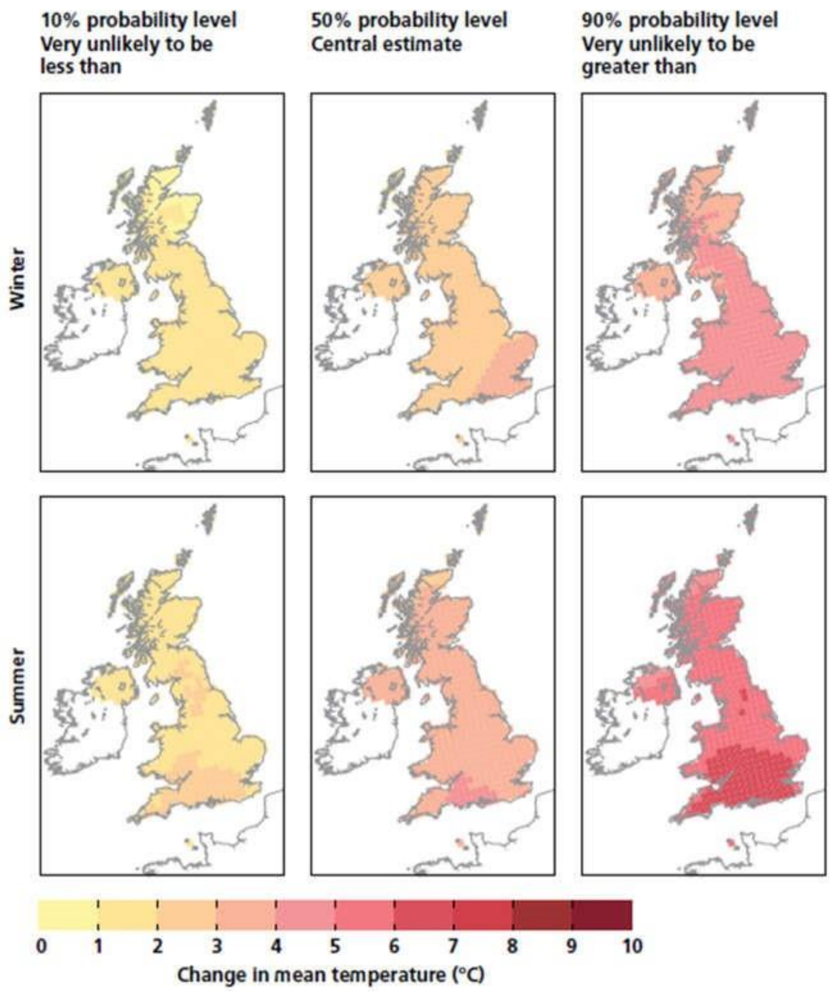


Figure 16 - 10, 50 and 90% probability levels of changes to the average daily mean temperature (ºC) of the winter (upper) and summer (lower) by the 2080s, under Medium emissions scenario. Reproduced from UKCIP, 2009

Under this premise, higher probabilities must be assigned to geotechnical assets that are based in the Southern regions, and lower probabilities of effects from climate change to affect the more Northern Regions, including Scotland.

2.4.1.1.8.5 UKCIP18

Following the proposal of the Paris Agreement on Climate Change in December 2015 at the United Nations Framework Convention on Climate Change, Defra announced that the UK Climate Projections will be updated to reflect the most up-to-date information on the future of our climate. (DEFRA, 2016)

UKCP18 builds upon the current set of projections (UKCP09), which provide crucial information about how climate can be expected to change in future decades. These tools, like the UKCIP09, will aim to help decision-makers assess the full range of risks from the changing climate and provide advice on adapting to these changes.

UKCP18 project updates the UKCP09 projections across the UK and provide further projections of sea-level rise. It is anticipated to give greater regional detail, and expand the existing analysis of the risks posed, including more information on potential extremes and impacts of climate change.

2.5 Summary of the Literature Review and Research Gap

Asset Management for the Highways sector is a defined concept incorporating ground-level maintenance and operations activities whilst simultaneously setting policy and strategy to meet an asset-owning organisation's needs.

As discussed, asset management is not new, but has a significant difference to historic processes of managing assets (IAM, 2017). The successful operation of a road network requires effective management and operation of more than two categories of assets: pavements and bridges. However, over the years, these two asset categories have had an overwhelming emphasis within the asset management sector due to supporting mandates and requirements (Boadi, 2018) Other asset types not currently included within the carriageway or bridges, which can be thought to include road markings, footways, street lighting, traffic signals, traffic signs, utilities inspection covers, and earth retaining structures (FHWA, 2005; Li & Madanu, 2008; Hawkins & Smadi, 2013; Akofio-Sowah et al., 2014). Geotechnical asset management is an emerging practice within industry (Spink, 2020, Thompson et al 2016). Thompson et al (2017) both highlight the importance of developing risk-based asset management plan, the latter with a defined focus for geotechnical assets, to be deployed at all three levels of asset management strategic, tactical and operational.

The Highway Agency's Adaptation Framework Model (HAAFM) (Highways England, 2009), outlines a process that identifies activities impacted by climate change and determines associated risks and opportunities, and preferred options for mitigation. The study found over 60 percent of the risks identified against these activities are expected to be affected by current predicted levels of climate change (UKCIP, 2007) within their design life. Further, the approach to risk identification enables the resulting outcomes to be prioritised based upon several criteria including their potential to disrupt the operation or availability across all asset types forming the strategic road network, compared to previous investigations this provided important in opening up non-pavement or bridge assets to a consistent approach that can evaluate the network as a whole.

There is a wealth of theoretical and empirical literature on maintenance and management of assets of all types, only a few studies focus specifically on geotechnical assets or on the tools needed to manage them, especially when considering the application and identification of assets at risk of requiring maintenance to support them against climate change impacts. Many of the studies that exist are focused on understanding the mechanisms of the deterioration to support forecast modelling (CLIFFS, BIONICS, iSMART)

The iSMART research project (Glendinning et al. 2018), has confirmed through extensive field testing that rates of deterioration will worsen with the current UK climate change predictions of drier summers, wetter winters and an increase in the intensity and frequency of extreme events (Met Office 2018). This is supported by Lane et al (2019) who state that currently at least 74% of earthwork failures been found to have an issue in the inventory or condition of the drainage asset as the cause. Furthermore, many existing geotechnical assets are not designed to manage the predicted increasing rate of extreme weather events. As a result, the is likely to be an increase in the number of failures of the geotechnical assets due to inadequate drainage asset provision on the network (Spink, 2020).

The outputs from CLIFFS, BIONICS and iSMART provide engineers and managers with the tools needed to support the future design requirements of geotechnical assets to meet the requirements of a changing climate and its impact on the road network (Briggs et al 2017). However, for many of these assets, they are already designed and constructed and heading into a future unknown. Any tool designed by the researcher must be a useful operational tool to define where the critical impact factors are and support the engineer by determining the potential scale of the uncertain future climate change behaviour. As described above, the sources of unpredictable future behaviour of geotechnical assets is the reason that a risk-based approach is required, and that using a series of scenarios which can be applied independently is an appropriate means of describing future behaviour.

Mian et al., (2011) use on geotechnical assets as the base for their Risk-based framework; however, it is unclear how the outcomes of using the framework on future maintenance needs. The work produced presents a risk-based framework, which is an important baseline for the management of geotechnical assets, while the objective of this study is to present a tool to identify the assets most at risk of significant impact from climate change effects.

Boadi (2015) focuses future research requirements on evaluating the effect of climate change on geotechnical assets, asset vulnerability, and how this affects the risk assessment process can offer great information in the risk-informed decision process. In the author's experience, many organisations are very capable of identifying the risks, however understanding of the importance of the next steps to ensure that the risk is appropriately mitigated and its impact on the organisation fully understood, can be the limiting factor in the full adoption of a Risk-based approach.

The project outlined in this thesis should consider the key factors that are affected by changes to our climate. In Dixon, (2010) the BIONICS researchers group these factors at three levels:

(1) **material properties and processes**, including shear strength, plasticity, permeability, unsaturated conditions, etc;

(2) **site-specific conditions**, including stratigraphy and hydrogeology (e.g. bypass flow), vegetation cover, propensity for developing cracks, drainage provisions, topography (such as exposure, slope angle, micro-catchment), etc;

(3) **broad environmental context**: variation in climate influence, changes in infrastructure network use, etc.

The resultant risk tool should use these factors which can then be used as part of a wider risk matrix and can also be utilised to determine where current areas of weakness exist for the purpose of further investigation.

Amendola (2001) outlines how the identification of significant versus non-significant risk can be delivered by expert risk assessment; this researcher further asserts that this can be achieved using a partial FMECA combined with a risk assessment approach i.e. an expert-led risk assessment should be undertaken for each asset and location to determine the presence and extent of climate change impacts. This project, or operational level approach can then be followed, using other tools as appropriate, with the project prioritisation, occurring within the tactical asset management space for developing a modular programme of maintenance projects. The requirement for this project is that a specific risk assessment tool should be developed to be used to assess the long-term impact of climate change. The resultant tool must be simple to use and understand, give clear outputs and not be onerous on the engineers using it.

Almost all the models and the tools discussed above assist decision makers in identifying solutions given the budgetary constraints. The resultant tool is slightly different in that it enables engineers to identify an 'at risk' asset by appraising them in terms the presence of factors that can be significantly impacted by climate change effects. It offers a snapshot view of the potential future conditions resulting from climate change that may affect the performance of the geotechnical asset and allows the engineering to take this information forward when considering the geotechnical asset management maintenance plan. In that sense, this risk tool can be viewed as complementing some of the models and systems discussed above by providing an 'easy to use' indicator for use in the wider planning process.

Finally, the approach to conceptualising climate change risk within the context of asset management offers further room for improvement. The existing approaches rely heavily on deterioration models of geotechnical assets, either as a tool to support future design requirements or in other decision-support tools focus on asset performance over a certain time frame or under set budget conditions. A tool which presents a comprehensive approach to estimating the risk of climate change effects on assets as part of a wider future asset planning approach is not yet regularly undertaken within Highways England. This study adopts a multi-dimensional future-focused approach to estimating the significance of the risk posed by climate change, thus enabling engineers and senior manager to determine the extents in terms of both scale and scope, and allow more effective decision-making, maintenance prioritisation and design choices. By mitigating the risks of future impact now, the longer-term effects should be minimised.

In sum, the proposed tool fulfils the need for a long-term risk tool that enables engineers to determine the degree of risk posed by climate change to their assets and enables the user to plan more effectively the outcome solution for the management of geotechnical asset the that can affect the lifetime of the asset.

3 Methodology of Research

3.1 Introduction

This section details the process and methodology undertaken by the researcher to deliver this project. The output of this research provides a tool that applies a solution for solving a long-term problem, by using an evidence and data-based approach to improve decision-making around the impacts of climate change faced by infrastructure owners. The requirement for this knowledge is because of a global change to improve and address accountability and understand the implications of long-term climate change to geotechnical assets, and how asset owners can use existing data to assess these changes and understand their impact.

The researcher has undertaken work as part of this research to understand the scope of the problem and focus on meeting this critical business need through the production of a tool which provides an assessment and allows the user to improve their decision-making process.

By using applied business and risk assessment research techniques, the research provides a validated solution which drives forward the understanding of climate change impact for critical infrastructure in the UK.

The applied business research techniques used as part of the research for this project are outlined by Zikmund et al (2012) as an application of the scientific method in searching for the truth about business challenges. The process of applied business research includes activities such as

- defining the business problems,
- generating and evaluating potential solutions,
- monitoring performance.
- idea and theory development,

- searching for and collecting information,
- analysing data,
- communicating the findings and their implications

Business research techniques provide an opportunity for the researcher to apply an existing theory or analyse a real business problem or explore and analyse general business issues. It also involves the application of techniques and procedures to highlight the problem and offers solutions to address the identified issues (Collins and Hussey, 2008).

The researcher undertook this project with a clear and defined problem for Geotechnical Asset Owners – there is a lack of a long-term process for evaluating of the effects of climate change on geotechnical assets, and in turn, a lack of provision of an evidence-based decision-support tool for evaluating the extent of this issue. This business problem poses a challenge for asset management and geotechnical engineering professionals, as there is a number of tools and research outcomes that can provide guidance, support and information on regarding the long-term health of assets in the context of a changing climate. For geotechnical assets, short term impact of climate change and impact of severe weather events modelling tools are currently available; however long-term planning and decision-making considerations are based on engineering judgement supported by technical knowledge of ground conditions, condition assessment, risk management and by developing maintenance strategies based on available budgets. Currently, most of the tools currently available in the current market provide direction at a network-wide level (not for an individual asset) and the focus lies predominantly on factors which are currently, or imminently, affecting the operation and maintenance of the assets (Transport Resilience Review, 2014). Other resilience studies, of which this research could be considered part, often include criticality studies, risk-based approaches and the development of factors affecting the condition, availability and performance of the network.

Risk and resilience-based workflows are often not specifically responsible for the development of asset management frameworks, nor do they regularly consider long-term future of the assets (Thompson, et al, 2019). In the researcher's experience, this is often limited to 5 years, or following severe weather events. As such, the researcher has chosen to use established qualitative research techniques in the development and refinement the decision-support tool presented within this project. The techniques to be used within this project with be discussed later in Section 3.4.

3.2 Boundaries of Research

The boundaries of this research fall entirely within the remit of geotechnical assets. Of these, this research and presented toolkit will consider the impact of climate change on cuttings, slopes, embankments and retaining walls within the context of the UK Strategic Road Network (SRN). The project will review the critical impacting factors which determine the condition of the asset and provide an insight into the future impact of climate change using current climate change prediction models to determine the long-term (25-30 year) outcome. Figure 17 indicates the elements of asset management that this thesis addresses:

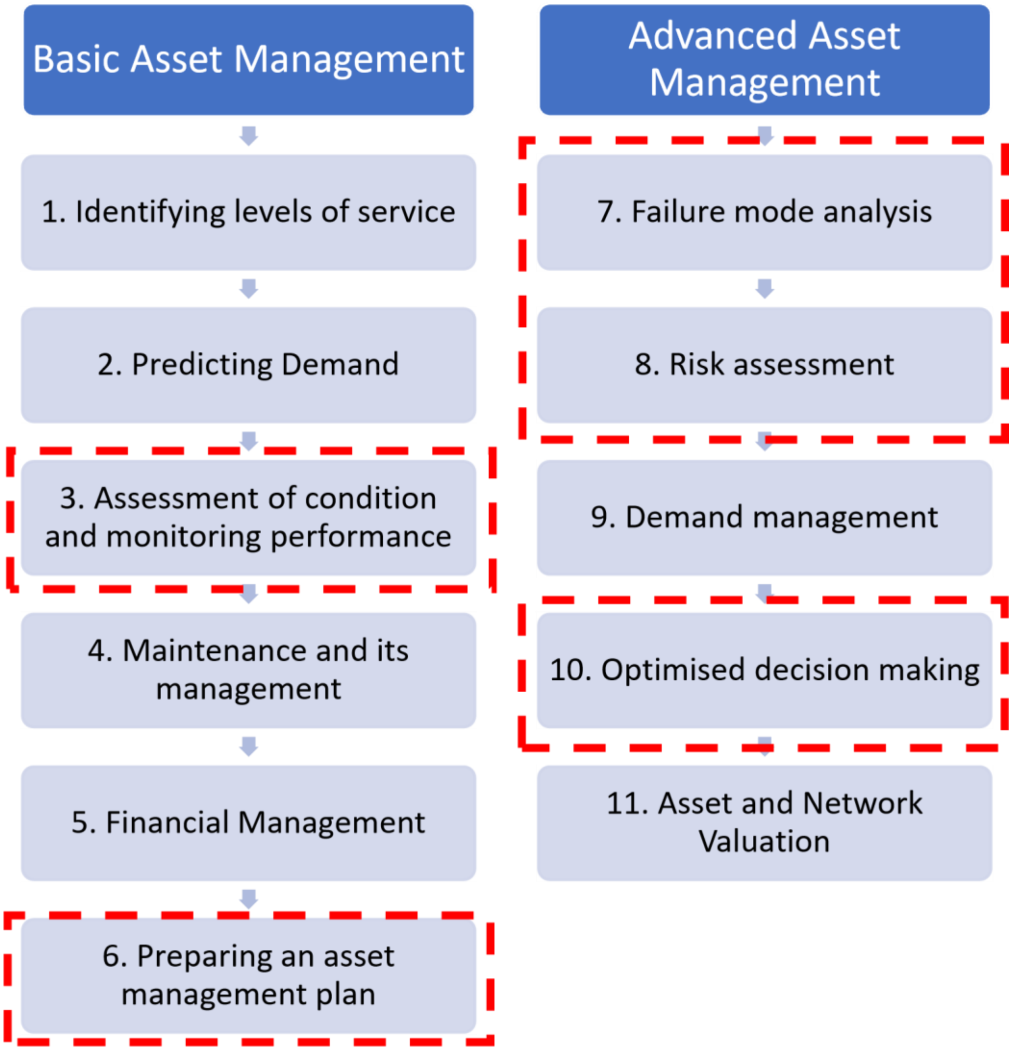


Figure 17 - Basic and Advance Asset Management Activities (Burrow, et al., 2016) in terms of the boundaries of this research

From Table 16- the risk assessment tool presented in this research will consider the Failure mode analysis (7), by means of the condition assessment (3), evaluate the impacting factors, and undertake a risk assessment (8) to lead to optimised decision making as part of a risk-based approach (10). From this analysis, the research will predict how the maintenance should be programmed (2) and determining if a plan (6) should be made to accommodate climate change mitigation measures as part of the asset management plan. The tool will evaluate individual assets at an operational or project level, in order that the results can be easily considered as part of the scheme development process.

Table 16 - Research Methodology and method of study

STAGE.	Objectives of the Research	Research Method	Output
1	**Objective 1:** To review the state-of-the-art asset management systems and practices for transportation networks in the UK and around the world including geotechnical assets **Objective 2:** To examine long term planning needs and resilience assessment in asset management with the road transportation infrastructure (with focus on geotechnical industry).	**Thematic literature review** The online databases and search engines used by the researcher, included the ICE library, Science Direct, Google Scholar, Highways England libraries, peer-reviewed articles and material from high-quality conference proceedings along with other reputable sources for technical documentation. Keywords used for the searches included the following: “infrastructure asset management” “asset management” + “roads” + “transport sector” “roads” + “asset management” + “geotechnical assets” “planning tools” + “geotechnical assets” + “UK” “decision support” + “geotechnical assets” + “tools” “climate change” + “geotechnical” Risk assessment” + “asset management” Backward and forward journal searches References, authors and keywords obtained from the literature review were used to discover more information. Papers that had cited the articles obtained from the review were also considered.	12 Impacting factors that defined the change to stability associated with climate change effects. The subfactors that determine the mode of deterioration of geotechnical assets were derived from the literature study

STAGE.	Objectives of the Research	Research Method	Output
2	**Objective 3:** To study the geotechnical asset failure modes to determine the hierarchy of factors affecting the performance of the geotechnical assets including groundwater fluctuations, seepage, soil properties, geology and hydrogeology.	Determining the impacting factors affecting the performance of geotechnical assets and their inter relationships and considered link to climate change	A list of critical factors and the interrelation between the same.
3	**Objective 4:** To develop a geotechnical asset management climate change risk mapping approach for use in the planning stage of an asset management life cycle and to develop a tool to support these assessments.	Develop a risk matrix to assign a risk level, according to the scored severity and the anticipated level of climate change. And boundary set thresholds for risk impacts and likelihood	Climate Change Needs Risk Assessment Tool

4	**Objective 5:** To test the framework through case studies and validate the tool.	Workshop to Validate the decision-support tool and the methodology; using pilot projects i.e. case studies and structured interviews with industry experts. Integrate feedback from the validation stage and develop the framework as a finished tool.	Case Studies demonstrating use and outcomes of the Climate Change Needs Risk Assessment Tool

In order to make the proposed decision-support tool robust and comprehensive, consideration must be given to the lifecycle of the asset and its current position within that lifecycle. The toolkit will act as a planning aid that can be revisited at different stages of the scheme or project, or on receipt of updated condition information- for example, following a principle or general inspection. For assets currently in consideration as part of a scheme, this may include,

- inception
- design and construction
- operation and maintenance
- end of design life stage (including demolition or reuse)

Each of these stages must be given consideration by the engineer when utilising the results from this tool and provide a stage-gated decision to confirm if further action will be undertaken based ultimately on the asset condition and the type of project being considered.

This research aims to answer the problem of defining the scale and scope of geotechnical assets on the Highways England SRN which will be adversely affected by the impact of climate change effects. The researcher will address this problem by evaluating existing asset management climate change strategies, tools, and industry practice with respect to highway transport networks holistically, and with respect to geotechnical assets in particular. The research has identified a gap in tools and methods for the support of geotechnical assets and proposes a methodology to fill that gap.

An asset management process should consider not just events in the short-term, but those in the long-term as well; Climate change will affect assets by affecting both the long-term deterioration profile of the asset, but also by increasing the likelihood and severity of severe weather events which may lead to a catastrophic failure.

Asset owners should consider identifying assets at most risk to ensure that the transportation network remains functional and serviceable by maintaining network availability, even in changing conditions, whilst continuing to undertake maintenance, operational and upgrade activities in a systematic way which provides the desired level of service. This definition therefore ties in with the definition of asset management and resilience provided earlier in this thesis.

3.3 Research Approach

The research undertaken to develop this thesis is not based on traditional laboratory studies and experimentation, but instead the outcome is more qualitative. The very nature of asset management is more akin to business and management research than most pure engineering design disciplines. Research literature considers the approaches to research to be either quantitative or qualitative in nature, and much of research and literature can be found to support both methods. The perspective from which the research problem is viewed (Collis and Hussey, 2008) directs the researcher toward the choice of the most appropriate methods available to them, in combination with the nature of the research field.

The nature of the proposed research into long-term climate change considers the impact of risk in a future-focused environment, where the exact degree of change cannot be confirmed, and as such requires a more qualitative approach in its adoption in order to be relevant to the business and broader industry, especially where stakeholders are not subject matter experts. The purpose of the research is to address the existing business need to understand the potential impact of climate change on geotechnical assets. This will be achieved via the development of a long-term planning and decision-support tool that enables the evaluation of risk for climate change impacts.

To identify the most appropriate or resilient solution from the options available, the researcher must consider the plausible future conditions that may affect the asset (including drivers discussed in Chapter 2, section 2.4 e.g., political, social, environmental, and financial). For research projects such as the one presented in this thesis, where there is a clearly defined outlook into a less predictable and more future focused environment, the findings and outcomes fall broadly into the category of futures research. However, the researcher would also argue that the research develops an understanding of risk in such a manner as to define, through data, a list of assets with potential future maintenance needs occurring as a result of climate change where the time horizon is not known. Unlike forecasting approaches, such as deterioration modelling, which includes simulation and regression analysis of past data for future projections, futures research is more reliant on outcomes to prepare for future events. For practitioners of such research, a key concern is the usability of the research results (Mannermaa, 1986). The type of research undertaken within this project is strongly linked with impacts on an organization, the government, the environment, or society at large. When considering this research as part of a risk identification protocol the researcher argues that the outcomes of the tools will provide the necessary evidence (or lack thereof) of climate change and it's impacts, thereby improving sight of future organisation experiences on events that may impact achievement of strategic objectives.

3.4 Research Methods

Fundamentally this long-term, risk and resilience research deals with identifying options for the purpose of examining impacts as a result of climate change events with an unknown time to fruition. Consideration for future events which are known to exist is imperative if an asset owner wishes to prepare for the future. Gordon (1992), asserts that the purpose of planning activities usually involves investigating the linkages between the plausible and the desirable future outcomes. As a result, the emphasis of futures-focussed research, such as that presented in this thesis, lies on understanding the scale and scope of needs to be planned and mitigated through decision support functions. It is also true that the approach and methodologies undertaken within this research scenario have been successfully applied to a series of much wider nonrelated disciplines, including economics, policy making and business management. The inter-disciplinary nature of these subjects instils an approach which is dynamic, frequently used and necessary, although the approach can at times appear to be more simplistic in nature. (Mannermaa, 1986; Schwarzet al, 1982). Given that the long-term nature of this research considers non-tangible events, which are thought to take place at an unknown horizon up to 50 years in the future, a single approach to this research methodology would be inadequate to determine the necessary aspects of this project comprehensively.

The techniques and methods used within the futures research field are widely addressed by a range of authors including; Börjeson et al., 2006; Godet, 2000; Gordon, 1992; Gordon, Glenn, & Jakil, 2005; and Popper, 2008. The inter-disciplinary nature of this research approach (Risk, Futures, Resilience and Management) provides a number of techniques and tools to complete a research methodology using both qualitative and quantitative means.

Examples of Quantitative techniques to predict future events include:

- Probabilistic Modelling
- Cross-impact analysis, including multi-criterion analysis
- Regression analysis
- Time-series analysis

Qualitative methods include:

- Decision trees

- Scenario modelling
- FMECA (Failure mode, effects and criticality analysis)

Both qualitative and quantitative approaches must consider that the nature of these future climate change events that cannot be wholly predicted, nor can they be confidently forecast based on past events or scenarios. This dilemma is often the case for research undertaken in other fields including business management and social sciences.

Qualitative research methods have previously been used in the field of asset management, and this research uses the techniques to develop the long-term climate change decision support tool. The reasons for this decision were as follows:

- The risk assessment tool supports designers and engineers in identifying geotechnical assets that are the most at risk of the impact of climate change resulting in deterioration or instability of the asset. While there is much debate about the ability to use past events to predict future conditions, a common approach used in existing deterioration modelling; The use of a qualitative multi-criterion to deliver a tool was considered by the researcher to be a more appropriate direction given the uncertainty about the nature, level and outcomes of the climate change impact, combined with the need to develop an easy to use tool that can support engineers in assessing the significance of the risk posed by climate change effects.
- Risk assessment modelling tools are extremely prevalent within the field of asset management. Many are used to predict the probability of specific outcomes occurring in near-future and current timescales. This research project focussed on the development of a risk assessment tool to further define and identify the geotechnical assets that are at risk, i.e., identify the asset 'needs'. The inter-related impact factors affecting the asset can be complex and variable. Therefore, the process to be adopted must consider the relative impacts against one another, using a quantitative approach to compare like-for-like allows this.

- The most critical element of research of this nature is buy-in by stakeholders and users of the tool. Using structured interviews with experts in geotechnical engineering, asset management, and geotechnical asset management ensures validation of the approach and assumptions made within the project and instils confidence in the tool and suggested outcomes. In order to achieve the aim and objectives set out at the beginning of this thesis, the researcher used the following techniques:

    - Detailed Literature Review
    - Cross Impact analysis through pairwise comparison
    - Risk Analysis techniques
    - Technical Consultation.

3.5 Research Techniques used in Tool Development

3.5.1 Detailed Literature Review

The backbone to any research project is a clear, detailed and systematic review of existing literature. Taking the time to fully investigate the existing body of work allows researchers to hone and define their topic of research, and to concentrate on gaps in the body of knowledge. Phillips and Pugh, 2010, assert that recognising gaps and identifying linkages can support researchers in their quest to adequately define the 'contribution to knowledge'. Throughout the course of this project, the research has conducted a multi-strand literature review, with the primary focus on infrastructure asset management for geotechnical assets. The literature review has collected and analysed the wider body of work to provide the researcher with a comprehensive understanding of the field of infrastructure asset management for the purpose of this thesis.

The literature review was predominantly undertaken online, using a keyword approach within reliable academic databases to find high-quality pieces of peer-reviewed work.

Phillips and Pugh, 2010 and other sources recommend this approach to completing a literature review.

The online databases and search engines used by the researcher, included the ICE library, Science Direct, Google Scholar, and Highways England libraries, along with other reputable sources for technical documentation.

A selection of the keywords used to compile the literature review were as follows:

- “infrastructure asset management”
- “asset management” + “roads” + “transport sector”
- “roads” + “asset management” + “geotechnical assets”
- “planning tools” + “geotechnical assets” + “UK”
- “decision support” + “geotechnical assets” + “tools”
- “climate change” + “geotechnical”
- Risk assessment” + “asset management”

Beginning with Infrastructure asset management, the researcher narrowed the keyword search to focus the outputs on the roads asset management sector, reviewing tools and approaches commonly used within the UK and internationally. Bringing in the geotechnical assets, the researcher found detailed works on the deterioration of assets with respect to climate change as well as a range of tools for managing assets. The search was tightly controlled to remove financial asset management topics and remain focussed on infrastructure assets. To ensure initial brevity, abstracts were collated and reviewed prior to the review of the full work in order to ensure the pertinence of the piece.

By targeting key works within the body of work, the researcher was able to undertake further searches in those references to determine the provenance of the pieces, and future searches to determine articles siting the key texts.

Undertaking the literature review enabled the researcher to outline the premise of the project by identifying the considerable gaps in both academic literature and industrial tools for the prediction of long-term condition impacts across all asset types. For geotechnical assets, although work is being undertaken to both better understand how assets will deteriorate (BIONICS, CliFFs) and design resilience frameworks to support asset longevity (Shah, 2016), there is still a gap for a tool which can support asset owners in the identification of assets most at risk of the impacts of climate change, using existing and available data.

The literature review provided the researcher with the tools to identify the most critical factors which can affect the condition of a geotechnical asset, understand which of those can be impacted by climate change, and with the support of HAGDMS, identify the key data fields that are required to assess such an impact.

By conducting a detailed literature review, the researcher was able to justify the need for a long-term risk planning and decision-support tool specifically targeted towards the long-term climate change impacts against geotechnical assets. The review highlighted the absence of a long-term climate change evaluation tool that can provide evidence to decision makers of the need to consider climate change as part of the long-term asset management planning process. Geotechnical assets are designed to have long lifespans, and as such require continued monitoring of the risk factors that their condition brings. These impacts support to the needs-based planning process, since the estimation of future changes that are likely to affect asset performance require the choice of a solution that is appropriate and long-lasting, delivered at the right time. The literature review undertaken as part of this research, supported the approach to achieve 3 milestones, including:

- It supported the researcher identify a set of 12 impacting factors that are integral to defining the effects of climate change on geotechnical assets on the UK Strategic road network (Phase 1),
- Several methods were analysed to establish the most appropriate approach for the assessment of the data to effectively evaluate the risk level (Phase 2) and,

- the literature reviewed, along with the researcher’s industry experience provides the foundation for the development of the risk assessment tool (Phase 3).

3.5.2 Cross Impact Analysis – developing the risk assessment

Cross-impact analysis is a widely used method of research for future-focused projects. It is used by researchers to analyse how a variable impact on other related variables, thereby providing linkages and ties between variables (Richards & Pherson, 2011 and Gordon, 1992). A cross-impact matrix provides a platform for establishing (For-Learn, 2005) and recording how a variable is affected by the interaction of the other variables within a set.

3.5.2.1 Multi-Criterion Decision Making

Multi-criteria decision making is a protocol for making decision between multiple variables which may behave as opposites (Hwang and Lin., 2012). Multi-criterion decision-making describes a process to determine the most appropriate criteria to demonstrate a state. (Keenay et al., 1993). The resulting solution is found to either meet all the criteria set, or as a minimum, to be the best fit of all potential solutions.

Group decision-making poses several significant challenges, especially where there are multiple criteria to be evaluated. Group members may exhibit opposing objectives, strong personalities may dominate or manipulate an agenda, and outcomes may not in fact be shard within the group. Alternatively, criteria may also be found to be opposing or challenging to compare- a state of ‘apples vs oranges’ where both criteria have equal standing.

This research presented a toolkit to a group of interviewees as part of the validation process. Within this process, the interviewees were asked to review the impacting criteria and assess the weighting provided to each element by way of Pairwise comparison

(Bradley et al., 1952). The researcher provided an example of a Pairwise to the interviewees in order to establish to method for those unaware.

The Pairwise did not target any specific weightages for the impact criteria, but rather provided a first draft of the tool with arbitrary weightages applied. The interviewees were then able to take away the Pairwise to complete independently. The researcher was informed that several groups of interviewees collaborated to complete the Pairwise, prompting discussion and justification conversations throughout. The sections below outline methods of MCA group ranking which were considered in the application of this research.

3.5.2.2 Group Ranking Methods

Group ranking used within the multiple decision-making process can be based on a variety of techniques such as social choice theory, voting, expert judgement/group participation analysis which discusses the variety of pros and cons for a project, or a game theory approach that considers the individual strategy of each decision maker (Hwang et al., 2012). For the purpose of this research, the method used was a combination of 'voting' and expert judgement/group participation analysis, as this would allow all the stakeholders (who for the research were the group of experts on geotechnical asset management) to discuss the pros and cons of each solution in light of all future conditions to arrive at the weightings. Stakeholders were then asked to vote for their preferred choice using pair wise comparison technique which is discussed in detail below.

There are many techniques for ranking preferences or voting methods as a means of measuring meaningful preference data (Straffin 1980, Cook et al., 1978, Brams et al., 2007 and Nurmi, 2012). Some of these are briefly explained below, and the choice of the technique used for this research is explained in greater detail along with the reasons for the same.

3.5.2.2.1 Majority Method

This approach applies a 'majority wins' rule, meaning that one criterion should score more than 50% to achieve the majority. However, where a criterion set numbers more than three, this is not always possible, (Wright et al., 1989). This approach was discounted due to the number of impacting factors.

3.5.2.2.2 Plurality Method

In this easy-to-use approach, only criteria ranked 1st are considered, leaving no room for lesser preferences. (Wright et al., 1989). This method was discounted as it left room for criteria to be un-evaluated.

3.5.2.2.3 Instant Runoff Technique

Similar to the plurality technique, the Instant Runoff Technique (IRT) eliminates the lowest ranking criterion and redistributes any votes to the next lowest choice, continuing until a majority is observed. (Wright et al., 1989). This approach was used in part through discussion with industry experts who determined that one of the impacting factors should not be considered as its impact on slope stability in the long term would be negligible.

3.5.2.2.4 Borda Count

The borda count approach uses a ranking system equivalent to the total number of criteria to be assessed. Each first-place vote received is multiplied by the total number of criteria (the maximum number of points available). Each lower placed criterion receives 1 less point. Each criterion scores the sum of the product of the number of votes and the rank. The winner receives the highest score. (Hwang et al. 2012). Given the approach to be used in the tool, with 12 impact factor categories and subcategories beneath them, this method was rejected as insufficient nuance was present in the resulting hierarchy of factors.

3.5.2.2.5 *Pairwise Comparison*

The pairwise comparison technique ranks paired criteria. All permutations of pairs are to be considered, each winning criterion out of the pair is scored 1 whilst tied criteria score 0.5. Losing criteria do not score. The ‘winner’ is the criteria which has won the most pairs or has scored the most points. (Bradley et al., 1952). Like the Borda count approach, other preferences are taken into account using this scoring methodology.

As discussed earlier, a pairwise comparison was used within this research methodology for the following reasons:

- It covers all options and pairings, considering non-first place choices.
- Provides a method to address tied criteria by halving the score. This is the only method able to do this.
- It was also considered to be the most repeatable method for industry experts, by asking the single question “which of the two factors being considered has the highest impact of the long-term stability of the asset?”

3.5.3 Tool Validation – Structured Interviews

As discussed earlier, long-term asset management solutions require buy-in from stakeholders. In line with other futures research projects, this research has undertaken validation of the tool with a panel of selected technical experts. As explained earlier, involvement of experts is central to futures research methods (Amara, 1989). The knowledge and experience of the technical experts is paramount for determining the suitability of the tool, especially in terms of the impacting factors causing asset deterioration (Ruitenburg et al., 2014). Given that the researcher’s industry experience lies predominantly in the field of asset management, as opposed to geotechnical engineering, the technical experts were invaluable in providing validation of the impacting factors and their relationships to each other. To validate the decision-support tool developed in this study, the researcher conducted a multi-criteria decision-making exercise with 8 experts from the field of geotechnical asset management, all holding mid to senior level experience. Each of the experts was able to provide insights into the use of the tool, it's limitations, and the use of asset information within it. The technical expert panel consisted of both geotechnical experts, and asset management experts.

During the first set of interviews, the experts were provided with a copy of the tool and the first case study with a set of arbitrary weightages and asked to assess the suitability of the chosen impact criteria. The experts provided feedback about the tool from ease of use and clarity, to the inclusion of the impacting criteria. The data contained within each of the 3 case studies was obtained from HAGDMS, with permission from the client.

The tool was then refined and updated prior to the second case study. During the second interview, the experts were provided with the updated tool and a copy of the Researchers pairwise comparison to prepare the interviewees for the completion of the pairwise.

Following the completion of the pairwise comparison by the experts, the researcher then collated the results to produce a single set of refined weightages for the impacting factors, presented in the third case study.

The validation exercise with three case-studies and involving a panel of experts allowed the researcher to demonstrate the full usability of the tool as well as its robustness. Thus, from the perspective of fulfilling the objective of the validation, the sample can be regarded as adequate.

The validation exercise confirmed the usability of the planning and decision-support tool and provided open-ended feedback on the tool from the experts following the interviews.

3.6 Summary

In summary, this chapter considers at the overarching research philosophy undertaken within this project in relation to the research question, objective and outlines the research outputs. The research methodology adopted by the researcher for this project is a multi-disciplinary approach which considers both Quantitative and Qualitative research approaches and includes a literature review, and cross impact analysis.

The chapter highlights the pros and cons of a range of detailed research techniques and provides a justification for selecting the research techniques including the use of multi-criteria decision analysis using group ranking techniques (Pairwise comparison) for assigning weightages to the impact factors. The chapter also evaluates the methodology of undertaking Stakeholder Engagement as validation of the tool; using the involvement of technical experts in a structured interview setting, to test the approach, tool user interface and approach to selecting an appropriate sample for validation.

The validation exercise was completed with three case-studies used a panel of experts to allow the researcher to demonstrate the full usability of the tool as well as its robustness. Further the validation confirmed the usability of the planning and decision-support tool and provided open-ended feedback on the tool from the experts following the interviews.

4 Detailed Tool Design and Development

4.1 Introduction

This chapter discusses the design and development stage of the risk assessment tool. As such it provides a detailed description of Design Phases 1, 2 and 3 (Section 4.2 to 4.4 respectively), and highlights the various iterative process undertaken throughout.

The primary result of the risk-based approach presented within this thesis will be the ability to make informed programming decisions, using a scoring method which has been developed using an understanding of the critical factors that impact condition and the rate of deterioration along with the associated long-term risk posed by the UKCIP 09 climate change scenarios. Consideration may also be given to the potential cost implications for the work to be undertaken by the asset owner/managing organisation. The approach will also give guidance to the management of future changes in environment and asset condition change.

4.2 Design Stage 1 - Critical Factors affecting failure, determining the Impacting Factors

To achieve an accurate representation of how a geotechnical asset will deteriorate, the impact factors which affect the failure mechanisms associated with geotechnical assets must be considered. The Impact factors in the context of a given geotechnical asset are those which affect the performance, serviceability, stability, or safety of the asset. **Error! Reference source not found.** shows the main categories of critical impacts determined by the literature review and provides a descriptive summary and lists the key elements that describes that risk factor.

Table 17 - Critical Impacts affecting geotechnical asset deterioration

Critical Impact	Impact Elements	Descriptor
Geology, Topography and Ground Conditions	Geology • Geological Features • Made ground/fill • Drift deposits • Soil ground conditions Topography • Slope geometry (angle, height or length) • Proximity to other assets • Vegetation Soil Parameters • Soil strengths and mechanics (Stress, Young's modulus, Cohesive properties, friction angle • Soil Physical properties (void spaces, propensity for shrink/swell behaviour, incorporation of organic material)	Describes the physical conditions of the asset, geometry, underlying material and composition. It does not include Hydrology features or movement of groundwater.
Interaction between assets	Pavement Structures Drainage	Describes the interaction with and impact or other asset in the proximity
Environmental Impacts	Effects of Climate Change • Temperature • Precipitation • Flood Events • Drought Events Vegetation cover and animal burrowing • Vegetation type (ground cover, shrubs, trees) • Small animal burrowing causing undermining of the structure	Describes the external environmental factors which can impact the overall stability and structural integrity of the asset

Asset History	Age History of asset Construction Design Planning Maintenance Whole Life Costing	The history of the asset details nots only the initial design and construction information, but also subsequent maintenance and remedial works requirements, as well as inspection history and may also include records detailing network changes and/or long-term resilience issues, such as seasonal changes to traffic flows, major flooding events or asset collision history.
Hydrogeology and Groundwater movement	The impact of groundwater and changes to levels Effects on pore water pressure Presence of Aquifers/The drainage catchment	Describes the conditions, movement and levels of groundwater
	Seasonal changes (see effects on climate change)	

The use of these factors, along with their associated deterioration profiles, is commonplace within modelling tools used to provide decision support. Some modelling tools use extrapolation techniques, taking a very small amount of data (as little as 3% of known condition data) to produce a deterioration model that will aid decision making with respect to maintenance funding. However, questions remain as to the ‘certainty’ of these predictions; i.e., can a holistic and thorough analysis of the data provide any further evidence for directed funding? For example, following the multi-factor and time-sensitive analysis indicated by Leroueil (2001), if ground and surface water has an impact on the stability of the geotechnical asset, it would be logical to improve the condition of the drainage as a priority. With the impacts thus mitigated, other maintenance or repairs can be carried out as necessary. This multi-factor understanding of asset behaviour, interaction, and performance will preserve the integrity of the asset by tackling root cause problems and will result in lower maintenance costs over it's working life. Potentially higher initial costs will result in reduced long-term spend and result in a more resilient and long-lasting asset.

In the short term, many of the critical impacts only cause small-scale failures (Clayton, 2003), where the performance of the asset is limited (Serviceability Limit State failure), as opposed to catastrophic failures which impact on the long–term network availability and endanger the safety of users (Ultimate Limit State failure). In fact, in the UK, very few embankment failures lead to a catastrophic failure resulting in flow disruption at large scale (Perry et al 2003). Critical failure impacts, and more detail on how they can affect slopes and embankments are described in detail below.

4.2.1 Geology, Topography and Ground Conditions

Work by both Dijkstra and Dixon (2010) and Perry et al., (1995), asserts that the deformation of a slope is dependent on a series of inter-related elements which can be broadly grouped together into site conditions (both topography of the site and base geology), soil properties, the hydrogeology and drainage properties of the site, the type and level of vegetative cover, and wider environmental impacts surrounding the geotechnical asset (including severe weather and climate change). Additionally, Pantelidis (2009) highlights that risk assessments and resulting policies developed in subsequent years have displayed a lack of consideration for the impact that geology, geomorphology and climate change has on geotechnical assets, and often fails to highlight the input triggers that can lead to slope failure. As an example, increased rainfall can result in an increase in groundwater level, resulting in increased in pore water pressures, which in turn reduces the effective stress of the soil and effects the stability of the slope (Craig, 2004). Further, Ridley et al. (2004) states that a key aspect in determining the condition of a geotechnical asset is pore water pressure, and the impact that relative changes can have on a particular asset.

Slope topography has been shown to play a significant role in the movement of groundwater through a geotechnical asset. Anderson and Kneale (1982) assert that the movement of water through the asset can be better understood by comprehending the interaction of soil moisture and slope geometry (both slope height and angle). catchment properties of the area surrounding the asset.

4.2.2 Interaction between Assets

Failure of a supporting or adjacent geotechnical asset can have a critical impact on surrounding infrastructure. Bernhard et al., (2003) asserts that geotechnical assets are often, arguably incorrectly, considered mainly as supporting assets interacting with a primary asset, such as pavements, bridges, or drainage. In the researcher's experience, many asset-owning organisations (particularly smaller organisations) do not have specific KPIs, objectives, or goals with respect to maintaining their geotechnical assets, and any remediation or maintenance arises in response to the needs of the primary assets listed above. Even in organisations with dedicated geotechnical resources and extensive geotechnically complex holdings such as Network Rail, large slopes are subject to localised interventions to preserve the short-term operation of the network without considering a long-term remediation strategy. In these instances, the classification of the geotechnical asset as a supporting feature is not necessarily incorrect *per se* – the key performance indicator of NR or a local authority infrastructure team in Scotland or Wales is the performance of the road and rail traffic, not well-maintained embankments. As maintenance on the primary asset is cheaper in the short term than even localized geotechnical intervention (Clayton, 2000), the result is often short-term repeat maintenance cycles on the primary asset rather than root cause remediation.

An inverse relationship, where lack of maintenance on a primary asset has secondary implications, is also true- particularly in the context of drainage, and in connected geotechnical assets. Slope failures can cause failure or movement of nearby retaining structures, and as discussed improper or poorly maintained drainage can cause changes to the soil moisture content or pore water pressure that can lead to catastrophic failure of the asset.

Where these complex interactions affect assets such as bridges, remediation costs and loss of service can present an expensive and embarrassing problem for the responsible body (Clayton, 2000), even where safety is not directly impacted (i.e., a serviceability state failure). Where safety is impacted, failures may be catastrophic. As acknowledged, whilst catastrophic failure is relatively rare in the UK (Perry et al., 2003), inefficient repeat interventions are frequently the norm. Geotechnical asset management techniques should be designed to provide an integrated approach and promote interactions with other assets as a progressive step in development of such systems.

4.2.3 Climate

The effects of climate (and particularly climate change) on infrastructure-heavy networks has gathered significant attention and funding as an area of research in recent years. Inclement or severe weather events can have wide reaching effects, which can be inconsistent across a network depending on local geography and supporting infrastructure. Historically, geotechnical assets have been designed with a minimum design life of 120 years; this lifespan, however, anticipates minimal change in the climate and only very limited exposure to severe weather events (Clarke et al., 2010).

The link between climate and slope deterioration can be summed up by Bromhead, Hopper & Ibsen, (1998). They identify the climate factors considered important for the activation of geotechnical asset failure, including landslide movement as "…annual temperature ranges, seasonal variability, intensity and duration of precipitation and the changeable nature of the climate over the decades". It is therefore important to consider how the asset deteriorates and map these factors into the future climate scenarios.

Climate change is a concern, as many existing assets were designed to accommodate historic weather patterns that may not hold in future. Shah 2016 suggests that should the effects of climate change element not be considered, the result may manifest as increased maintenance costs, contractual liabilities, and a lack of robustly operating infrastructure. Shah also highlights the damage to the reputation of transportation network owners, managers, and stakeholders when service interruptions or budget overruns are caused by what the public perceives as 'inclement weather'. This argument is supported by several further authors, including Wilks (2010) who suggests that UK transportation networks will be directly affected by changing climate. The author goes on to suggest that these risks may be mitigated by forecasting the behaviour of slopes subjected to climate change conditions, and the output of these forecasts used to develop of more suitable maintenance and asset management
strategies.

In Clarke et al., (2006) there is reference to Perry et al. (2003) which estimates that the impact of climate change may mean that slopes on the UK Strategic Road Network are, at minimum, three times more likely to fail if no preventative action is undertaken. Clarke also highlights the need for concern linked to the long-term stability of the slopes which, because of changes to seasonal weather patterns and increased frequency of extreme weather events, are subject to changes in water content and temperature that are beyond their designed parameters. The resulting effect of these changes is an increase in total soil stress, and therefore a reduction in overall slope stability. Further information on the impacts and effects of climate change can be found in chapter 2.

4.2.4 The Impacts of Groundwater Level

As discussed earlier in this chapter, it is understood that groundwater and drainage is often the most critical factor to consider when measuring deterioration of geotechnical assets to failure.

In its most simple form, groundwater levels fluctuate when the recharge-discharge equilibrium becomes unbalanced, e.g. a rise in water table will occur when the recharge is greater than discharge and vice versa (Hillel, 1982). Recharge can occur in the form of precipitation and by through flow (seepage) caused by a hydraulic gradient. It is also possible for leaking pipes and mass water retaining structures to recharge the local water table (Varnes, 1978). Discharge of a water table occurs through drainage and evapotranspiration.

Evapotranspiration is a process whereby moisture is lost from the soil due to evaporation and transpiration of plant. Wells and dewatering schemes are a form of water extraction carried out by humans which also has the effect of discharging water from the ground.

4.2.4.1 Groundwater Fluctuations

The impact that ground water fluctuations can have on the stability of a geotechnical asset is challenging to ascertain. Groundwater fluctuations can occur as the result of a number of different impacts on the asset including:

- Flooding events
- Damaged/Blocked or Inadequate Drainage
- Drought
- Excessive Rainfall
- Frost/Thaw Processes
- Seasonal Fluctuations

Groundwater fluctuations can occur as the result of excess water physically entering the asset through the soil, or surface cracks or by capillary action. The fluctuations may alter the soil moisture content of the geotechnical asset or the underlying geology on which the asset sits. Essentially, changes in the soil moisture content change the fundamental strength properties within the soil. Increases or decreases in soil moisture content as the result of changes in pore water pressure will affect the overall stress experienced by the asset.

The resultant change in effective stress because of change in moisture content can cause significant alterations to the way in which the asset handles the loading and stresses place upon it. This may, in turn, bring about the failure of the asset. Additionally, there may be physical weathering effects as the result of water flows or run-off which may occur as the result of groundwater fluctuations.

Conversely, during times of drought, the asset may be exposure to drier period when the soil can dry out and crack. This desiccation can be further compounded by the withering of vegetation during the drought period. The cracks caused during periods of drought, if significant enough, may lead to shallow failures of the asset, or may aid the influx of water into the asset during wetter periods.

4.2.4.2 The Groundwater System

Groundwater is dynamic and reacts to the seasonal variations of precipitation and evapotranspiration and is intrinsically linked to the drainage conditions associated with it. Long-term groundwater levels are measured using standpipes and piezometers, where the depth at which the water stands in the borehole is defined as the groundwater level. Above the water is a zone where water is subjected to a form of suction known as capillary rise; water is drawn up by negative pore water pressures caused by the capillary action between soil particles and surface tension of the water. The soil below the water table, by definition, is fully saturated and the soil above the water table is partially saturated. Understanding the geotechnical relationships with groundwater is key to the understanding the importance of groundwater fluctuations as a critical factor in long-term deterioration.

The geotechnical properties of soils have a corresponding influence on groundwater movements. Soil is a three-phase material, i.e. made up of solid, liquid and air. Connected voids of varying sizes provide the pathway for water to flow through the material. Factors such as permeability, porosity and degree of saturation are the most significant properties and are described below.

4.2.4.3 Porosity

Porosity is defined as the ratio of the volume of voids to the total volume of soil (Craig, 2004). By the definition of a three-phase material, the voids will contain air and/or water depending on the level of saturation. In fully saturated soils the voids are filled with water, whereas in unsaturated soils the void spaces are full of air. The porosity of a soil changes with rate consolidation. Unconsolidated soils have higher porosities compared to consolidated soils. The process of consolidation removes the air and water from the soil and therefore decreases the void space. A result of decreasing the void spaces is the increase of effective stress because the pore water pressures are increased. The potential water storage capacity is dependent on the porosity of the soil. As mentioned, the volume of voids is related to porosity whereby a high porosity indicates large volumes of voids. Precipitation recharging the groundwater will fill the empty void spaces. Water percolating through the soil to the water table will raise the water level by occupying the empty void spaces from the original water level upwards.

When a unit volume of rain is added to the system the water level will rise proportionally. The smaller the volume of free void space, the higher the rise in water will be. Conversely, if the volume of free void space is large, then the rise in water level is low. This is also true for the removal of water from the system. Through the process of evapotranspiration, water leaves the system resulting in a lowering of the water table. The removal of a unit volume of moisture would reduce the water level more in a low porosity soil than a high porosity soil. Water must be able to move through the soil to have an effect on the water table. If the water cannot enter the soil, then recharge will not occur. The resistivity of soil to the flow of water is known as permeability and is described below.

4.2.4.4 Permeability

The coefficient of permeability measures the rate at which water can flow through a soil. It is determined by the particle size and homogeneity of the soil. Soils such as sands and gravels have high values of permeability whereas silts and clays have lower permeabilities. Therefore, water can flow through sands faster than clays. Fissures and cavities in the soil and rock caused by over-consolidation and weathering also increase the permeability of the soil. Contrary to some of the other factors listed here, permeability can be directly measured for an asset in a number of ways – allowing for more effective management within the asset. A soil of low permeability can be tested using Falling Head Tests, where a specified volume of water is poured into a trench of known dimensions. As the water level falls, the time taken for the water to reach 'x' number of levels is recorded and placed into the relevant equation. Where the soil is highly permeable soils, the test used is the Constant Head Test, where water is pumped into hole at a constant pressure head with the rate and amount of water level rise recorded. The impact of the soil permeability is the influence the flow of water through the system, for example in areas of drainage and percolation, and the infiltration capacity.

4.2.4.5 Degree of Saturation

The degree of saturation denotes the ratio of volume of water to volume of voids, i.e. identifies the amount of water and air in the soil voids (Craig, 2004). In fully saturated soils the degree of saturation is 100 %, whereas in totally dry soils with no water in them the degree of saturation is 0 %.

4.2.4.6 Hydrogeological Modelling

Slope hydrology analyses the distribution of rainfall between overland flow and subsurface flow as it passes through vegetation and soil (Kirkby, 1988). It is often complex due to variations in soil permeability and topography which change the flow potentials of the soil. A number of factors of slope hydrology are described below to clarify the reasons for changes in ground water level.

4.2.4.7 Surface Run-off

Surface run-off is the loss of precipitation to infiltration due to soil permeability, surface vegetation cover and slope angle. It is therefore a significant factor to consider with regard to a hydrological model. Surface run-off and rainfall are directly related (Small, 1989). The ability and/or capacity of the soil to absorb water is a vital component of surface run-off and is determined by a number of factors. The degree of saturation is important to the allowable capacity because it dictates the maximum volume of water, at a specific time that can be absorbed into the soil. In the winter months the degree of saturation is higher because of the great amounts of rain accumulated. This results in progressively lower absorption rates through the winter months. Conversely, in the summer the degree of saturation is lower as a result of the low rainfall volumes and the significant effect of evapotranspiration. This results in a higher capacity of absorption.

The actual volume of water the soil can absorb depends of the rate of precipitation and the permeability of the soil. If the rainfall intensity is lower than the rate of permeability, then the absorption capacity can be achieved (depending on degree of saturation). However, if the rainfall intensity is greater than the permeability of the soil then surface run-off will occur from the excess rain. The degree of surface vegetation cover and its type have a paradoxical effect on rain run-off and infiltration. On the one hand, a high coverage of ferns and trees will reduce the amount of surface run-off, however, at the same time they reduce the available water for infiltration. The reason for this is that the vegetation, to an extent, will retain some of the rain in its foliage.

4.2.4.8 Flows through soil

Infiltration and drainage are determined by the permeability of the soil, fissuring and the different characteristics of layered soils (Knapp, 1978). Once water has entered into the ground it is caused to flow by a hydraulic gradient, which is the process where water travels from high to low pressure points. The maximum rate that water can travel through a soil is determined by its permeability, however, water does not necessarily travel at this rate, and it is dependent on the pressure head. In slopes the water usually flows downwards due to the head difference. The majority of the water will travel along the easiest line of flow, which is determined by the permeability and fissuring of the different soil layers (Freeze & Cherry, 1979). At the juncture between a soil with moderate permeability overlying a soil of lower permeability, the majority of the water will flow parallel to the moderately permeable layer. This is because it is harder for it to pass through the soil with the lower permeability than the moderately permeable soil. On the other hand, where a soil of low permeability overlies a soil of high permeability, the water will tend to flow into the lower layer, as a result of suction action.

As described in the previous subsection, the water storage capacity of soils is governed by degree of saturation. This property also has an important relationship with flow through soil because it moderates the height of the water table. A large storage capacity at a specified degree of saturation will indicate a low water table and a small storage capacity at the same degree of saturation will indicate a high-water table (close to the surface).

The expected rise in ground water levels due to the increase in winter precipitation and frequency unexpected extreme weather events as the result of climate change could cause an increase in the number and magnitude of asset failures in the UK. Work currently ongoing being undertaken to model the relationships between geotechnical assets, groundwater, vegetation cover and climate change are ongoing as part of the BIONIC programmes (Hughes, 2009).

4.2.5 Vegetation Cover and Animal Burrowing

Vegetative cover of slopes and embankments can be responsible for both positive and negative effects on the stability of the asset. Some, often low-level (i.e., Shrub) vegetation can provide positive effects such as the reduction of small-scale land slips and soil erosion (Power et al, 2019). Similarly, (Ref) notes that while vegetation improves the aesthetic value of the embankment, choosing vegetation types which have larger water requirements may result in a reduction of soil moisture and therefore a reduction in the stability of the asset. Careful consideration of the choice of vegetation for embankments, and careful maintenance of vegetation in place is paramount.

Negative effects of slope vegetation should also be considered. In the context of the UK rail network, vegetation and obstructed visibility along the line is a major safety concern (and therefore source of costs) for lineside teams. Further, the choice of vegetation type may exacerbate the effects of shrink/swell actions within the soil, and cause instability. With respect to climate, consideration should also be made to the consequences of die-back, leaf fall, and the consequences for drainage management. Environmental and habitat concerns also present a problem with regards the management of vegetated slopes, as well as overgrowth impeding routine geotechnical inspections.

4.2.6 Age and History of asset construction, design, planning and maintenance

By grouping the factors of asset age and history together, the researcher can consider impacts of the age of the asset, design, construction (mechanisms and materials) and maintenance history, (Glendinning et al., 2009, Anderson et al., 2012, Loveridge et al., 2012 and Ridley, 2004).

Many of the geotechnical assets situated on the British infrastructure networks are reaching an age where they may face significant requirements for maintenance or remediation. For Highways England, on average geotechnical assets are over 50 years old. For Network Rail, many are exceeding a century. Historically, geotechnical assets were built and maintained using locally sourced materials which were not necessarily of sound quality or performance and would not meet current materials standards. In terms of construction methods, poor control of quality and lack of adequate maintenance often results in serviceability issues related to current geotechnical assets.

Ridley (2004) discusses how many of the older Network Rail assets were designed and built prior to the publication of some of the more fundamental soil mechanics principles and methods that design is currently based upon (Craig, (2004) points out Terzaghi's Principle of Effective Stress, for example). This, in combination with the changes to the condition of construction material and long-term asset deterioration has permanently affected the performance and maintenance capability of the asset.

A 2004 investigation of 49 Geotechnical Assets built of soft ground by Gue and Tan (2006) found that 45% failed largely due to inadequacy of the design and 15% due to poor construction, workmanship and lack of adequate supervision, with the remaining 40% as a combination of both. However, the researcher notes that this unsurprising, given that all the assets were built on soft ground and all had failed; the investigation did not continue to include non-failed assets built on soft ground to understand the extent of poor design in these instances.

However, Gue and Tan go on to make some important points; avoiding asset failure requires careful planning in terms of development control, modelling, design and construction. Construction should be carefully monitored, appraised and undertaken by suitably qualified staff.

For more recent designs and in order to circumnavigate some of these issues, Wilks (2010) maintains that while maintenance, inspection, emergency and other reactive works are necessary and often unavoidable; ensuring a strategic approach to the allocation of resources for proactive planned and preventative measures is equally important and the researcher notes often preferable in terms of both time, reducing returns to site and undertaking work at times where instances of inclement weather are less, and cost, by considering the grouping of maintenance activities to drive efficiencies including reducing traffic management requirements. Conversely, Marr (2001), advocates the advantages a 'data rich approach' using instrumentation and advanced monitoring of geotechnical assets which can forecast condition changes, forthcoming failure and minimises damage to adjacent structures. The author highlights in his 2001 paper that adequate and timely monitoring of assets aids and streamlines the control over construction and operational activities and provides information on selecting appropriate future remedial methods. Beena (2011) stressed that the use and upkeep of an adequate and accurate database of geotechnical assets, along with a programme of adequate inspections, monitoring and instrumentation are essential for the future long-term maintenance of geotechnical assets.

4.2.7 External Changes to Loading

There are several causes for a change in loading of an asset. In order of descending impact:

- **Excavation:** Changes to loading of assets caused by excavation at the toe or the crest of the structure could fundamentally change the profile of the asset, which could lead to instability or failure. The overall stability of the asset may be affected as the result of trenches dug at the extremities of the assets (toe or crest) for the purposes of the installation of underground services or drainage paths. Work undertaken to strengthen pavements for hard shoulder running schemes may have a similar impact.
- **Subsidence:** Subsidence may occur where deformation of the asset foundation has occurred. Other sources for subsidence may be as a result of chemical ground changes, such as the washout of organic material, or the dissolving or materials like chalk or limestone.
- **Construction of New Assets:** The construction of a new geotechnical asset adjacent to an existing asset may impose additional loading to the assets. The result may be a change in drainage, groundwater conditions or the occurrence of settlements. Additionally, movement caused by heavy construction traffic may trigger small instabilities within the asset.
- **Scour:** Scour may affect geotechnical assets sited adjacent to watercourses or drainage outlets.

4.2.8 Impacting factors

Upon reviewing the critical factors listed above and following the structured interviews with industry experts, the researcher used the knowledge and information provided in the literature to expand the geographical, topological and ground conditions critical factor and consolidated the issues outlined by the free flow of water in the vicinity of the asset. This results in the following impacting factors selected for inclusion within the risk assessment tool:

Table 18 - Critical Impacts affecting geotechnical asset deterioration

Impacting reference Factor	Impacting Factor	Comments
IF1	Groundwater fluctuations	
IF2	Change in Loading Conditions	
IF3	Underlying Geology	
IF4	Geographical Location	
IF5	Age of Asset	
IF6	Inter-network Node Point	
IF7	Vegetation	
IF8	Construction Materials	
IF9	Maintenance History	
IF10	External Weathering	
IF11	Geotechnical Hazard Event	
IF12	Collision Trauma History Requiring Maintenance within the last 5 years? (Or Since last Principle Inspection?)	Discounted in second iteration of the project as the result of industry expert feedback.

4.3 Design Stage 2 – Building the Risk Assessment Tool

Design stage 2 focuses on developing both the data collection elements of the risk assessment and the toolkit itself. This stage with focus on establishing and quantifying the relationship between the Impacting factors to develop a hierarchy of weightings that can be applied to assets subjected to the assessment.

4.3.1 Assessing risk – building the framework

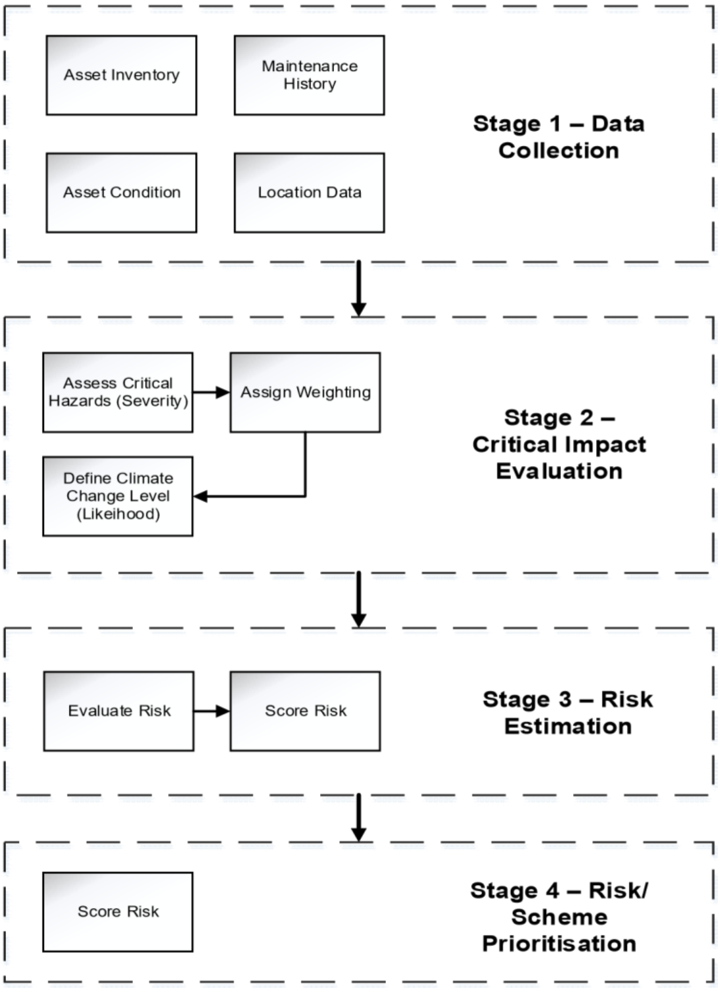


Figure 18 - Stage Methodology Approach for the toolkit

The first stage of the framework is a definition of general asset information to include information on the asset inventory, condition and history, including any proposed changes or maintenance which will significantly impact the geometry, stability or durability of the asset.

The second stage will evaluate the critical hazards and failure mechanisms for geotechnical assets, which will inform the overall severity/consequence score for the asset.

The third and major stage of the framework is the estimation of risk, based on the critical factors associated with geotechnical asset deterioration (consequence) and the UKCIP09 Projections (likelihood). The result of this estimation will improve understanding of the long-term impact of climate change to Geotechnical Assets and provide a tool which can evaluate the current and future risk of failure as the direct result of the changes brought about at the result of climate change. A simple risk matrix, based on qualitative assessments of likelihood and consequence, is suggested as a way to evaluate a potential risk without measurement. The consequence level is a combined consequence rating based on a weighting of all of the main critical deterioration factors.

The evaluated risk will indicate which of three main groups the asset falls into.

- Red or essential or high risk, are those with an imminent or very high risk of deterioration due to climate change actions, these assets require immediate and significant attention;
- Amber or high to moderate risk for those requiring some action, which could include immediate maintenance or increased monitoring,
- Green or low priority where no action is required, but regular monitoring and updated scored advised.

For those geotechnical assets in the moderate to high risk category, which may require some moderate maintenance, the decision should be optimised on the basis of engineering judgement; to include an understanding of the network position (is it a cross authority node point? Or a high usage area?). The output of the risk evaluation stage is a programme for potential projects, which have an associated score and risk characterisation for use within decision support/value management processes.

The final output, Figure 19 from the risk assessment is a scored evaluation of the risk which can be applied to the table below. This score is the basis for a framework that acts as a clear route to prioritising decisions about renewals and interventions, with a clear communication of the risks as the reason for making the decisions, as well as the residual risks where a decision not to intervene is made.

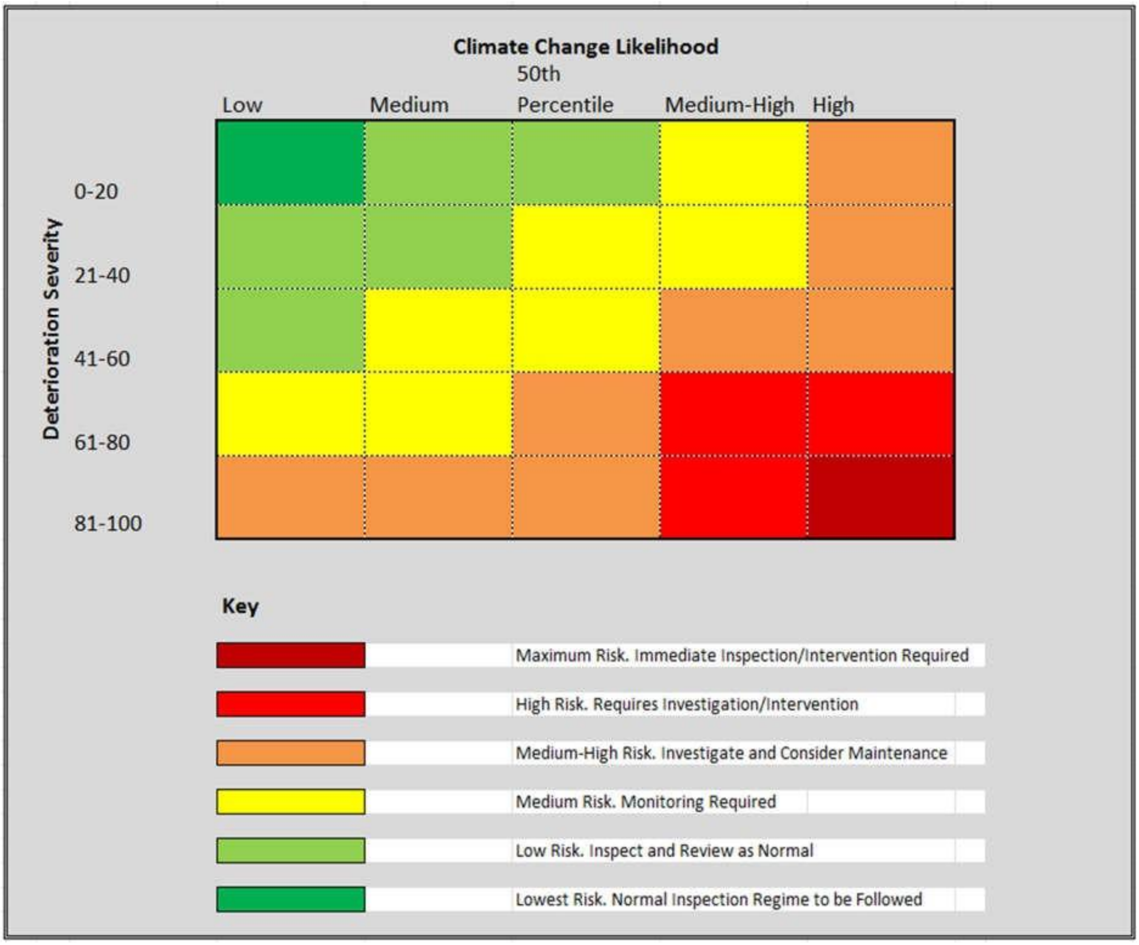


Figure 19 - Risk Matrix Outcome

4.3.2 Assessing risk – critical deterioration factors

4.3.2.1 Use of pairwise comparison for assigning weightages for Impacting factors

As discussed in the previous section, there are numerous techniques available for group ranking or voting in a multiple criteria analysis process. For this research, the pairwise comparison discussed in section 3.5.5.4 was chosen technique to assess the impacting factors and determine an associated hierarchy for them and the weightages required within the tool. The rankings were first established by the user and then again as a subsequent task during the structured interviews held with industry experts. The industry stakeholders assign the ranking in a group participation method. The detailed methodology of undertaking a pair wise comparison process is explained in this section with an example. The selection of the pairwise comparison technique was as the result of a review of methods available. It offers the user a 'one-to-one match' against two factors and provides a quantitative output to the often-challenging comparison of 'this or that'. Each pair of alternatives are compared against the question, in this case 'which impacting factor will be most affected by climate change?'. The 'more popular' of the two is selected by the user and is awarded a point, where the factors are tied, both options are awarded a 0.5 score. This is a further benefit provided by the pairwise comparison technique, unlike some other group ranking techniques which supply a binary output, the pairwise allows for the instance of a tie to be considered and incorporated.

4.3.2.2 Methodology of undertaking pairwise comparison

The methodology comprises of the 5-stage process to setting up the pairwise comparison chart for each of the industry stakeholders. Each participant then completed the pairwise comparison and them these were collated by the researcher and provided for feedback. This approach was used to ascertain the hierarchy of impacting factors that can affect a geotechnical asset when considered with climate change. The pairwise was used to obtain the weightages for the impacting factors used in the case studies and embedded into the risk assessment tool.

Step 1: Identify the alternatives to be ranked.

For this research, these are the impacting factors outlined in the section above, Groundwater fluctuations, Change in Loading Conditions, Underlying Geology, Geographical Location, Age of Asset, Inter-network Node Point, Vegetation, Construction Material, Maintenance History, External Weathering, Geotechnical Hazard Event and Collision Trauma History Requiring Maintenance within the last 5 years? (Or Since last Principle Inspection?) (see table 4.3) which are to be weighed by the first pass, subsets of factors that sit below these were then reviewed, for example, Flooding Event, Damaged/Blocked/Inadequate Drainage, Drought, Excessive Rainfall, Frost/Thaw, and Seasonal Fluctuations were then ranked for groundwater fluctuations. To note, in discussion with industry experts, IF12 was removed from the Pairwise as feedback provided removed this factor from the scoring, as it was felt that collision damage was likely to be much smaller in the scale of impact and less likely to be affected by long-term climate change.

Table 19 - Impacting Factor Distribution

Impacting Factor reference	Impacting Factor
IF1	Groundwater fluctuations
IF2	Change in Loading Conditions
IF3	Underlying Geology
IF4	Geographical Location
IF5	Age of Asset
IF6	Inter-network Node Point
IF7	Vegetation
IF8	Construction Materials
IF9	Maintenance History
IF10	External Weathering
IF11	Geotechnical Hazard Event

IF12	Collision Trauma History Requiring Maintenance within the last 5 years? (Or Since last Principal Inspection?)

Step 2: Set up the pairwise comparison matrix.

This includes impacting factors (IF1 to IF11) populated as columns and rows. In this instance, there will be a 11x11 matrix i.e. 11 rows and 11 columns of impacting factors will be reviewed (See **Error! Reference source not found.**. To note, there are a number of additional surplus cells that can be discounted or blanked. For example, cell pair IF1 versus IF2 will contain the same result as the cell representing IF2 versus IF1. The remaining cells forms one triangle of the matrix where the voter is able to populate the results from ranking individual pair of alternatives.

Table 20 - Pairwise Comparison Matrix

	IF1	IF2	IF3	IF4	IF51	IF6	IF7	IF8	IF9	IF10	IF11
IF1	-	1 vs 2	1 vs 3	1 vs 4	1 vs 5	1 vs 6	1 vs 7	1 vs 8	1 vs 9	1 vs 10	1 vs 11
IF2	-	-	2 vs 3	2 vs 4	2 vs 5	2 vs 6	2 vs 7	2 vs 8	2 vs 9	2 vs 10	2 vs 11
IF3	-	-	-	3 vs 4	3 vs 5	3 vs 6	3 vs 7	3 vs 8	3 vs 9	3 vs 10	3 vs 11
IF4	-	-	-	-	4 vs 5	4 vs 6	4 vs 7	4 vs 8	4 vs 9	4 vs 10	4 vs 11
IF5	-	-	-	-	-	5 vs 6	5 vs 7	5 vs 8	5 vs 9	5 vs 10	5 vs 11
IF6	-	-	-	-	-	-	6 vs 7	6 vs 8	6 vs 9	6 vs 10	6 vs 11
IF7	-	-	-	-	-	-	-	7 vs 8	7 vs 9	7 vs 10	7 vs 11
IF8	-	-	-	-	-	-	-	-	8 vs 9	8 vs 10	8 vs 11
IF9	-	-	-	-	-	-	-	-	-	9 vs 10	9 vs 11
IF10	-	-	-	-	-	-	-	-	-	-	10 vs 11
IF11	-	-	-	-	-	-	-	-	-	-	-

Step 3: Compare Pairs of Impacting Factors (IF) using the pairwise matrix.

For example: The voter can compare IF1 and IF2. Based on which is a more important impacting factor when considering geotechnical asset stability, the result of this comparison is populated in the cell marked IF1 vs IF2. Similarly, the voters can populate the remaining cells in the matrix. The result will appear as per **Error! Reference source not found.**.

Table 21 - Pair wise comparison matrix with voter results (example)

	IF1	IF2	IF3	IF4	IF51	IF6	IF7	IF8	IF9	IF10	IF11
IF1	-	1	1	1	1	1	1	1	1	1	1
IF2	-	-	2	2	2	2	2	2	2	2	2
IF3	-	-	-	3	3	3	3	3	3	3	11
IF4	-	-	-	-	4	4	4	4	4	4	11
IF5	-	-	-	-	-	5	5	5	5	5	11
IF6	-	-	-	-	-	-	6	6	6	6	11
IF7	-	-	-	-	-	-	-	7	7	7	11
IF8	-	-	-	-	-	-	-	-	tie	8	11
IF9	-	-	-	-	-	-	-	-	-	9	11
IF10	-	-	-	-	-	-	-	-	-	-	11
IF11	-	-	-	-	-	-	-	-	-	-	-

The output of this exercise shows that by comparing IF1 and IF2 the voter has ranked IF1 over IF2, therefore giving IF1 a score of 1. Similarly, this voter has ranked IF8 and IF9 as a tie, allowing each factor to score 0.5.

Step 4: Creating the ranking for future conditions

The next stage was to tabulate the number of points added to impacting factor conditions by the voter. Where an impacting factor is found to 'win' the condition is scored with a rank of 1, for every tie, the future conditions are awarded 0.5. The sum of scores should be the same as the number of cells in the matrix. For the example used **Error! Reference source not found.** provides the ranking of future conditions.

Table 22 - Ranking of Future Conditions

Impacting factor	Ranks
IF1	11
IF2	10
IF3	8
IF4	7
IF5	6
IF6	5
IF7	4
IF8	2.5
IF9	1.5
IF10	1
IF11	8

These results show that IF1 is highest rank, followed by IF2, followed by a tie between IF3 and IF11 and finally lowest ranked future condition is IF10. This is the extent of implementing pair wise comparison technique. However, for the purpose of the research, the rankings were converted into weightages (%) which is explained below in equation 1. The weightages are scored out of 100 and it follows the qualitative ranking above.

100 = 11x+10x+8x+7x+6x+5x+4x+2.5x+1.5x+1x+8x - Equation 1

x = 100/64= 1.5625

Thus, the weightages (rounded to the nearest whole number) are as shown in **Error! Reference source not found.** for this voter.

Table 23 - Weightages for future conditions

Future Conditions	Provisional Weightage
IF1	17
IF2	16
IF3	13
IF4	11
IF5	9
IF6	8
IF7	6
IF8	4
IF9	2
IF10	2
IF11	13
Total	100

In this instance we have 8 stakeholders to undertake the pairwise and calculate their weightings, so the exercise is repeated for each stakeholder and, then we repeat the above exercise 8 times and group the rankings as shown in figure 4.7. The final result can be shown in figure 4.7 as follows:

Table 24 - Summary of Ranking

Stakeholder	1	2	3	4	5	6	7	8
Number of Votes	1	1	1	1	1	1	1	1
First	IF1	IF1	IF1	IF1	IF1	IF1	IF1	IF1
Second	IF2	IF2	IF2	IF2	IF2	IF2	IF2	IF2
Third	IF3	IF3	IF3	IF3	IF3	IF3	IF3	IF3
Fourth	IF11	IF4	IF4	IF4	IF4	IF4	IF4	IF4
Fifth	IF4	IF5	IF5	IF5	IF5	IF5	IF5	IF5
Sixth	IF5	IF6	IF6	IF6	IF6	IF6	IF6	IF6
Seventh	IF6	IF7	IF7	IF7	IF7	IF7	IF7	IF7
Eighth	IF7	IF8	IF8	IF8	IF8	IF8	IF8	IF8
Ninth	IF8	IF9	IF9	IF9	IF9	IF9	IF9	IF9
Tenth	IF9	IF8	IF8	IF8	IF8	IF8	IF8	IF8
Eleventh	IF8	IF11	IF11	IF11	IF11	IF11	IF11	IF11

The **Error! Reference source not found.** shows that across all 8 stakeholders have selected IF1 as the most important impacting factor as most important giving it first rank followed by IF11 followed by IF2 and IF10 has the lowest rank. There is a small amount of difference between the evaluation by the experts, especially for IF2 and IF11, and IF4 and 5. On comparing each pair of potential impact factor combinations, there will be 55 pairs as shown in Table 20.

Once the ranks have been determined, the researcher was then able to undertake a count for each occurrence where a single Impact factors was deemed to 'win' or 'tie'. This count is then completed is undertaken for all pairs of impacting factors, and the score approach discussed above implemented where each win will score the impacting factor 1 point, and for each tie 0.5 points, we get the following result, shown in Table 25.

Table 25 - Result of pair wise comparison

Condition Number	Total Score	X	Weightages
1	12	1.48148148	18
2	9		13
3	8		12
4	7		10
5	7		10
6	6		9
7	4		6
8	2.5		4
9	2		3
10	1		1
11	9		13
12	0		0

From this exercise, we can say that IF1 is the highest-ranking future condition, followed by a tie between IF2 and IF11, then IF3, IF4 and IF5 tied, IF6, IF7, IF8, IF9 and then IF10 ranking least.

Using equation 1 these scores can be converted into weightages as seen below:

100=12x+9x+8x+7x+7x+6x+4x+2.5x+2x+1x+9x - Equation 1

x = 1.481481

Thus, weightages are as follows:

- IF1 = 18%
- IF2 = 13%
- IF3 = 12%
- IF4 = 10%
- IF5 = 10%
- IF6 = 9%
- IF7 = 6%
- IF8 = 4%
- IF9 = 3%
- IF10 = 1%
- IF11 = 13%

This technique is used to derive the weightages in use in the 3 case studies discussed in section 5.4. The process of deriving the weightages of both case studies involved substantial discussions amongst stakeholders relating to the project requirements which was effective for arriving at weightages. The final results for both the case studies are in section 5.4 of Chapter 5

Table 26 - Final Risk Tool Weightings

Impact Group	Impact Element	Justification	Element Weighting (within Group)	Element Weighting (within Total)
Groundwater fluctuations	Flooding Event		30	
	Damaged/Blocked/Inadequate Drainage		20	
	Drought		15	
	Excessive Rainfall		15	
	Frost/Thaw		12.5	
	Seasonal Fluctuations		7.5	
Change in Loading Conditions	Additional Material Added at Base or Top of Asset		33	
	Removal of Material at Base or Top of Asset		33	
	Subsidence Causing a Change in Loading Profile		33	

Impact Group	Impact Element	Justification	Element Weighting (within Group)	Element Weighting (within Total)
Underlying Geology	Unknown		25	
	Organic Materials		25	
	Clays		20	
	Silts		15	
	Sands		8	
	Gravels/Boulders/Cobbles		5	
	Weak Rock		2	
	Rock		0	
Geographical Location	Site Previously Flooded (within 10 yrs.)			
	Sited in Flood Plain			
	Critical Node Point			

Impact Group	Impact Element	Justification	Element Weighting (within Group)	Element Weighting (within Total)
	High Traffic Location (≥ 80 mesa)			
Age of Asset	≥70 Years		50	
	70 Yrs. – Max Design Life		35	
	Max Design Life -10 Yrs.		15	
	≤ 10 Years		0	
Inter-network Node Point	Yes		100	
	No		0	
Vegetation	Vegetation Removed		40	
	Grasses		30	
	Low Level Shrub		20	
	Trees		10	

Impact Group	Impact Element	Justification	Element Weighting (within Group)	Element Weighting (within Total)
Construction Materials	Construction Materials Unknown		50	
	Construction Material Known but Non-compliant with Current Design Standards		40	
	Construction Material Known, Materials Compliant with Current Design Standards		10	
Maintenance History	Asset not been Inspected or Maintained within last 5 years		45	
	Asset has been Inspected; no Maintenance required with last 5 years		25	
	Asset has been Inspected; Minor Maintenance required with last 5 years		15	
	Asset has been Inspected; Major Maintenance required with last 5 years		15	
External Weathering	Water Scour		33	

Impact Group	Impact Element	Justification	Element Weighting (within Group)	Element Weighting (within Total)
	Wind Scour		33	
	Chemical Changes to Soil		30	
Collision Trauma History Requiring Maintenance within the last 5 years? (Or Since last Principle Inspection?)	Yes		100	
	No		0	

4.3.3 Assessing risk – using climate change projections

The UKCIP18 Projections can fundamentally be split into four independent scenarios to determine the extent of the effects experience due to the change in the climate patterns by the year 2080.

As stated in chapter 3, the UKCIP average predictions for climate change in the UK are UKCCIP, 2018:

- Temperature:
  - For all scenarios, average annual temperature will rise by between 0.5°C and 3.5°C by 2020, and by a further average of 2.5°C and 3.0°C by 2080.
- Precipitation
  - On average to 2020, Annual rainfall shows little change
  - However, Winter rainfall is predicted to increase by up to 30% by 2080
  - Summer rainfall is predicted to decrease by up to 50% by 2080
- Soil Moisture Content
  - Relatively small predicted changes in annual, winter and spring soil moisture content by 2020
  - Predicted soil moisture content decreases of up to 30% and 50% in summer and autumn respectively by the 2080s
  - Predicted soil moisture content increases of up to 30% and 50% in spring and winter respectively by the 2080s
- Wind speed
  - Possible increase of up to 10% in the winter months
- Snowfall
  - Predicted 60% to 90% decrease by the 2080s

It should also be noted that the probability of Storm conditions and other extreme weather events increases as the effects of climate change increase. This also means that the likelihood of flooding events increases. Additionally, the likelihood of accident damage occurring increases as the result of the hazardous driving conditions associated with extreme weather events.

It should also be noted that there is a geographical pattern to the predictions; the highest change in temperature and average annual rainfall are experienced in the South East region of the UK. The South East also experiences the highest fluctuation range of rainfall in the UK, indicating that the potential for desiccation and cracking in summer, and swelling in winter are likely. The impact of this is increased instability due to the cracking along with increase groundwater and soil moisture content in winter, as the result of increased permeability of the water.

Applying these predictions is subjective; regions in more South-Eastern parts of the UK trend towards experiencing more frequent and more severe weather pattern changes. However, assets which are subjected to multiple flooding events are potential more likely to fail as the result of a climate change related deterioration.

As an initial recommendation the 50th percentile for climate change probability was chosen (Table 27). This scenario uses the median value as a descriptor for the level of climate change experienced by 50% of the geographical area of the UK. This value has within it a series of effects that can be attributed to climate change by 2080, for example, the Median Temperature change will be +4.8ºC on average temperatures experienced in 2008, and the median Precipitation levels change is -25% in Summer and +20% in Winter. Given the potential for the values taken from extreme weather events, this figure appears too high.

Table 27 - Anticipated Climate Change Effects (UKCIP 2018)

Scenario	% Probability	Average Temperature Change (ºC)	Average Summer Precipitation Change (%)	Average Winter Precipitation Change (%)	Summer-Autumn Soil Moisture Content Change (%)	Winter-Spring Soil Moisture Content Change (%)	Average Wind Speed Change (%)	Average Snow fall Change (%)
Low	10	2.5	-10	10	-10/-10	10/10	0	-60
Medium	33	3.8	-18	13	15/19	16/20	-3	-68
Medium-High	67	5.4	-37	26	25/40	24/41	-7	-82
High	90	7.9	-50	30	-30/-50	30/50	-10	-90
50% Percentile	50	4.8	-25	20	-20/-30	20/30	-5	-75

The application is regional and can be considered to follow the broad region network breakdown applied by Highways England. **Error! Reference source not found.** outlines the regional scoring approach

Table 28 - Climate change likelihood scoring

UK Region	HE Area	Climate Change Likelihood Score
London	5	High
South East	3, 4	High
South West	1,2	Medium High
East	6,8	Medium High
West Midlands	9	Medium
East Midlands	7	Medium
North West	10,13	Medium Low
North East	12,14	Medium Low
Scotland	Outside of Highways England Remit	Low
Wales		Medium

4.3.4 The Risk Severity Scorecard

Table 29 - Draft Risk Scorecard

Site Name		
Route		
Highways England Region (if applicable)		
Grid Reference		
Unique Identifier		
Impact Factor	Outcome	Weighted Score

Groundwater Fluctuations	None	0.0
Change in Loading Conditions	No Change	0.0

Underlying Geology	Rock	0.0
Geographical Location	No Special Features	0.0
Age of Asset	1993 - resent	0.0
Inter-network Node Point	No	0.0
Vegetation	Mixed	0.0

Construction Materials	Construction Material Known, Materials Compliant with Current Design Standards Known Slope Angle	0.0
Maintenance History	Asset has been inspected, No defects, No maintenance	0.0
External Weathering	None Visible	0.0
Geotechnical Hazard Event	None	0.0
Collision Trauma History within the last 5 years?	No	0.0

TOTAL SCORE	0.0

The above **Error! Reference source not found.** is a copy of the risk severity scorecard used to record the second stage of the risk assessment methodology. During this stage the factors which are known to have had, or are currently impacting on the condition are scored, dependent on their severity and their place within the hierarchy of critical impacting factors. The user selects the most appropriate options from the dropdown menus presented in the scorecard. The dropdown options are the impacting factors and their sub options. Upon selecting the most appropriate option, the scorecard will auto populate with the weighted score, as defined by the pairwise comparison. In the next section, the researcher will present 3 case studies that demonstrate the approach in use.

4.4 Design Stage 3 – Structured Interviews

This section discusses the structured interview approach used throughout the research project to validate the approach and test the outputs.

The structured Interviews act as a Validation stage that is considered necessary to ensure that the proposed tool both works as designed, i.e. the tool is physically usable, and also that it provides a useful and practical approach for application in industry as a decision support tool. As discussed in Chapter 3, long-term asset management solutions require engagement and buy-in from stakeholders. This research has undertaken validation of the tool with a panel of selected technical experts. Given that the researcher's industry experience lies predominantly in the field of asset management, as opposed to geotechnical engineering, the technical experts were invaluable in providing validation of the impacting factors and their relationships to each other. To validate the decision-support tool developed in this study, the researcher conducted a multi-criteria decision-making exercise with 8 experts from the field of geotechnical asset management, all holding mid to senior level experience. Each of the experts was able to provide insights into the use of the tool, it's limitations, and the use of asset information within it. The technical expert panel consisted of both geotechnical experts, and asset management experts.

During the first set of interviews, the experts were provided with a copy of the tool and the first case study with a set of arbitrary weightages and asked to assess the suitability of the chosen impact criteria. The experts provided feedback about the tool from ease of use and clarity, to the inclusion of the impacting criteria. The data contained within each of the 3 case studies was obtained from HAGDMS, with permission from the client.

The tool was then refined and updated prior to the second case study. During the second interview, the experts were provided with the updated tool and a copy of the Researchers pairwise comparison to prepare the interviewees for the completion of the pairwise.

Following the completion of the pairwise comparison by the experts, the researcher then collated the results to produce a single set of refined weightages for the impacting factors, presented in the third case study.

The validation exercise with three case-studies and involving a panel of experts allowed the researcher to demonstrate the full usability of the tool as well as its robustness. Thus, from the perspective of fulfilling the objective of the validation, the sample can be regarded as adequate.

The validation exercise confirmed the usability of the planning and decision-support tool and provided open-ended feedback on the tool from the experts following the interviews.

5 Research findings and discussion

5.1 Introduction

This chapter explains in detail the working of the ‘Climate Change Risk assessment tool as a four-stage methodology with three real case studies to illustrate its application on real projects. Observations made on the working of the tool, taken from the multi-stage structured interview process, along with discussions of the outputs of toolkit from each of these Case Studies are discussed in detail in Section 5.2.1.

5.2 Research Findings - The 4-Phase Methodology Approach

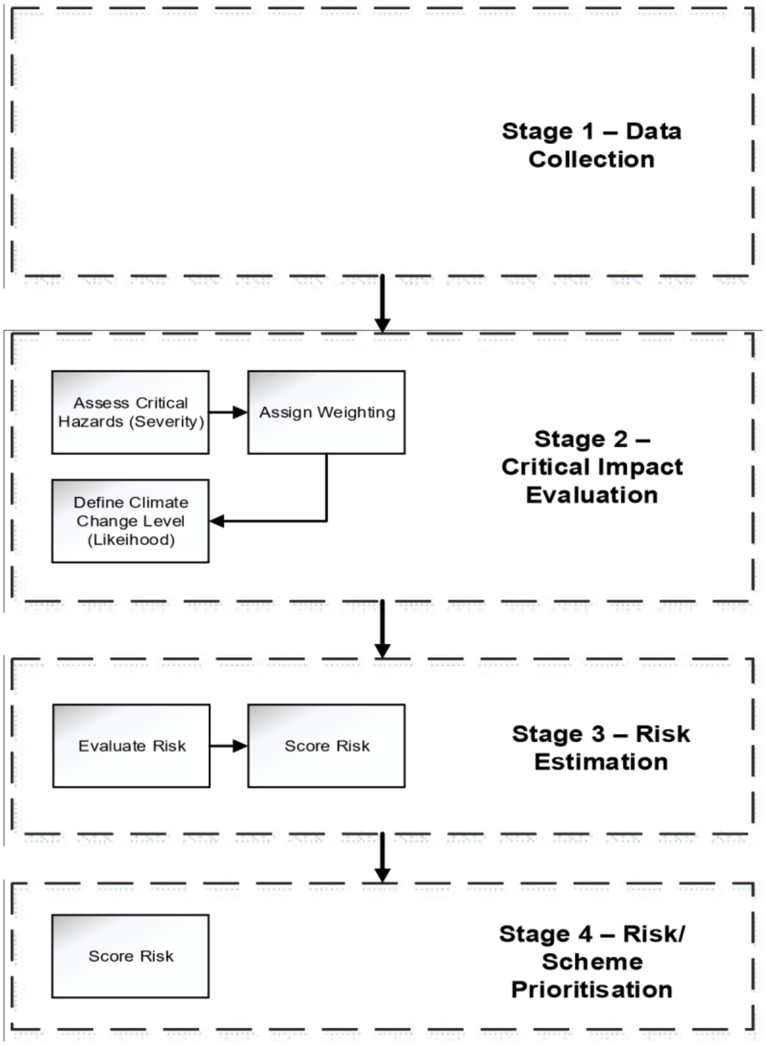


Figure 20 - Index tab in the Climate Change Assessment Tool

Design Stage 1 (Steps 1-3) – Data Collection

This forms the basic data gathering stage of the assessment. As a minimum, any existing geotechnical or asset management scheme where a solution is proposed based on the condition of the existing asset (e.g. an option of remedial actions, long term maintenance repair or replacement) should be assessed for its long-term climate change support criteria. However, it is recommended that this be undertaken for any geotechnical asset, irrelevant of current condition. Since publishing this work, Highways England has begun the development of their approach to measuring short- and long-term asset needs, this approach review a range of conditions level to determine the risk posed to the asset in accordance with the corporate risk criteria, for more information see section X.X.

This step identifies the asset inventory and condition information taken from the most recent inspection data along with any further history and detailed location data which may impact the output of the tool. It must also identify any scheme projects to be undertaken, (e.g. Smart Motorways All-Lane-Running, a road widening scheme, a slope failure remediation scheme).

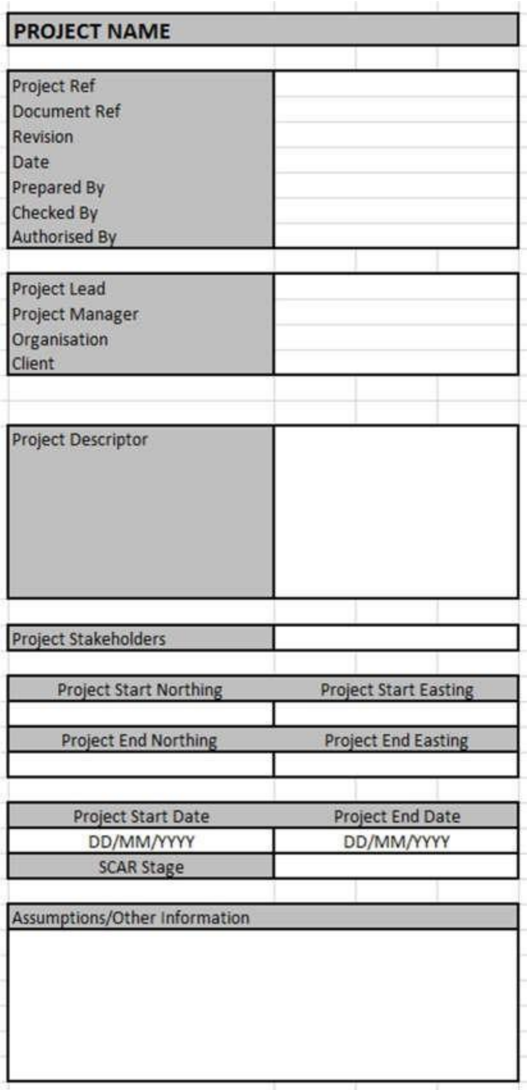
Step 1 – Data Collection

The Stage 1 incorporates 4 Steps of the risk assessment process as seen in Figure X, plus the project information sheet. The first sheet comprises of the index tab shown in figure 5.1 which showcases the overall Climate Change Risk assessment tool with hyperlinks to each stage in the process.

Step 1 - Project Information Sheet

This is an input step, where the user provides details about the asset, scheme/project and stakeholders involved. This step forms the basis of the risk assessment as it provides the base-level of evidence uses to determine if there is a risk posed to the asset by climate change, along with the specific asset features being used to determine the scale of the impact. It includes information such as proposed project start and end dates, assumptions/considerations, information on the type of project, SCAR stage at which the toolkit is applied etc. It is the second tab in the excel workbook (Figure 21).

For example: An asset is part of a proposed SMART motorways scheme. The asset inspection shows deteriorated asset condition requiring remediation. Remediation will be undertaken to improve condition whilst the Smart Motorway Scheme will be completed as part of Highways England's Roads Investment Scheme (RIS) where. strategic parts of network are targeted with improvement budgets to reduce congestion and improve safety, availability and reliability.



PROJECT NAME

Project Ref	
Document Ref	
Revision	
Date	
Prepared By	
Checked By	
Authorised By	

Project Lead	
Project Manager	
Organisation	
Client	

Project Descriptor	

Project Stakeholders	

Project Start Northing	Project Start Easting
Project End Northing	Project End Easting

Project Start Date	Project End Date
DD/MM/YYYY	DD/MM/YYYY
SCAR Stage	

Assumptions/Other Information

Figure 21 - Project information tab

Step 2 – Asset Information – Asset Inventory and Condition

In this step, asset information, both Inventory and Condition data is collated (Figure 22). The information will be gathered from HAGDMS and from additional desk studies and inspections. It is the third tab in the excel workbook.

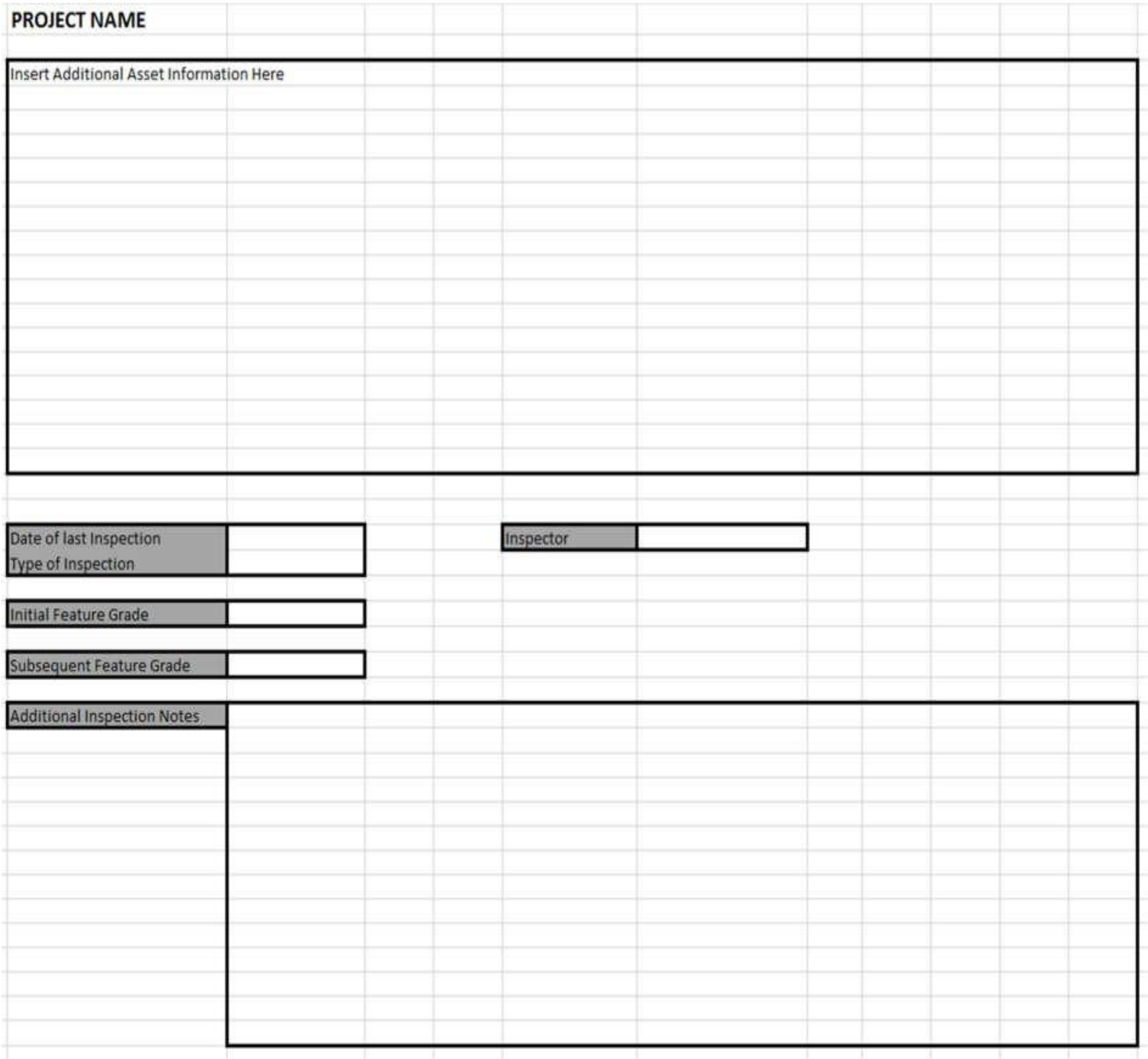


Figure 22 - Asset Information tab

This tab should also be used to record the findings and comments from the most recent visual inspection of the asset. The designer/engineer is then expected to provide the Initial and Subsequent Feature Grade for the asset, taken from the most recent inspection. This will provide an assessment of the current and likely condition of the asset in 5 years' time. The period of 5 years is selected taken from the geotechnical inspection process, as outlined in HD 41/15.

Step 3 – Maintenance History Scheme

In this step the Maintenance and Scheme history and future is collected. The user inputs historic maintenance scheme and future planned works, providing information of the scale, scope, cost and duration of the works, along with information on the scheme action (i.e. Do minimum, Do Something (partial) etc), falling out of a whole life costing or value management exercise undertaken by the user (Figure 23). This toolkit is not a whole-life costing tool for provisional projects, rather it provides a context for the long-term planning opportunities and provides evidence for determining the future impact of climate change on the asset. It is the fourth tab in the excel workbook.

PROJECT NAME

Scheme Ref	
Asset Ref	
Scheme Type	
Scheme Action	
Full Scheme Description	
Geotechnnical Asset Specific	
Duration	
Completion Date	
Cost	
Comments	
Scheme Ref	
Asset Ref	
Scheme Type	
Scheme Action	
Full Scheme Description	
Geotechnnical Asset Specific	
Duration	
Completion Date	
Cost	
Comments	
Scheme Ref	
Asset Ref	
Scheme Type	
Scheme Action	
Full Scheme Description	
Geotechnnical Asset Specific	
Duration	
Completion Date	
Cost	
Comments	

Figure 23 - Maintenance Scheme History tab

STAGE 2 – Critical Impact Evaluation

Step 5 – Assess Critical Hazards – Risk Severity Scorecard tab

This step provides the engineer with a list of impacting factors for selection, based upon the detail provided in the previous steps (Figure 24). The list of impacting factors determines the severity of climate change on the asset by considering the current factors impact in the condition. The impacting factors, as discussed previously, can be determined from as the impact on the asset as a direct result of climate change, but could be considered to effect both the network and the geotechnical assets. This is the sixth tab in the excel workbook.

Impact Factor	Outcome	CASE STUDY 1 Weighted Score	CASE STUDY 2 Weighted Score	CASE STUDY 3 Weighted Score
Groundwater Fluctuations	Damaged/Blocked/Inadequate Drainage	14.0	12.8	15.0
Change In Loading Conditions	No Change	0.0	0.0	0.0
Underlying Geology	Rock	0.0	0.0	0.0
Geographical Location	No Special Features	0.0	0.0	0.0
Age of Asset	1993 - resent	0.0	0.0	0.0
Inter-network Node Point	No	0.0	0.0	0.0
Vegetation	Mixed	0.0	0.0	0.0
Construction Materials	Construction Material Known, Materials Compliant with Current Design Standards Known Slope Angle	0.0	0.0	0.0
Maintenance History	Asset has been inspected, No defects, No maintenance	0.0	0.0	0.0
External Weathering	None Visable	0.0	0.0	0.0
Geotechnical Hazard Event	None	0.0	0.0	0.0
Collision Trauma History within the last 5 years?	No	0.0	0.0	0.0
	TOTAL SCORE	14.0	12.8	15.0

Figure 24 - Risk Severity Scorecard tab

This step assigns a weighing to the Impact factors. The weighting assigned is as a direct output of the pairwise comparison approach undertaken with Interviewees. The impacting factor with the highest weight is y considered the most significant to the asset. The weightages have important influence on the severity of the climate change impact, and as a result the overall risk score; as such, the pairwise outputs were considered, as opposed to use assigned weightages, by both the researcher and as outputs from the structured interviews to be more robust and provide a more reliable result.

The structured interviews provided context and robustness of the weightages. Technical experts in their field, the interviewees provided commentary to the weightings, along with an overview of appropriateness of the weightages assigned by the probabilistic pairwise comparison method. However, it should be noted that this is somewhat controversial, Costello et al., (2011) noted that many of the existing stochastic or deterministic approaches cannot be applied to the lifecycle planning of geotechnical assets, it is simply too challenging to predict future changes in asset behaviour based on past condition issues or asset performance. It was agreed by the structured interviewees that the nature of the tool meant that applied a locked weighting at this stage would prevent any artificial manipulation of the scoring to artificially enhance the risk to achieve a more desirable result.

Step 6 – Application of a climate change prediction score

In this stage the User is asked to provide information on the location of the asset, by region. Each region of the UK is assigned to a climate change likelihood score (Table 30), based upon the Medium emissions scenario provided by the UKCIP18 Climate change prediction models.

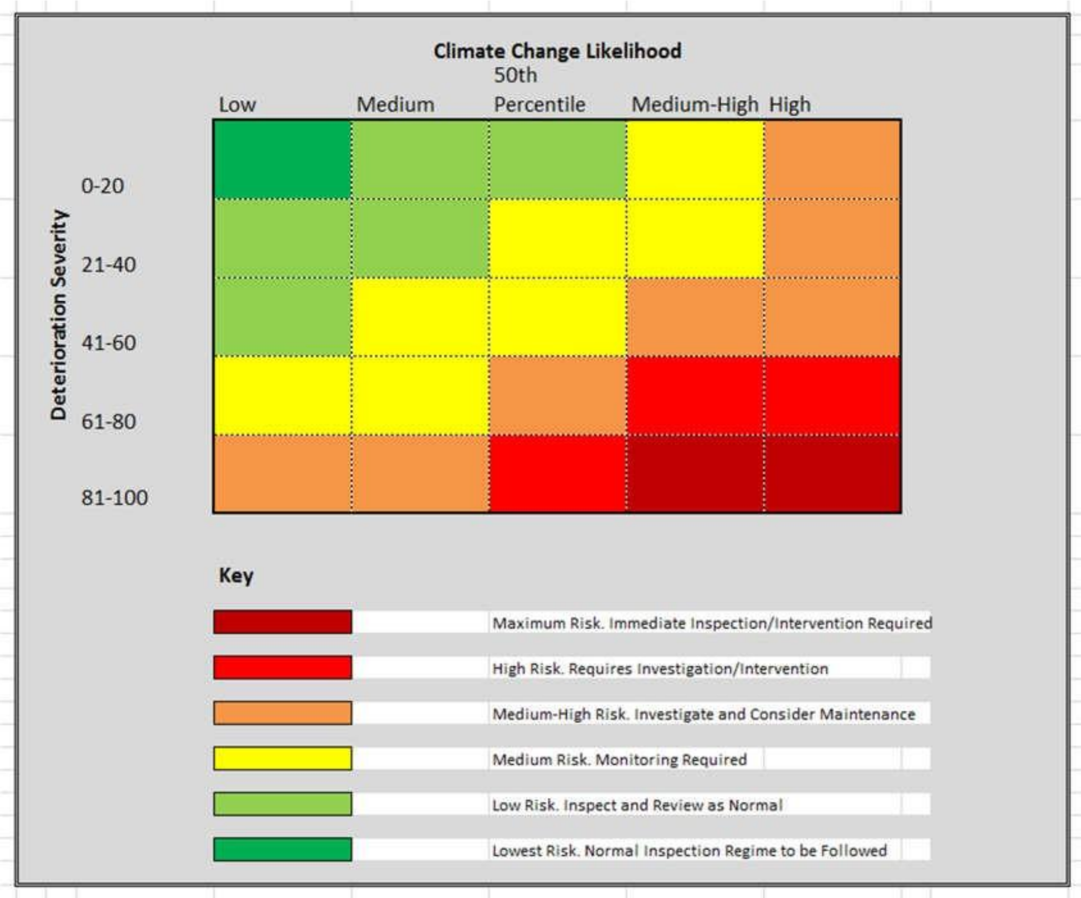
Table 30 - Climate Change Likelihood Scores

Region	Climate Change Likelihood Score
South-East	High

South-West, The East	Medium-High
East Midlands, West Midlands, Wales	Medium (50th Percentile)
North East, North West	Medium-Low
Scotland	Low

STAGE 3 Assign Risk Score

Following the completion of the Risk Severity Scorecard and the climate change likelihood a risk score and category is then calculated and can be displayed on the Risk matrix tab of the workbook.



STAGE 4 Determine Further Action

In light of the implications highlighted from STAGES 2 and 3, an assessment should now be made by the engineer/designer as to the nature of the action result from the completion of the process. Further work is anticipated in the area to address the development of a tool to review this process.

5.2.1 Research findings - Case Studies

This section discusses the case studies used for validating the research and the usability of the risk assessment tool. The data for the 3 case studies considered, was obtained from three live sites in the UK. The sites were chosen at random upon consultation with the Industry experts and the data collected from HAGDMS. The database contains information on all geotechnical assets on the strategic and trunk roads in the UK and is maintained, operated and managed by Highways England. First site is a slope on the Northbound side of M3 at the Junction of the A303. The second site is an embankment on the South side of the M5 at Junction 13 (HAPMS Section ref 1600M5/554). The final study is another embankment on the M1 between junction 36 and 37. These sites are representative of geotechnical assets throughout the UK and they are considered by the researcher to provide an average amount of data through the HAGDMS system.

While validating the tool through structured interviews, the researcher worked with the expert panel members, to arrive at the weightages for the impacting factors, as discussed in section 4.2.

5.2.1.1 *Case Study 1 - M3/A303*

This case study was completed during the first stage of works as a proof of concept design and for use by the researcher as a demonstration tool for use with the industry experts.

5.2.1.1.1 Case Study 1 Introduction

This case study is a slope situated on the Northbound side of the M3 at the junction with the A303. (Figure 25 - Site Plan for Case Study 1, taken from HAGDMSFigure 25)

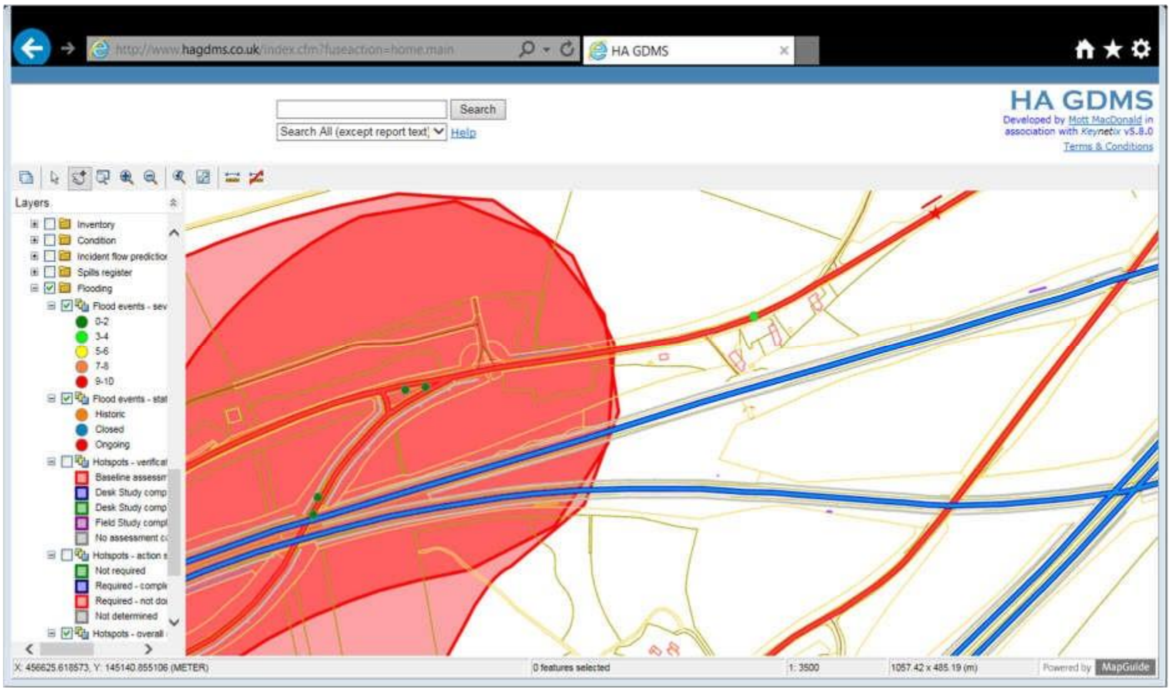


Figure 25 - Site Plan for Case Study 1, taken from HAGDMS

Step 1 – Project Information

The Project Information tab contains the details of the project including the location, scope and deliverables, the stakeholders/Clients involved and project delivery team. Figure 26

PROJECT NAME	M3/A303
Project Ref	JCT M3/A303 Slope
Document Ref	A1
Revision	v1
Date	Oct-16
Prepared By	AC
Checked By	AC
Authorised By	AC
Project Lead	Name
Project Manager	Name
Organisation	Contractor
Client	Highways England
Project Descriptor	NB Slope - Not currently active
Project Stakeholders	AM lead, Geotechnical Enginnering Lead
Project Start Northing	Project Start Easting
455922	145012
Project End Northing	Project End Easting
Project Start Date	Project End Date
Mar-20	Mar-22
SCAR Stage	0
Assumptions/Other Information	

Figure 26 - Project Information Sheet for Case Study 1

Step 2 – Asset Information

The asset information collected and recorded in this step includes information from a preliminary desk study presented here. It includes information on the most recent inspection of the asset and include the Initial and Subsequent Feature grades. See Figure 27 for a snapshot of the Asset Information tab for Case Study 1.

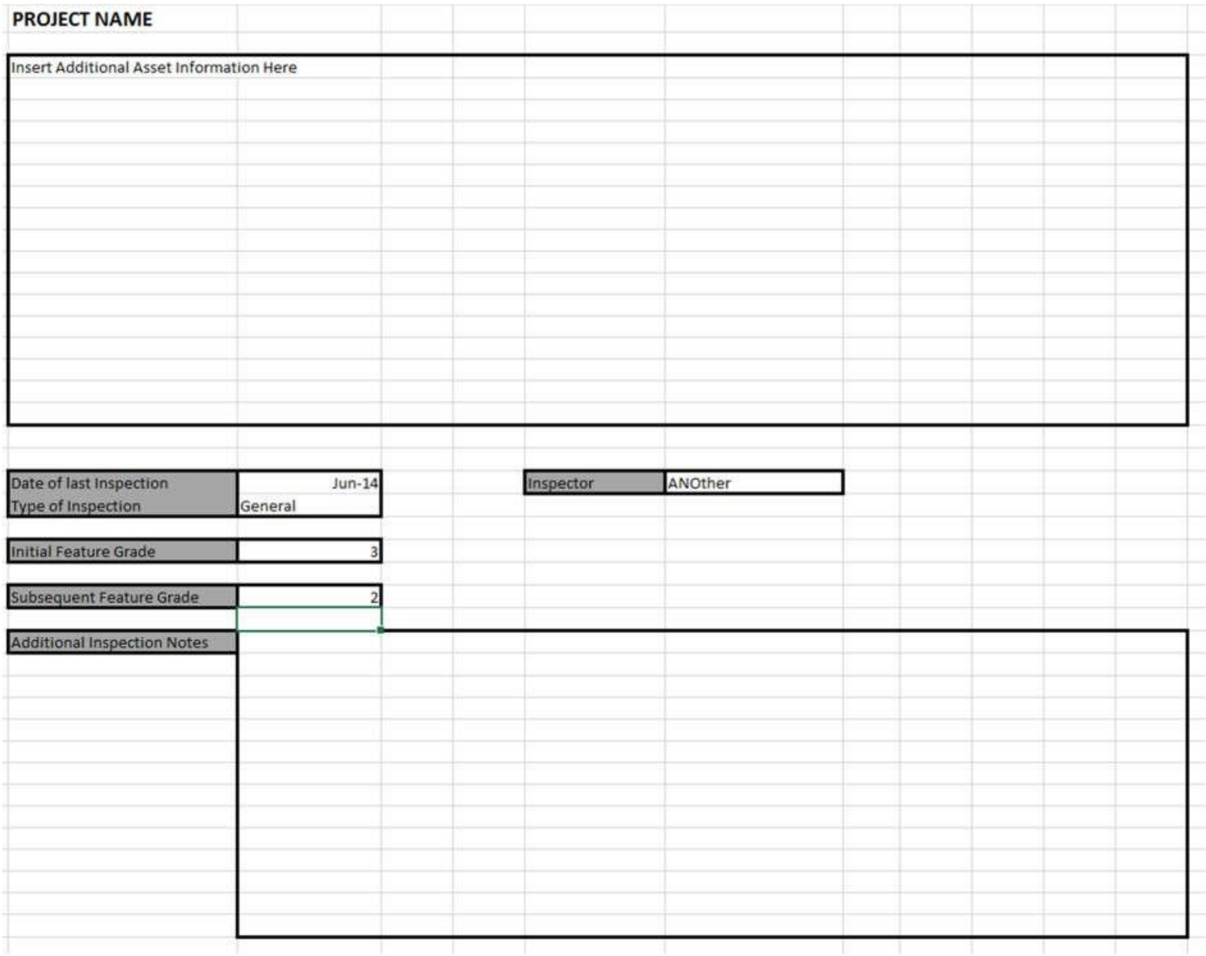


Figure 27 - Asset Information Sheet for Case Study 1

Step 3 – Maintenance-Scheme History

Given that this site does not currently have any planned works to the researchers' knowledge, this tab has been left blank. See Figure 5.9 for a snapshot of the Maintenance-Scheme History tab for Case Study 1.

PROJECT NAME

Scheme Ref	
Asset Ref	
Scheme Type	
Scheme Action	
Full Scheme Description	
Geotechnnical Asset Specific	
Duration	
Completion Date	
Cost	
Comments	

Scheme Ref	
Asset Ref	
Scheme Type	
Scheme Action	
Full Scheme Description	
Geotechnnical Asset Specific	
Duration	
Completion Date	
Cost	
Comments	

Scheme Ref	
Asset Ref	
Scheme Type	
Scheme Action	
Full Scheme Description	
Geotechnnical Asset Specific	
Duration	
Completion Date	
Cost	
Comments	

Figure 28 - Maintenance-Scheme History Sheet for Case Study 1

Step 4 – Severity Scorecard

At this stage the site information from HAGDMS was used to select the appropriate impacting factors from the options. For information, the process refinements from Case Studies 2 and 3 have been added to show the impact of the refinement of the impact criteria weightages.

Geotechnical Risk Assessment Tool

Impact Factor	Outcome	CASE STUDY 1 Weighted Score	CASE STUDY 2 Weighted Score	CASE STUDY 3 Weighted Score
Groundwater Fluctuations	Damaged/Blocked/Inadequate Drainage	14.0	12.8	15.0
Change In Loading Conditions	No Change	0.0	0.0	0.0
Underlying Geology	Unknown	20.0	12.8	9.0
Geographical Location	Site Previously Flooded (within 10 yrs)	12.5	4.8	5.0
Age of Asset	1973 - 1977	2.3	7.3	6.4
Inter-network Node Point	Yes	5.0	9.0	9.0
Vegetation	Mixed	0.0	0.0	0.0
Construction Materials	Construction Material Known, Materials Compliant with Current Design Standards Known Slope Angle	0.0	0.0	0.0
Maintenance History	Asset has been Inspected, Minor Maintenance required with last 5 years	3.8	5.0	0.0
External Weathering	None Visable	0.0	0.0	0.0
Geotechnical Hazard Event	In Progress	2.5	2.0	13.0
Collision Trauma History within the last 5 years?	No	0.0	0.0	0.0
	TOTAL SCORE	60.0	53.6	57.4

Figure 29 - Severity Scorecard for Sheet for Case Study 1

As discussed earlier, the weightages assigned in this case study and across the first phase of each of the three case studies, were arbitrarily assigned by the following the literature review.

Step 5 and 6 – Climate change likelihood and Risk output

Given that the site reviewed in case study 1 is located in the South-East region, this is selected as the region for the likelihood. By combining the scores of severity and likelihood the risk output achieved is High risk – recommended investigation/intervention.

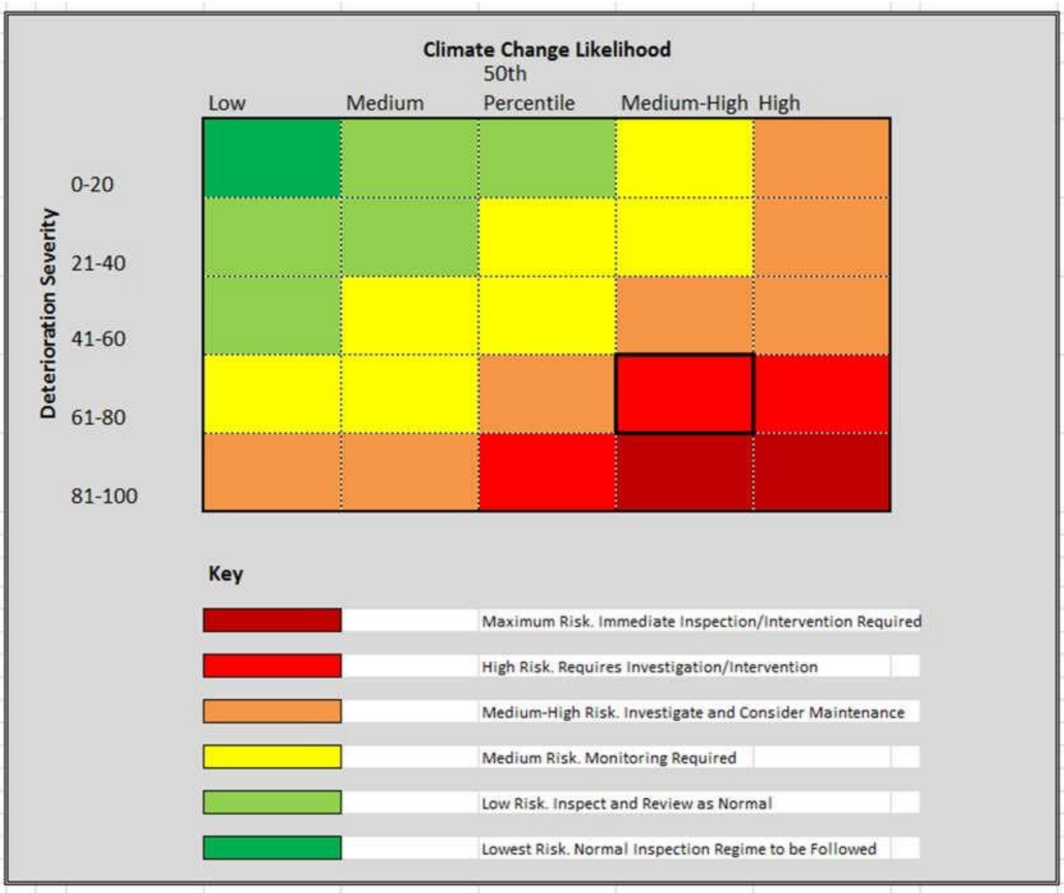


Figure 30 - Risk output for Case Study 1

5.2.1.1.2 <u>Observations from Case Study 1</u>

- This case study was used as a proof of concept with the expert panel for the purpose of the structured interviews.

- Feedback from the interviews concluded that the toolkit required more guidance for completion, however once the process was understood by the experts, the agreed that is was simple to use.
- Three panel members recommended removing the Collision History Impact group from the toolkit as it was deemed to be less important when reviewed against other items.
- The weightages assigned to the impact groups and individual factors were deemed to be acceptable, however there was concern that they may be a little high.
- Question raised about whether adding multiple factors in each group was feasible.
- Further comments include the limited inclusion of finance information.

5.2.1.2 Case Study 2 - M5 J13

Both this case study and case study 3 were completed during a structured interview session with industry experts who were knowledgeable of both the site in question and the researchers' approach. The experts used their knowledge of the site to select the appropriate impacting factors occurring on site which was verified against data held in HAGDMS.

5.2.1.2.1 Case Study 1 Introduction

This case study is a slope situated on the Northbound side of the M3 at the junction with the A303.

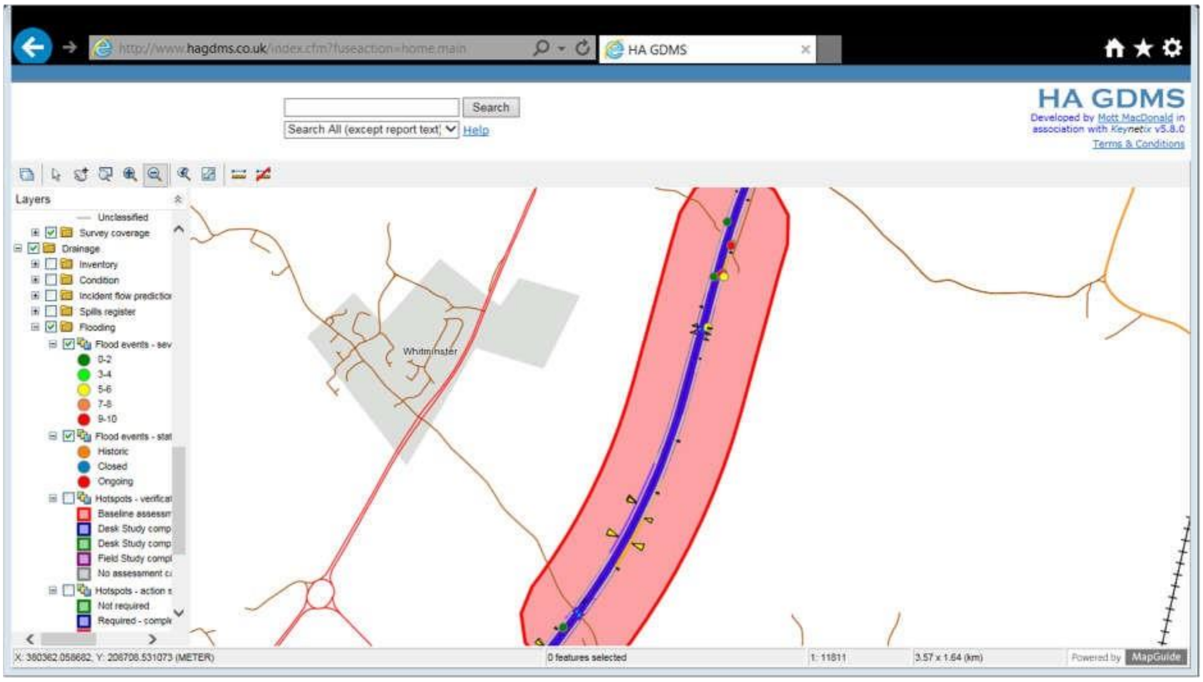


Figure 31 - Site Plan for Case Study 2, taken from HAGDMS

Step 1 – Project Information

The Project Information tab contains the details of the project including the location, scope and deliverables, the stakeholders/Clients involved and project delivery team.

PROJECT NAME	M5 J13
Project Ref	M5 JCT 13
Document Ref	A1
Revision	v1
Date	Oct-16
Prepared By	AC
Checked By	AC
Authorised By	AC
Project Lead	Name
Project Manager	Name
Organisation	Contractor
Client	Highways England
Project Descriptor	NB Embankment - Not currentl
Project Stakeholders	AM lead, Geotechnical Enginnering Lead
Project Start Northing	Project Start Easting
378655	208321
Project End Northing	Project End Easting
Project Start Date	Project End Date
Mar-20	Mar-22
SCAR Stage	0
Assumptions/Other Information	

Figure 32 - Project Information sheet for Case Study 2

Step 2 – Asset Information

The asset information collected and recorded in this step includes information from a preliminary desk study presented here. It includes information on the most recent inspection of the asset and include the Initial and Subsequent Feature grades. See Figure 5.14 for a snapshot of the Asset Information tab for Case Study 2.

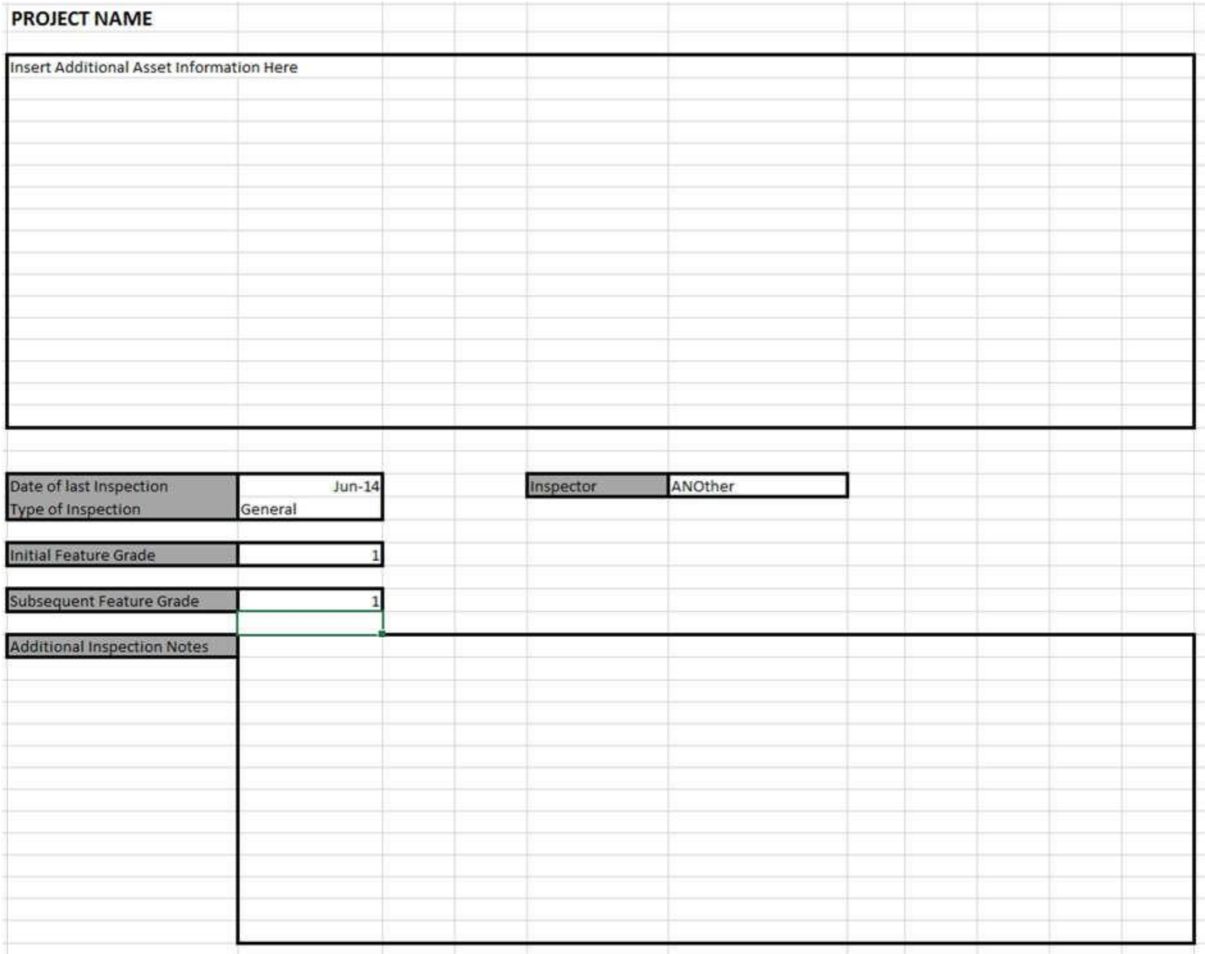


Figure 33 - Asset Information Sheet for Case Study 2

Step 3 – Maintenance-Scheme History

Given that this site does not currently have any planned works to the researchers' knowledge, this tab has been left blank. See Figure 8.15 for a snapshot of the Maintenance-Scheme History tab for Case Study 1.

PROJECT NAME

Scheme Ref	
Asset Ref	
Scheme Type	
Scheme Action	
Full Scheme Description	
Geotechnnical Asset Specific	
Duration	
Completion Date	
Cost	
Comments	

Scheme Ref	
Asset Ref	
Scheme Type	
Scheme Action	
Full Scheme Description	
Geotechnnical Asset Specific	
Duration	
Completion Date	
Cost	
Comments	

Scheme Ref	
Asset Ref	
Scheme Type	
Scheme Action	
Full Scheme Description	
Geotechnnical Asset Specific	
Duration	
Completion Date	
Cost	
Comments	

Figure 34 - Maintenance-Scheme History Sheet for Case Study 2

Step 4 – Severity Scorecard

At this stage the site information from HAGDMS was used to select the appropriate impacting factors from the options. For information, the process refinements from Case Studies 1 and 3 have been added to show the impact of the refinement of the impact criteria weightages.

Geotechnical Risk Assessment Tool

Impact Factor	Outcome	CASE STUDY 1 Weighted Score	CASE STUDY 2 Weighted Score	CASE STUDY 3 Weighted Score
Groundwater Fluctuations	Drought	8.0	12.8	10.5
Change In Loading Conditions	No Change	0.0	0.0	0.0
Underlying Geology	Unknown	20.0	12.8	9.0
Geographical Location	Sited in Flood Plain	12.5	2.4	2.5
Age of Asset	1968 - 1972	2.9	7.3	7.3
Inter-network Node Point	No	0.0	0.0	0.0
Vegetation	Mixed	0.0	0.0	0.0
Construction Materials	Construction Material Known, Materials Compliant with Current Design Standards Known Slope Angle	0.0	0.0	0.0
Maintenance History	Asset has been inspected, No defects, No maintenance	0.0	0.0	0.0
External Weathering	None Visable	0.0	0.0	0.0
Geotechnical Hazard Event	None	0.0	0.0	0.0
Collision Trauma History within the last 5 years?	No	0.0	0.0	0.0
	TOTAL SCORE	43.4	35.2	29.3

Figure 35 - Severity Scorecard for Sheet for Case Study 2

As discussed earlier, Case study 2 outlined the first pairwise comparison as completed by the researcher. This proof of concept provided evidence of the method to the expert panel for completion prior to the third case study.

Step 5 and 6 – Climate change likelihood and Risk output

Given that the site reviewed in case study 2 is located in the South-West region, this is selected as the region for the likelihood. By combining the scores of severity and likelihood the risk output achieved is Medium risk – consider inspection and maintenance.

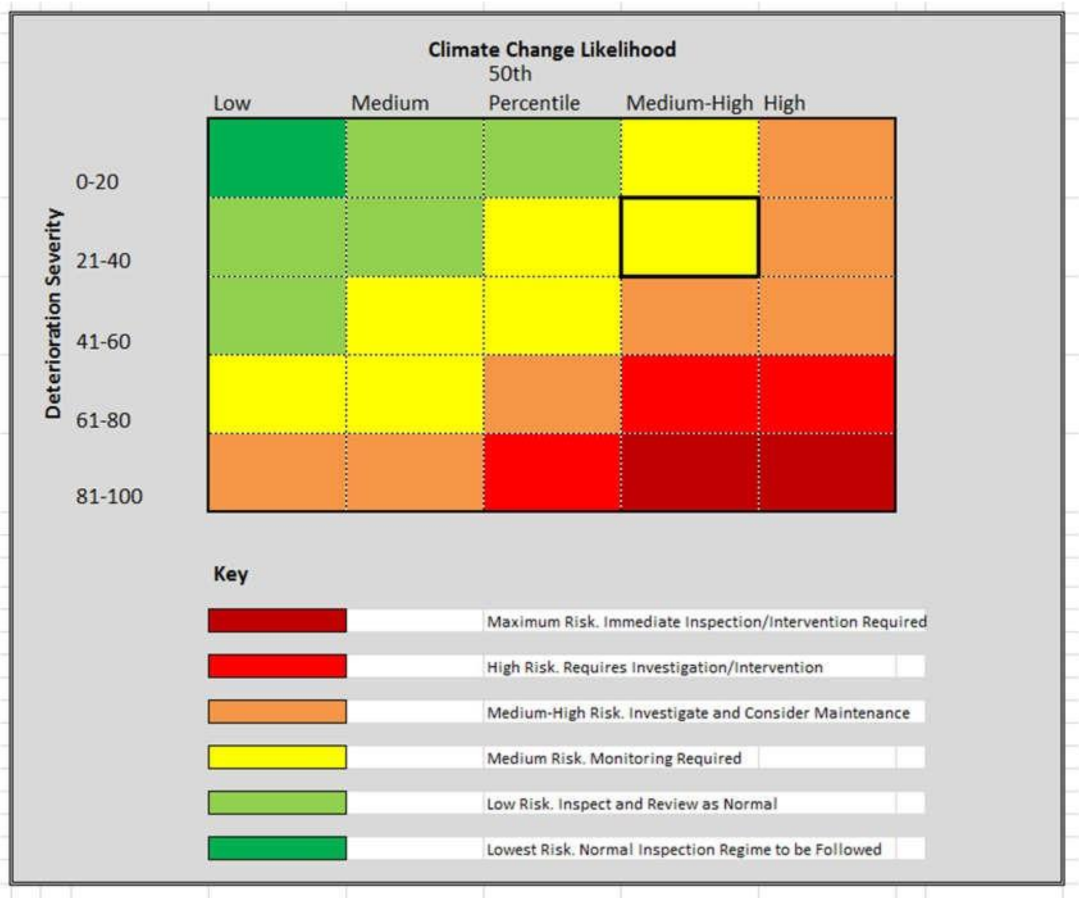


Figure 36 - Risk output for Case Study 2

5.2.1.2.2 <u>Observations from Case Study 2:</u>

- This case study was used as the researcher's test case for the pairwise comparison.
- Feedback from the interviewees: Case study two followed a better format, clearer and easier to read
- Provision of a manual and pairwise comparison examples very useful.
- The weightages provided in by the pairwise comparison, provided similar values to those derived from the literature. Providing confidence in both the initial impact factor selection and the pairwise comparison method.

5.2.1.3 Case Study 3 – M1 J36/37

5.2.1.3.1 <u>Case Study 3 Introduction</u>

This case study is a slope situated on the Northbound side of the M1 between Junctions 36 and 37.

Figure 37 - Site Plan for Case Study 3, taken from HAGDMS

Step 1 – Project Information

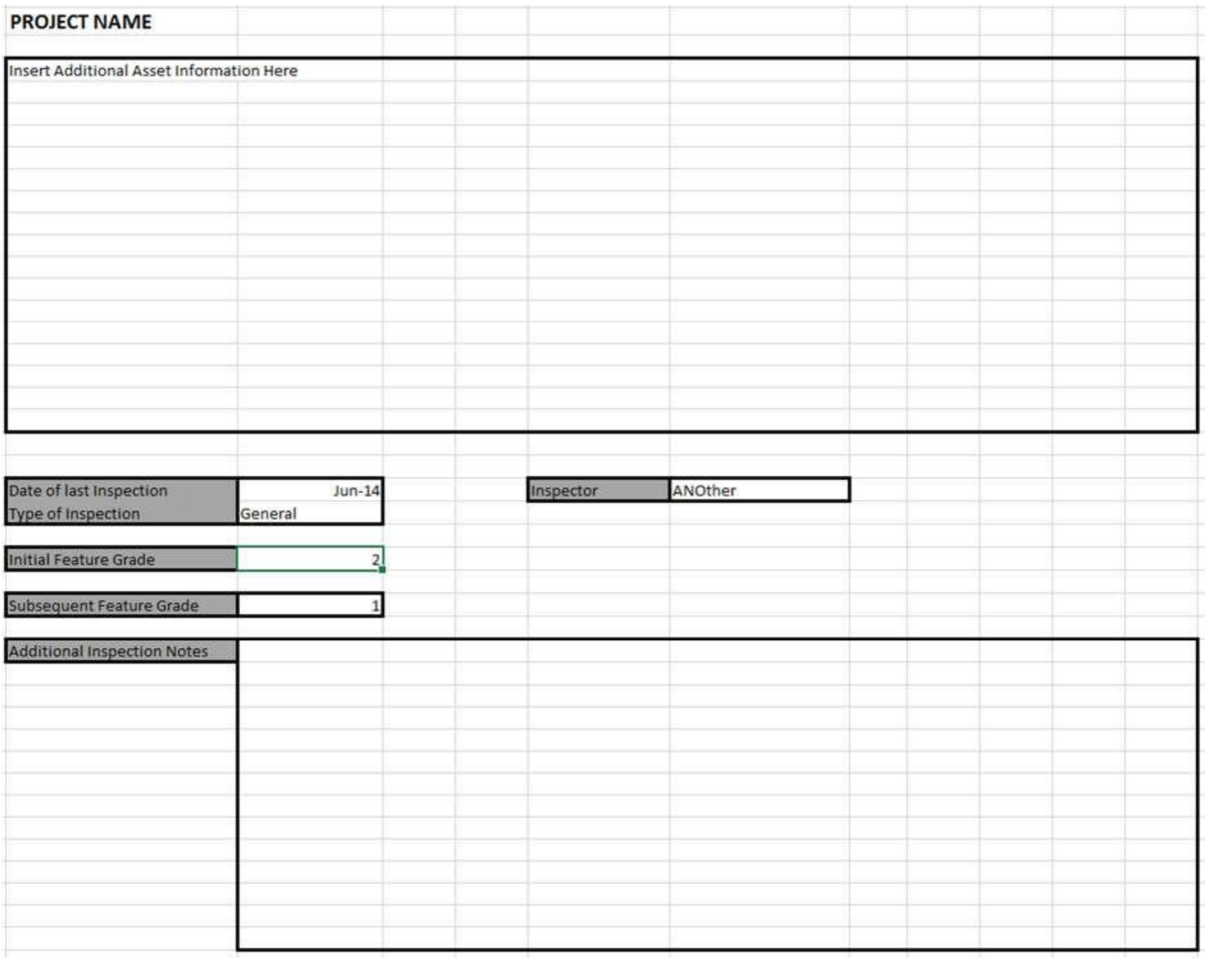
The Project Information tab contains the details of the project including the location, scope and deliverables, the stakeholders/Clients involved and project delivery team.

PROJECT NAME	M1 J36/37
Project Ref	M1 J36/37
Document Ref	A1
Revision	v1
Date	Oct-16
Prepared By	AC
Checked By	AC
Authorised By	AC
Project Lead	Name
Project Manager	Name
Organisation	Contractor
Client	Highways England
Project Descriptor	NB Cutting
Project Stakeholders	AM lead, Geotechnical Enginnering Lead
Project Start Northing	Project Start Easting
430450	408338
Project End Northing	Project End Easting
Project Start Date	Project End Date
Mar-20	Mar-22
SCAR Stage	0
Assumptions/Other Information	

Figure 38 - Project Information sheet for Case Study 3

Step 2 – Asset Information

The asset information collected and recorded in this step includes information from a preliminary desk study presented here. It includes information on the most recent inspection of the asset and include the Initial and Subsequent Feature grades. See Figure 5.20 for a snapshot of the Asset Information tab for Case Study 3.



PROJECT NAME

Insert Additional Asset Information Here

Date of last Inspection	Jun-14	Inspector	ANOther
Type of Inspection	General		
Initial Feature Grade	2		
Subsequent Feature Grade	1		
Additional Inspection Notes			

Figure 39 - Asset Information Sheet for Case Study 3

Step 3 – Maintenance-Scheme History

Given that this site does not currently have any planned works to the researchers' knowledge, this tab has been left blank.

PROJECT NAME

Scheme Ref	
Asset Ref	
Scheme Type	
Scheme Action	
Full Scheme Description	
Geotechnnical Asset Specific	
Duration	
Completion Date	
Cost	
Comments	

Scheme Ref	
Asset Ref	
Scheme Type	
Scheme Action	
Full Scheme Description	
Geotechnnical Asset Specific	
Duration	
Completion Date	
Cost	
Comments	

Scheme Ref	
Asset Ref	
Scheme Type	
Scheme Action	
Full Scheme Description	
Geotechnnical Asset Specific	
Duration	
Completion Date	
Cost	
Comments	

Figure 40 - Maintenance-Scheme History Sheet for Case Study 3

Step 4 – Severity Scorecard

At this stage the site information from HAGDMS was used to select the appropriate impacting factors from the options. For information, the process refinements from Case Studies 1 and 2 have been added to show the impact of the refinement of the impact criteria weightages.

Geotechnical Risk Assessment Tool

Impact Factor	Outcome	CASE STUDY 1 Weighted Score	CASE STUDY 2 Weighted Score	CASE STUDY 3 Weighted Score
Groundwater Fluctuations	Flooding Event	18.0	17.0	18.0
Change In Loading Conditions	No Change	0.0	0.0	0.0
Underlying Geology	Organic Materials	12.5	14.0	12.0
Geographical Location	No Special Features	0.0	0.0	0.0
Age of Asset	1950 - 1967	3.9	11.0	10.0
Inter-network Node Point	No	0.0	0.0	0.0
Vegetation	Mixed	0.0	0.0	0.0
Construction Materials	Construction Material Known, Materials Compliant with Current Design Standards Known Slope Angle	0.0	0.0	0.0
Maintenance History	Asset has been Inspected, Minor Maintenance required with last 5 years	3.8	5.0	0.0
External Weathering	None Visable	0.0	0.0	0.0
Geotechnical Hazard Event	None	0.0	0.0	0.0
Collision Trauma History within the last 5 years?	No	0.0	0.0	0.0
	TOTAL SCORE	38.1	47.0	40.0

Figure 41 - Severity Scorecard for Sheet for Case Study 3

As discussed earlier, Case study 3 outlined the first pairwise comparison as completed by the researcher. This proof of concept provided evidence of the method to the expert panel for completion prior to the third case study. The third case study was completed individually and in small groups by the expert panel.

Step 5 and 6 – Climate change likelihood and risk output

Given that the site reviewed in case study 2 is located in the South-West region, this is selected as the region for the likelihood. By combining the scores of severity and likelihood the risk output achieved is Medium risk – consider inspection and maintenance.

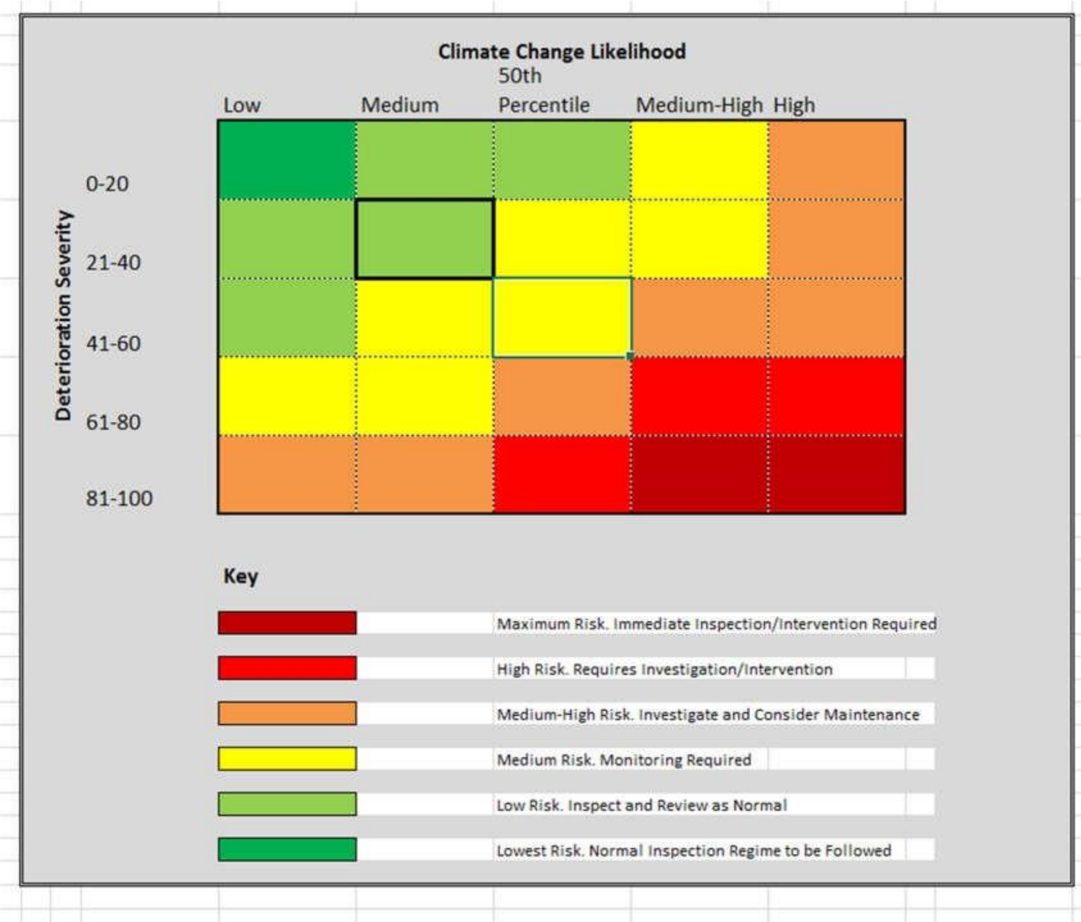


Figure 42 - Risk output for Case Study 3

5.2.1.3.2 Observations from Case Study 3:

- This case study provided the expert panel the opportunity to evaluate the weightages.

- Feedback from the interviewees: Unanimous, the pairwise comparison would be too challenging if required for completion for each asset, however, if it is to remain static, then this would be acceptable.
- Collision trauma can be removed
- The geographical location is most favoured for multiple criteria selection
- Overall confidence in the toolkit and the refinements undertaken. Staged updates to the weightages have been useful to understand how the tool has been developed and why choices have been made. The weightages provided in by the pairwise comparison, provided similar values to those derived from the literature. Providing confidence in both the initial impact factor selection and the pairwise comparison method.

5.2.1.4 Additional Observations made by Industry Experts while using the Climate Change Risk Assessment tool

Several observations made by the expert panel while using the tool to influence decision making for the appropriate resilient solutions in Case studies 2 and 3. These are:

1. The use of the tool can be implemented as part of a long-term planning suite within the wider asset management process. This work is currently being undertaken within Highways England
2. There is a significant gap in the understanding of long-term climate change and its effects on the assets within Highways sector.
3. By using an uncomplicated approach, the tool can present evidence that can be reviewed and analysed by senior managers to approximate the level of risk posed by climate change to the asset portfolio
4. The toolkit could potentially be used to evaluate other asset types, including bridges and drainage.

5. The toolkit provides and iterative approach to the management of climate change risk.
6. The tool must include deterioration modelling outputs and evaluate on a network level basis.
7. The weighting should be fixed and unchangeable.
8. The sensitivity of the toolkit it limited, by using a pairwise approach to the weightings of both the groups and the elements the overall impact on scores is limited.

5.2.2 Discussion of research findings

Asset Management is a now accepted method for the long-term management of transportation networks through multiple organisational levels. Asset management is a tool for looking into the future, by monitoring and extrapolating condition data, decision support tools can forecast potential condition for the purposed of budgeting and forward planning. At present, the ‘forward look’ is limited to less than ten years, with some forecasts extending beyond this; however, the confidence associated with these predictions is low. The reasons for the low confidence are that there are restrictions on the funding capability from central government; most funding cycles can only confirm funding levels for 5 years, with some 10-year Major Infrastructure Development Plans in place. In addition, many asset types, particularly those assets which historically have been considered, by those outside of the management community to provide a supporting role to the main asset, for example the physical carriageway, often have less data availability or do not have approaches in place to develop the long-term place with any level of certainty. This is especially true in local authorities.

Beyond this are the data requirements for developing a central asset database for the collation and archiving of all data on the inventory and condition of the asset networks. The Highways Agency Geotechnical Data Management System (HAGDMS) is thought to be one of the most highly populated databases held by Highways England. It boasts reporting and quality assurance functionality, along with historic maintenance and inspection data for the purposes of long-term infrastructure planning.

5.2.2.1 The limitations of the Research

The deployment of the risk assessment tool developed in this work requires extensive development to background technology to integrate the tool with existing systems in order to streamline the process for inputting data. Currently, the tool does not use sophisticated data or algorithms to generate its output. The current approach, while easy-to-use, is labour-intensive for the user given this lack of connection with existing data systems. By undertaking this development, not only could the tool be quicker to identify the risks for a single asset, but also would benefit from the ability to consider multiple assets at a time, or indeed regional areas. The implication for providing this functionality is that be being able to visualise the risk at this scale provides engineering teams with more data with which they can create or amend existing Planning strategies to incorporate this future risk potential.

By assessing all asset at a regional or even national level, the tool will provide an oversight into the true scale and scope of the impending risk that climate change presents. However, undertaking this expansion of functionalities poses some significant challenges. When consider a wider regional approach the tool must review the weightages accordingly, this significant expansion in stakeholder engagement to assign the of robust weightages to factors which may vary between regions and would require consensus for adoption. This would be a critical step in the developing the organisational thinking and the approach to long-term climate change risk. However, the involvement of stakeholders is an important step in the education of organisation in asset management improvements and effective decision making within the asset management domain (Ruitenburg et al., 2014). Early involvement and effective communication between engineers, planners and stakeholders which has been known to contribute to the success of asset management practices (Geiger et al., 2005 and Holt et al., 2010).

This tool cannot replace existing risk managements outlining current risks, which may have a different time horizon for realisation. Nor can it replace deterioration modelling and whole life costing methodologies, which provide engineers and managers with data to support long-term maintenance strategies and planning approaches, where define treatment strategies and budget forecast play an important role in determining the prioritisation of activities. However, the tool provides insight for the users into risks which may not be fully appreciated, understood or accounted for in the planning process. The tool supports the current industry practices which are developing to support network-level decision making to influence regional and area specific approach to planning for current and future asset needs.

The objective of the researcher was to adopt an exploratory approach to analysing the risk associated with long-term climate change impacts for the UK SRN only. The tool developed offers a snapshot view of the level of risk that can be expected for a given asset, which can affect the long-term stability and performance of the asset. By understanding this risk profile, maintenance works can then be tailored or adapted to incorporated design improvement or maintenance actions that can minimise the level of risk that is realised. It can also support prioritisation planning for the individual asset, but also to indicate where increased benefits may be realised if maintenance works are undertaken in conjunction with other asset maintenance works as part of a ‘hybrid’ scheme. In this sense, this tool can be viewed as complementary some of the planning tools, models and systems discussed above.

The strength of this tool lies in its ability to provide a macro-level overview of risk for climate change to geotechnical assets, to inform engineers at the planning stage. While the tool does not provide an action plan to mitigate such risks, it enables the identification of patterns, clusters and trends that highlight expected performance issues for particular asset groups or regions, where applied more widely. These outputs can be used in devising appropriate mitigation actions or, as appropriately used to encourage asset owners to develop organisational policies, strategies and objectives for climate change mitigation.

5.2.2.2 The limitation of Long-term infrastructure planning

Predicting condition to determine the best maintenance programme for an asset is a substantial challenge. Using risk to determine the severity of a potential decline in condition is beneficial; however, the lack of certainty surrounding these predictions severely limits their impact. Asset Owners are often government-owned organisations who are entrusted with keeping the country’s infrastructure operational and intact. Given that geotechnical asset for only part of a very large, very costly network, it is understandable that these assets can often be overlooked.

Funding is limited; central government has taken a view in recent years to press for 'more service for less money'. Using asset management and condition deterioration models to determine how assets will inevitably change over time, along with showing how budgetary decisions directly impact infrastructure condition change is invaluable. However, there are still fundamental limitations on the certainty of funding availability across the asset network. The limitation to asset owners for a lack of foresight to funding (i.e. beyond the 4/5-year political cycle) can prevent much of the work on future condition being viewed objectively, thus leading to the appearance of a dismissive and unconcerned attitude towards any long-term planning solution beyond 10 years. Many asset owners, whilst addressing the remits for long-term infrastructure planning by the UK government, are limited to what can be undertaken with guaranteed funding. Other elements fall onto a 'wish list', which leads to non-action, should funding not be available. The approach outlined in this research allows an organisation to evaluate its geotechnical assets on an iterative basis, throughout their life.

5.2.2.3 Geotechnical Assets on the UK Strategic Road Infrastructure Network

Geotechnical assets are a critical element of the Strategic Road Network (SRN), and as such are classified as one of most critical asset types including Pavements, Structures and Drainage. Assets are inspected and maintained regularly as part of the maintenance contract. Asset condition is variable and can be exposed to defects which can cause small of more catastrophic failures. Geotechnical Assets can form both point and linear assets; they support authority node points as well at transition zones between the strategic road network and smaller urban and rural networks. Geotechnical assets within the UK vary widely in age and construction type. They sit on a wide range of underlying geology, and are often impacted by events taking place on, or within the other assets on the network.

Geotechnical asset condition deterioration is complex. The impact of both internal and external factors can cause deterioration or even failure. An asset is inspected within a regular programme to determine if the asset exhibits any features or defects or is undergoing a geotechnical event. The outcome of the inspection is then applied to a risk matrix to assess the current condition category for the asset. This information is then input into HAGDMS for reference and as the initial stage of the forward programming cycle.

This research presents a methodology for the determination of the critical factors that influence the deterioration of geotechnical over the long-term, in excess of 25-30 years. Whilst the current inspection process review and assesses if the asset is being currently impacted by any of these factors, along with if there are any defects as a result and, ultimately, if any failure is occurring or is imminent, it does not predict the future beyond the next principal inspection. This methodology presents a hierarchy of critical impact factor, which eliminates current condition to focus on the future deterioration and the likelihood of this being exacerbated by climate change events.

A summary of the factors affecting geotechnical asset condition, in descending order of influence, which have been used to create the risk severity scorecard are shown in
the table below:

Element Group	Specific Element	Internal/External	If External, which asset group impacting	Included in risk assessment
Groundwater fluctuations	Flooding Event	Both	Drainage	Yes
	Damaged/Blocked/ Inadequate Drainage			
	Drought/Desiccation			
	Excessive Rainfall			
	Frost/Thaw			
	Seasonal Fluctuations			
Change in Loading Conditions	Additional Material Added at Base or Top of Asset	Both	All	Yes
	Removal of Material at Base or Top of Asset			
	Subsidence Causing a Change in Loading Profile			
Underlying Geology		Internal	-	Yes

Element Group	Specific Element	Internal/ External	If External, which asset group impacting	Included in risk assessment
Geographical Location	Site Previously Flooded (within 10 yrs.)	Internal	-	Yes
	Sited in Flood Plain			
	Critical Node Point			
	High Traffic Location (≥ 80 msa)			
Age of asset		Internal	-	Yes
Inter-network Node Point		External	All	Yes
Vegetation		Internal	-	Yes
Construction Material/Methods		Internal	-	Yes
Maintenance History		Internal	-	Yes
External Weathering		Internal	-	Yes

Element Group	Specific Element	Internal/ External	If External, which asset group impacting	Included in risk assessment
Geotechnical Hazard Event		Both	All	Yes
Collision Trauma History		External	All	Yes

5.2.2.4 Using the Critical Impacting Factors to determine the Risk Severity Scorecard

The risk severity scorecard is used as the first part of the risk assessment of climate change. The information input into the scorecard is site specific and taken from records in HAGDMS. For the 3 sites selected listed in the Case Study Chapter, this information was straightforward. There was a limitation for the underlying geology category access to relevant data, was via an external link which did not seem to work. As a result, this category was marked ‘Unknown’. Whilst the information is easy enough to find, it would require some interpretation which may not be known to the user of the scorecard. Had an underlying geology been available for all three sites, there may be potential to reduce the severity level and thus the overall risk rating.

The outcome of the case study scorecards proves that the tool works. Each site used differing data to score a different result, based upon the observations made during inspection, along with site specific data gave a score which reflected the location.

This score, combined with the climate change probability for each site, derived from the regional probability for a medium emissions scenario, gave the final risk rating for each site. As a result, each of sites tested fell into a different risk category, the lowest, in the North East, has a low risk rating and as such requires no action. The South West site requires monitoring for any evidence of increased amounts of defects. The final site, in the South East, had the highest rating evidence of historic flooding, geotechnical events and blocked drainage pushed this risk rating to a Medium-High. In this instance the suggested action is maintenance or repair. Given the site history, it would be recommended that this take the form of additional gully cleansing, to ensure that this area does not become a 'flooding hotspot' which could affect the stability of the asset.

The parameters for scoring the risk severity scorecard are based on the current hierarchy of impacting factors. This scoring can be changed for meet the requirements the asset owner, should they be more conservative or less cautious.

5.2.3 Links to Research Aim and Objectives

For more information on the research road map and research methodology can be found in chapters 1 and 3, respectively.

Research Objectives 1 & 2: Objective 1 – To review the approach to asset management and the development of suitable asset management systems and practices for highways networks in UK including geotechnical assets. Objective 2 – To examine the long-term approach to monitoring geotechnical asset condition and consider the impacts of climate change on support requirements when planning needs within the highways network (with focus on geotechnical) industry.

The goal of this research was to develop an approach to measure the risk impacts of climate change on geotechnical assets over the long term and provide geotechnical asset managers with a tool to assess the potential impact of climate change on site as evidence of an incoming need requirement for consideration by senior managers. To this end, the researcher conducted a detailed review of academic and industry literature, to establish the baseline for approaches, systems, frameworks, and tools and systems used within the highways and other sector for the management of assets, both within and outside the UK. The analysis revealed a broad gap of tool that focus on the needs of geotechnical asset specifically, most are focused on traditionally higher-spend assets, such as pavement, track or bridges. Further, most of the approaches used to consider climate change impacts require either vast amounts of data to support their outcomes or require specialist software to run. This makes them prohibitive in nature for many smaller highway authorities. Thus, by fulfilling the first two objectives of the study, by reviewing asset management systems and practices for highway networks and (2) examining the long-term approach to monitoring geotechnical asset condition and consider the impacts of climate change on support requirements when planning needs within the highways network, the researcher has established a gap in knowledge for which there is a need for a tool tailored to the measuring the risk of climate change impact on geotechnical in a manner appropriate to the level of certainty in a future-focus scenario.

Achieving Research Objectives 3: Objective 3 – To study the geotechnical asset failure modes to determine the hierarchy of factors affecting the performance of the geotechnical assets including ground water fluctuations, seepage, soil properties, geology and hydrogeology.

The research presented in this thesis establishes the nature and relationship between critical factors that impact the deterioration of geotechnical assets. Using a combination of expert consultation and literature review, the researcher developed a list of critical factors can lead to the direct or indirect deterioration of a geotechnical asset. These factors were then review in the context of slope stability and consolidation to 11 Impacting factors that can be affected by climate change impacts. With the use of the pairwise comparison technique, the impacting factors and their respective subsets were formed into a hierarchy through appropriate ranking and had corresponding weightages applied. Through this approach, the researcher is able to demonstrate the 3rd objective i.e. determine the hierarchy of climate change impacting factors affecting the performance of the geotechnical assets.

Achieving Research Objectives 4 and 5: Objective 4 – To develop a geotechnical asset management climate change risk mapping approach for use in the planning stage of an asset management life cycle and to develop a tool to support these assessments.

Objective 5 – To test the approach through case studies and validate the tool.

Finally, the last two objectives of this research yield the most significant contribution of this work - the development of a risk assessment tool for long term climate change impacts on geotechnical assets to be used in the planning stage of an asset management lifecycle; and validation of the tool using real life (not hypothetical) case studies. In order to provide a user interface that asset manager can use easily, the researcher developed an Excel-based spreadsheet model, which uses 11 impacting factors as the basis of a questionnaire to support the risk assessment. Each of the impacting factors is supported by a series of sub condition, for which the user selects the most appropriate, based on the available site data. The resulting score for each impacting factor is summed to determine the impact severity for climate change. A regional climate change profile is applied to determine the likelihood of climate change impacts, in accordance with UK climate change projection models. The impact factor with the highest weight is considered the most significant climate change impact tot the risk assessment. These weightages have influence on the overall risk score; therefore, it is important that they assigned robustly and with due communication with industry experts.

Ultimately, the output risk score presented by the tool provides the user with an indication of the degree of climate impact when compared with other scored sites, and thus a prioritisation against other scored sites. By applying the tool liberally across, say network lengths, or over a series of geotechnical assets in an area, there is an opportunity to determine the scale of the issue that climate change impact will have. Similar, by communicating the level of risk posed in a way that is already familiar to an organisation, means that users can communicate the outputs to senior leaders in a language that is understood and clearly recognisable. The purpose of the tool is to provide an understanding of the impact level, and thus the priority of a need to act.

The tool uses limited qualitative data to identify the potential risk potential of geotechnical failure in the light of future climate change conditions.

The use of industry experts to provide opinion of the validity, usefulness and to support the researcher in the assignment of weightings to the impacting factors is beneficial for two reasons. Firstly, given that these weightings have been assessed and developed by the ages are determined by the experts, confidence that a level of consistency has been applied and that the impacts are viewed with the appropriate level of importance and justification. The involvement of industry experts supports in overcoming problems associated with limited data availability. The experts use their knowledge and experience to provide the researcher with deep and valuable advice about the management of the asset and the 'correctness' of the outcomes. on the asset and its management.

The development of the tool in Excel was a considered choice. Like most other user-centric toolkits (e.g. HMEP), the use of Excel for the development of this tool ensures that the tool can be used by individuals without any specialist training or knowledge, unlike many other specialist platforms. The researcher believes that the tool can be used by geotechnical asset managers, planners and engineers either independently, or with the support of a more developed risk-based approach to undertake risk assessment to determine the impact of long-term climate change on geotechnical asset. The tool works at an operational level, gathering asset data to determine the risk profile. This output can then be used to support tactical level planning, as part of the wider asset management process, to support the prioritisation of scheme within the maintenance renewal programme. This tool can be applied iteratively as condition changes and at any stage of a renewal project, however it is probably best placed for delivery as an ongoing manager of asset need. This tool can contribute to this stage by introducing a long-term perspective to the priority and selection of asset management solutions.

Although this work focuses on geotechnical assets on the road network, the researcher is confident that the tool approach can be used for other asset types on a highway network.

6 Conclusions

Infrastructure asset management is a tool which, when used appropriately by asset owners and their maintenance contractors is powerful in the way that it encourages robust data management, optimised programming, and evidenced-based decision making. It encourages all organisations to think of their networks as a holistic system, and that maintenance needs to be undertaken accordingly. This leads to an environment where the ancillary assets, who's needs are often less obvious to the public and have been subject to lower relative investment historically, can get a fair share of budget to meet their deterioration requirements.

Although asset management has come a long way, for some asset types, the approach is still novel and not as well implemented leading to some asset owners and higher levels of government still choosing to focus on the design and construction phases of asset development, given that the holistic lifecycle approaches associated with asset management are not fully embedded. For Highways England, while consideration is now being given to the design phases as to how the long-term management will be undertaken, considering maintenance beyond a five-year programme is simply not done, although there is a push ongoing to move this towards an 8-year rolling cycle. Fundamental changes to the way that Engineers and asset owning staff consider assets, their management and even their definition of 'long-term' must be challenged in order to prepare the workforce for the likely changes to happen over the next 25 years and beyond.

Climate change is happening, and as a result the infrastructure industry needs to adopt methods of condition prediction which considers the long-term, along with working with all levels of government to gain political buy-in and confidence that funding will be available to meet the needs of our aging infrastructure assets.

In light of this need, the research undertaken as part of the development of the risk tool makes an important contributions to the discipline of asset management: it uses geotechnical asset data to evaluate the impact and severity of future climate change impact and present the resultant future in a familiar and easy to understand format to support asset managers in determining the extent of a future need and priority of any mitigation action.

The literature review shows that there is a significant gap in research of approaches to quantify the risk posed to geotechnical assets by long-term climate change and outlining a consistent methodology for prioritising the long-term maintenance of these assets through asset management. There is research specifically looking at how asset condition is changing and the effects that climate change will have on geotechnical assets. However, this is very scenario specific, and thus useful for future design, and for the sites where condition matches that of the test sites. There is a lack of tools determining how to identify asset risk over the long-term specifically related to climate change, and whilst several parties have submitted frameworks, these are often strategic and give limited guidance to the audience. The industry is currently looking to develop and use tools that can aid their decision-making process utilising the data that they have available. Therefore, this research has concluded that further investigations into resilience assessment tools is required. After a detailed review of the literature and methods available, it was decided that the most appropriate method was to utilise a format that is currently being used to assess geotechnical asset condition, a format which current geotechnical engineers are familiar with and have confidence in. This means that the tool required must be easy to use, work consistently across all sites, and be compatible with the data sets available.

The methodology presented uses a risk assessment, where the severity of the risk profile result from the assessment of the critical condition impact factors. These factors consider the current characteristics of the asset, without incorporating current condition levels. This is calculated within the scorecard, for subsequent inclusion in the final risk score. The likelihood element of the risk assessment uses regional-derived probability scores taken from the medium emission scenarios presented by the UKCIP 2018. The resultant risk score can then be utilised as a forward planning tool for maintenance, or increased monitoring, where appropriate.

As part of the research process, three case studies were assessed using the risk assessment methodology in order to show the practical application of the system. Each of the sites chosen was located out-of-town on a UK motorway. They differed in age, construction and history, however each of them had experienced groundwater fluctuations as the result of their location. Each of the sites chosen was not designed with climate change in mind, and each of the assets chosen has been inspected and maintained throughout the course of its life. The results of the case study assessments show that the risk assessment process works and produces results which are good indicators of where to target maintenance resources to mitigate for climate change impacts, demonstrating that climate change and location of the assets will have an effect on the change experienced.

6.1 Original Contribution to knowledge

This research has produced a tool which assesses the impact of climate change on geotechnical assets, by scoring the asset against a hierarchy of critical factors which impact deterioration and evaluating the severity of the impact against the climate change scenarios set out by UKCIP 2009. This work presents an approach for determining the risk profile for climate change effects on geotechnical assets that currently does not exist within the Highways England portfolio. It has been developed with operational functionality in mind and utilises existing data from HAGDMS to assess currently operational geotechnical assets.

The tool been tested validated using real case studies by geotechnical engineers and asset management experts. This methodology of the development provides a structured and consistent approach in assessing the geotechnical asset’s potential to continue being serviceable and fit for purpose even under the influence of climate change.

6.2 Future Work

This research work provides a starting point for wider climate change risk incorporation and the basis for further development in asset management and future-focused risk-based thinking to be applied at all level of a highway's maintenance organisation. Some suggested future work is listed as follows:

1. The tool can be extended to evaluate multiple geotechnical assets at once, becoming a systemised evaluation rather than a potentially cumbersome approach where multiple assets are considered.
2. The tool can be customised and further developed for different types of assets and not only geotechnical assets. The impacting factors studied in the research for geotechnical assets would be required to be replaced by identifying similar impacting factors for the asset type being assessed.
3. The approach can be developed and used as part of the corporate risk criteria. Many organisations use corporately agreed risk impact categories to identify, quantify and record risks across a range of areas that are known to influence the meeting of organisational objectives.
4. The tool can be developed into a system for use by multiple users or have web-based access. This would require a data transfer conduit or protocol to be in place in order to provide the amount and level of detail available

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8 Appendices

8.1 Appendix A – Summary of Structured Interview Questionnaire

Role	
Organisation	
Date	

Guidance and Instruction Manual					
Score from 1 (Poor) to 5 (Excellent)					
Overall	1	2	3	4	5
Content	1	2	3	4	5
Clarity	1	2	3	4	5
Ease of Navigation	1	2	3	4	5
Comments					

Risk Assessment Tool					
Score from 1 (Poor) to 5 (Excellent)					
Overall	1	2	3	4	5
Approach	1	2	3	4	5
Clarity	1	2	3	4	5
Ease of Navigation	1	2	3	4	5
Comments					

Pairwise Comparison Approach					
Score from 1 (Poor) to 5 (Excellent)					
Overall	1	2	3	4	5
Ease of Approach	1	2	3	4	5

Reproducibility	1	2	3	4	5
Logic of Approach	1	2	3	4	5
Comments					

Any Other Comments:

8.2 Appendix B – Summary of Pairwise Comparison Approach

Pairwise Comparison almalgamation from Structured Interviewees (8No.)

Impact Groups

Number Classifying Above	Condition Pair		Number Classifying Above
6.5	1	2	1.5
7.5	1	3	0.5
8	1	4	
8	1	5	
8	1	6	
8	1	7	
8	1	8	
8	1	9	
8	1	10	
8	1	11	
8	1	12	
8	2	3	
8	2	4	
7	2	5	1
8	2	6	
8	2	7	
8	2	8	
8	2	9	
8	2	10	
8	2	11	
8	2	12	
6.5	3	4	1.5
8	3	5	
8	3	6	
8	3	7	
8	3	8	
8	3	9	
8	3	10	
1.5	3	11	6.5
8	3	12	
8	4	5	
8	4	6	
8	4	7	
8	4	8	
8	4	9	
8	4	10	
0.5	4	11	7.5
8	4	12	
8	5	6	
8	5	7	
8	5	8	
8	5	9	
8	5	10	
	5	11	8
8	5	12	
8	6	7	
8	6	8	
8	6	9	
8	6	10	
	6	11	8
8	6	12	
8	7	8	
8	7	9	
8	7	10	
	7	11	8
8	7	12	
4	8	9	4
8	8	10	
	8	11	8
8	8	12	
8	9	10	
2	9	11	6
8	9	12	
	10	11	8
8	10	12	
8	11	12	

Condition Number	Total Score	X	Weightages
1	12	1.48148148	18
2	9		13
3	8		12
4	7		10
5	7		10
6	6		9
7	4		6
8	2.5		4
9	2		3
10	1		1
11	9		13
12	0		0

Groundwater Fluctuations

Number Classifying Above	Condition Pair		Number Classifying Above
1	1	2	8
2.5	1	3	5.5
3	1	4	5
	1	5	8
8	1	6	
8	1	7	
8	1	8	
6	2	3	2
8	2	4	
8	2	5	
8	2	6	
8	2	7	
8	2	8	
8	3	4	
8	3	5	
8	3	6	
8	3	7	
8	3	8	
4	4	5	4
8	4	6	
8	4	7	
8	4	8	
8	5	6	
8	5	7	
8	5	8	
1	6	7	
1	6	8	
1	7	8	

Condition Number	Total Score	X	Weightages
1	3		2
2	6		4
3	5		4
4	3.5	0.74074074	3
5	3.5		3
6	2		1
7	1		1
8	0		0

Changes to Loading

Number Classifying Above	Condition Pair		Number Classifying Above
4.5	1	2	3.5
3.5	1	3	4.5
8	1	4	
5.5	2	3	2.5
8	2	4	
8	3	4	

Condition Number	Total Score	X	Weightages
1	2		4
2	2	2.22222222	4
3	2		4
4	0		0

Underlying Geology

Number Classifying Above	Condition Pair		Number Classifying Above
	1	2	8
8	1	3	
4	1	4	4
4	1	5	4
8	1	6	
8	1	7	
8	1	8	
8	2	3	
8	2	4	
8	2	5	
8	2	6	
8	2	7	
8	2	8	
8	3	4	
8	3	5	
8	3	6	
8	3	7	
8	3	8	
8	4	5	
8	4	6	
8	4	7	
8	4	8	
8	5	6	
8	5	7	
8	5	8	
8	6	7	
8	6	8	
8	7	8	

Condition Number	Total Score	X	Weightages
1	5		2
2	6		3
3	5		2
4	4	0.45584046	2
5	3		1
6	2		1
7	1		0
8	0		0

Geographical Location

Number Classifying Above	Condition Pair		Number Classifying Above
8	1	2	
	1	3	8
	1	4	8
8	1	5	
	2	3	8
	2	4	8
8	2	5	
8	3	4	
8	3	5	
8	4	5	

Condition Number	Total Score	X	Weightages
1	2		2
2	1		1
3	4	1.03703704	4
4	3		3
5	0		0

Age of Asset

Number Classifying Above	Condition Pair		Number Classifying Above
	1	2	8
0.5	1	3	7.5
1	1	4	7
8	1	5	
8	1	6	
8	1	7	
4	2	3	4
8	2	4	
8	2	5	
8	2	6	
8	2	7	
4	3	4	4
8	3	5	
8	3	6	
8	3	7	
8	4	5	
8	4	6	
8	4	7	
8	5	6	
8	5	7	
8	6	7	

Condition Number	Total Score	X	Weightages
1	3.5		2
2	5.5		3
3	4		2
4	3.5	0.53181387	2
5	2		1
6	1		1
7	0		0

Inter-network Node Point

Number Classifying Above	Condition Pair		Number Classifying Above
6.5	1	2	1.5

Condition Number	Total Score	X	Weightages
1	1	8.88888889	9
2	0		0

Vegetation

Number Classifying Above	Condition Pair		Number Classifying Above
8	1	2	
8	1	3	
8	1	4	
8	1	5	
8	2	3	
8	2	4	
8	2	5	
8	3	4	
8	3	5	
8	4	5	

Condition Number	Total Score	X	Weightages
1	4		2
2	3		2
3	2	0.59259259	1
4	1		1
5	0		0

Construction Materials

Number Classifying Above	Condition Pair		Number Classifying Above
8	1	2	
4	1	3	4
4	1	4	4
8	1	5	
4	2	3	4
8	2	4	
8	2	5	
8	3	4	
8	3	5	
8	4	5	

Condition Number	Total Score	X	Weightages
1	3		1
2	2.5		1
3	3	0.38986355	1
4	1		0
5	0		0

Maintenance History

Number Classifying Above	Condition Pair		Number Classifying Above
8	1	2	
8	1	3	
8	1	4	
1	2	3	8
8	2	4	
8	3	4	

Condition Number	Total Score	X	Weightages
1	3		1
2	1	0.49382716	0
3	2		1
4	0		0

External Weathering

Number Classifying Above	Condition Pair		Number Classifying Above
0.5	1	2	0.5
1	1	3	
1	1	4	
1	2	3	
1	2	4	
1	3	4	

Condition Number	Total Score	X	Weightages
1	2.5		1
2	2.5	0.24691358	1
3	1		0
4	0		0

Geotechnical Hazard Event

Number Classifying Above	Condition Pair		Number Classifying Above
8	1	2	

Condition Number	Total Score	X	Weightages
1	1	13.3333333	13
2	0		0

Collision History

Number Classifying Above	Condition Pair		Number Classifying Above
5.5	1	2	2.5

Condition Number	Total Score	X	Weightages
1	1	0	0
2	0		0

Pairwise Author

Impact Group	Condition Number (C) Y-Axis Primary	Groundwater fluctuations	Change in Loading Conditions	Underlying Geology	Geographical Location	Age of Asset	Inter-network Node Point	Vegetation	Construction Materials	Maintenance History	External Weathering	Geotechnical Hazard Event	Collision Trauma History Requiring Maintenance within the last 5 years? (Or Since last Principle Inspection?)
		1	2	3	4	5	6	7	8	9	10	11	12
Groundwater fluctuations	1	-	1	1	1	1	1	1	1	1	1	1	1
Change in Loading Conditions	2	-	-	2	2	2	2	2	2	2	2	2	2
Underlying Geology	3	-	-	-	3	3	3	3	3	3	3	3	3
Geographical Location	4	-	-	-	-	4	4	4	4	4	4	4	4
Age of Asset	5	-	-	-	-	-	5	5	5	5	5	5	5
Inter-network Node Point	6	-	-	-	-	-	-	6	6	6	6	6	6
Vegetation	7	-	-	-	-	-	-	-	7	7	7	7	7
Construction Materials	8	-	-	-	-	-	-	-	-	8	8	8	8
Maintenance History	9	-	-	-	-	-	-	-	-	-	9	9	9
External Weathering	10	-	-	-	-	-	-	-	-	-	-	10	10
Geotechnical Hazard Event	11	-	-	-	-	-	-	-	-	-	-	-	11
Collision Trauma History Requiring Maintenance within the last 5 years? (Or Since last Principle Inspection?)	12	-	-	-	-	-	-	-	-	-	-	-	-
Pairwise Calculations	Count	11	10	9	8	7	6	5	4	3	2	1	0
	X	1.515151515											
	Weightages	17	15	14	12	11	9	8	6	5	3	2	0

	Impact Group		Groundwater fluctuations							
	Impact Element	Condition Number (C) Y-Axis Primary	Unknown	Flooding Event	Damaged/ Blocked/ Inadequate Drainage	Drought	Excessive Rainfall	Frost/Thaw	Seasonal Fluctuations	None
Impact Group			1	2	3	4	5	6	7	8
Groundwater fluctuations	Unknown	1	-	2	3	tie	tie	1	1	1
	Flooding Event	2	-	-	2	2	2	2	2	2
	Damaged/Blocked/Inadequate Drainage	3	-	-	-	3	3	3	3	3
	Drought	4	-	-	-	-	tie	4	4	4
	Excessive Rainfall	5	-	-	-	-	-	5	5	5
	Frost/Thaw	6	-	-	-	-	-	-	6	6
	Seasonal Fluctuations	7	-	-	-	-	-	-	-	7
	None	8	-	-	-	-	-	-	-	-
	Pairwise Calculation	Count	4	7	5	4	3	2	1	0
		X	0.641025641							
		Weightages	3	4	3	3	2	1	1	0

Impact Group	Impact Element	Condition Number (C) Y-Axis Primary	Change in Loading Conditions: Additional Material Added at Base or Top of Asset	Removal of Material at Base or Top of Asset	Subsidence Causing a Change in Loading Profile	No Change
Impact Group			1	2	3	4
Change in Loading Conditions	Additional Material Added at Base or Top of Asset	1	-	tie	tie	1
	Removal of Material at Base or Top of Asset	2	-	-	tie	2
	Subsidence Causing a Change in Loading Profile	3	-	-	-	3
	No Change	4	-	-	-	-
	Pairwise Calculations	Count	2	2	2	0
		X	2.525252525			
		Weightages	5	5	5	0

Impact Group	Impact Element	Condition Number (C) Y-Axis Primary	Underlying Geology: Unknown	Organic Materials	Clays	Silts	Sands	Gravels/ Boulders/ Cobbles	Weak Rock	Rock
Impact Group			1	2	3	4	5	6	7	8
Underlying Geology	Unknown	1	-	2	1	tie	tie	1	1	1
	Organic Materials	2	-	-	2	2	2	2	2	2
	Clays	3	-	-	-	3	3	3	3	3
	Silts	4	-	-	-	-	4	4	4	4
	Sands	5	-	-	-	-	-	5	5	5
	Gravels/Boulders/Cobbles	6	-	-	-	-	-	-	6	6
	Weak Rock	7	-	-	-	-	-	-	-	7
	Rock	8	-	-	-	-	-	-	-	-
	Pairwise Calculations	Count	5	7	5	4	3	2	1	0
		X	0.505050505							
		Weightages	3	4	3	2	2	1	1	0

Impact Group	Impact Element	Condition Number (C) Y-Axis Primary	Geographical Location: Site Previously Flooded (within 10 yrs)	Sited in Flood Plain	Critical Node Point	High Traffic Location (≥ 80 msa)	No Special Features
Impact Group			1	2	3	4	5
Geographical Location	Site Previously Flooded (within 10 yrs)	1	-	1	3	4	1
	Sited in Flood Plain	2	-	-	3	4	2
	Critical Node Point	3	-	-	-	3	3
	High Traffic Location (≥ 80 msa)	4	-	-	-	-	4
	No Special Features	5	-	-	-	-	-
	Pairwise Calculations	Count	2	1	4	3	0
		X	1.212121212				
		Weightages	2	1	5	4	0

	Impact Group	Condition Number (C) Y-Axis Primary	Age of Asset						
	Impact Element		Older than 1950	1950 - 1967	1968 - 1972	1973 - 1977	1978 - 1985	1986 - 1992	1993 - Present
Impact Group			1	2	3	4	5	6	7
Age of Asset	Older than 1950	1	-	1	1	1	1	1	1
	1950 - 1967	2	-	-	2	2	2	2	2
	1968 - 1972	3	-	-	-	3	3	3	3
	1973 - 1977	4	-	-	-	-	4	4	4
	1978 - 1985	5	-	-	-	-	-	5	5
	1986 - 1992	6	-	-	-	-	-	-	6
	1993 - Present	7	-	-	-	-	-	-	-
	Pairwise Calculations	Count	6	5	4	3	2	1	0
		X	0.505050505						
		Weightages	3	3	2	2	1	1	0

	Impact Group	Condition Number (C) Y-Axis Primary	Inter-network Node Point	
	Impact Element		Yes	No
Impact Group			1	2
Inter-network Node Point	Yes	1	-	1
	No	2	-	-
	Pairwise Calculations	Count	1	0
		X	9.090909091	
		Weightages	3	0

	Impact Group	Condition Number (C) Y-Axis Primary	Vegetation				
	Impact Element		Vegetation Removed	Grasses	Low Level Shrub	Trees	Mixed
Impact Group			1	2	3	4	5
Vegetation	Vegetation Removed	1	-	1	1	1	1
	Grasses	2	-	-	2	2	2
	Low Level Shrub	3	-	-	-	3	3
	Trees	4	-	-	-	-	4
	Mixed	5	-	-	-	-	-
	Pairwise Calculations	Count	4	3	2	1	0
		X	0.757575758				
		Weightages	3	2	2	1	0

Impact Group	Impact Group	Condition Number (C) Y-Axis Primary	Construction Materials				
	Impact Element		Construction Materials Unknown	Construction Material Known but Non-compliant with Current Design Standards Unknown Slope Angle	Construction Material Known but Non-compliant with Current Design Standards Known Slope Angle	Construction Material Known, Materials Compliant with Current Design Standards Unknown Slope Angle	Construction Material Known, Materials Compliant with Current Design Standards Known Slope Angle
Impact Group			1	2	3	4	5
Construction Materials	Construction Materials Unknown	1	-	1	1	1	1
	Construction Material Known but Non-compliant with Current Design Standards Unknown Slope Angle	2	-	-	2	2	2
	Construction Material Known but Non-compliant with Current Design Standards Known Slope Angle	3	-	-	-	3	3
	Construction Material Known, Materials Compliant with Current Design Standards Unknown Slope Angle	4	-	-	-	-	4
	Construction Material Known, Materials Compliant with Current Design Standards Known Slope Angle	5	-	-	-	-	-
	Pairwise Calculations	Count	4	3	2	1	0
		X	0.606060606				
		Weightages	3	2	2	1	0

Impact Group	Impact Element	Condition Number (C) Y-Axis Primary	Maintenance History			
			Asset not been Inspected or Maintained within last 5 years	Asset has been Inspected, Minor Maintenance required with last 5 years	Asset has been Inspected, Major Maintenance required with last 5 years	Asset has been inspected, No defects, No maintenance
Impact Group			1	2	3	4
Maintenance History	Asset not been Inspected or Maintained within last 5 years	1	-	1	1	1
	Asset has been Inspected, Minor Maintenance required with last 5 years	2	-	-	2	2
	Asset has been Inspected, Major Maintenance required with last 5 years	3	-	-	-	3
	Asset has been inspected, No defects, No maintenance	4	-	-	-	-
	Pairwise Calculations	Count	3	2	1	0
		X	0.757575758			
		Weightages	2	2	1	0

Impact Group	Impact Element	Condition Number (C) Y-Axis Primary	External Weathering			
			Water Scour	Wind Scour	Chemical Changes to Soil	None Visable
Impact Group			1	2	3	4
External Weathering	Water Scour	1	-	1	1	1
	Wind Scour	2	-	-	2	2
	Chemical Changes to Soil	3	-	-	-	3
	None Visable	4	-	-	-	-
	Pairwise Calculations	Count	3	2	1	0
		X	0.505050505			
		Weightages	2	1	1	0

	Impact Group	Condition Number (C) Y-Axis Primary	Geotechnical Hazard Event	
	Impact Element		In Progress	None
Impact Group			1	2
Geotechnical Hazard Event	In Progress	1	-	1
	None	2	-	-
	Pairwise Calculations	Count	1	0
		X	1.515151515	
		Weightages	3	0

	Impact Group	Condition Number (C) Y-Axis Primary	Collision Trauma History Requiring Maintenance within the last 5 years? (Or Since last Principle Inspection?)	
	Impact Element		Yes	No
Impact Group			1	2
Collision Trauma History Requiring Maintenance within the last 5 years? (Or Since last Principle Inspection?)	Yes	1	-	1
	No	2	-	-
	Pairwise Calculations	Count	1	0
		X	0	
		Weightages	3	0

Pairwise Interviewee 1

Impact Group	Condition Number (C) Y-Axis Primary	Groundwater fluctuations	Change in Loading Conditions	Underlying Geology	Geographical Location	Age of Asset	Inter-network Node Point	Vegetation	Construction Materials	Maintenance History	External Weathering	Geotechnical Hazard Event	Collision Trauma History Requiring Maintenance within the last 5 years? (Or Since last Principle Inspection?)
		1	2	3	4	5	6	7	8	9	10	11	12
Groundwater fluctuations	1	-	1	1	1	1	1	1	1	1	1	1	1
Change in Loading Conditions	2	-	-	2	2	2	2	2	2	2	2	2	2
Underlying Geology	3	-	-	-	3	3	3	3	3	3	3	11	3
Geographical Location	4	-	-	-	-	4	4	4	4	4	4	11	4
Age of Asset	5	-	-	-	-	-	5	5	5	5	5	11	5
Inter-network Node Point	6	-	-	-	-	-	-	6	6	6	6	11	6
Vegetation	7	-	-	-	-	-	-	-	7	7	7	11	7
Construction Materials	8	-	-	-	-	-	-	-	-	tie	8	11	8
Maintenance History	9	-	-	-	-	-	-	-	-	-	9	11	9
External Weathering	10	-	-	-	-	-	-	-	-	-	-	11	10
Geotechnical Hazard Event	11	-	-	-	-	-	-	-	-	-	-	-	11
Collision Trauma History Requiring Maintenance within the last 5 years? (Or Since last Principle Inspection?)	12	-	-	-	-	-	-	-	-	-	-	-	-
Pairwise Calculations	Count	11	10	8	7	6	5	4	2.5	1.5	1	8	0
	X	1.5625											
	Weightages	17	16	13	11	9	8	6	4	2	2	13	0

	Impact Group	Condition Number (C) Y-Axis Primary	Groundwater fluctuations							
	Impact Element		Unknown	Flooding Event	Damaged/ Blocked/ Inadequate Drainage	Drought	Excessive Rainfall	Frost/Thaw	Seasonal Fluctuations	None
Impact Group			1	2	3	4	5	6	7	8
Groundwater fluctuations	Unknown	1	-	2	3	4	5	1	1	1
	Flooding Event	2	-	-	2	2	2	2	2	2
	Damaged/Blocked/Inadequate Drainage	3	-	-	-	3	3	3	3	3
	Drought	4	-	-	-	-	tie	4	4	4
	Excessive Rainfall	5	-	-	-	-	-	5	5	5
	Frost/Thaw	6	-	-	-	-	-	-	6	6
	Seasonal Fluctuations	7	-	-	-	-	-	-	-	7
	None	8	-	-	-	-	-	-	-	-
	Pairwise Calculation	Count	3	7	6	4.5	3.5	2	1	0
		X	3.703703704							
		Weightages	11	26	22	17	13	7	4	0

Impact Group	Impact Group / Impact Element	Condition Number (C) Y-Axis Primary	Change in Loading Conditions: Additional Material Added at Base or Top of Asset	Removal of Material at Base or Top of Asset	Subsidence Causing a Change in Loading Profile	No Change
			1	2	3	4
Change in Loading Conditions	Additional Material Added at Base or Top of Asset	1	-	tie	tie	1
	Removal of Material at Base or Top of Asset	2	-	-	tie	2
	Subsidence Causing a Change in Loading Profile	3	-	-	-	3
	No Change	4	-	-	-	-
	Pairwise Calculations	Count	2	2	2	0
		X	16.66666667			
		Weightages	33	33	33	0

Impact Group	Impact Group / Impact Element	Condition Number (C) Y-Axis Primary	Underlying Geology: Unknown	Organic Materials	Clays	Silts	Sands	Gravels/ Boulders/ Cobbles	Weak Rock	Rock
			1	2	3	4	5	6	7	8
Underlying Geology	Unknown	1	-	2	1	tie	tie	1	1	1
	Organic Materials	2	-	-	2	2	2	2	2	2
	Clays	3	-	-	-	3	3	3	3	3
	Silts	4	-	-	-	-	4	4	4	4
	Sands	5	-	-	-	-	-	5	5	5
	Gravels/Boulders/Cobbles	6	-	-	-	-	-	-	6	6
	Weak Rock	7	-	-	-	-	-	-	-	7
	Rock	8	-	-	-	-	-	-	-	-
	Pairwise Calculations	Count	5	7	5	4	3	2	1	0
		X	3.703703704							
		Weightages	19	26	19	15	11	7	4	0

Impact Group	Impact Group / Impact Element	Condition Number (C) Y-Axis Primary	Geographical Location: Site Previously Flooded (within 10 yrs)	Sited in Flood Plain	Critical Node Point	High Traffic Location (≥ 80 msa)	No Special Features
			1	2	3	4	5
Geographical Location	Site Previously Flooded (within 10 yrs)	1	-	1	3	4	1
	Sited in Flood Plain	2	-	-	3	4	2
	Critical Node Point	3	-	-	-	3	3
	High Traffic Location (≥ 80 msa)	4	-	-	-	-	4
	No Special Features	5	-	-	-	-	-
	Pairwise Calculations	Count	2	1	4	3	0
		X	10				
		Weightages	20	10	40	30	0

	Impact Group	Condition Number (C) Y-Axis Primary	Age of Asset						
	Impact Element		Older than 1950	1950 - 1967	1968 - 1972	1973 - 1977	1978 - 1985	1986 - 1992	1993 - Present
Impact Group			1	2	3	4	5	6	7
Age of Asset	Older than 1950	1	-	2	3	4	1	1	1
	1950 - 1967	2	-	-	tie	2	2	2	2
	1968 - 1972	3	-	-	-	tie	3	3	3
	1973 - 1977	4	-	-	-	-	4	4	4
	1978 - 1985	5	-	-	-	-	-	5	5
	1986 - 1992	6	-	-	-	-	-	-	6
	1993 - Present	7	-	-	-	-	-	-	-
	Pairwise Calculations	Count	6	5	4	3	2	1	0
		X	4.761904762						
		Weightages	29	24	19	14	10	5	0

	Impact Group	Condition Number (C) Y-Axis Primary	Inter-network Node Point	
	Impact Element		Yes	No
Impact Group			1	2
Inter-network Node Point	Yes	1	-	1
	No	2	-	-
	Pairwise Calculations	Count	1	0
		X	100	
		Weightages	17	0

	Impact Group	Condition Number (C) Y-Axis Primary	Vegetation				
	Impact Element		Vegetation Removed	Grasses	Low Level Shrub	Trees	Mixed
Impact Group			1	2	3	4	5
Vegetation	Vegetation Removed	1	-	1	1	1	1
	Grasses	2	-	-	2	2	2
	Low Level Shrub	3	-	-	-	3	3
	Trees	4	-	-	-	-	4
	Mixed	5	-	-	-	-	-
	Pairwise Calculations	Count	4	3	2	1	0
		X	10				
		Weightages	40	30	20	10	0

Impact Group	Impact Group	Condition Number (C) Y-Axis Primary	Construction Materials				
	Impact Element		Construction Materials Unknown	Construction Material Known but Non-compliant with Current Design Standards Unknown Slope Angle	Construction Material Known but Non-compliant with Current Design Standards Known Slope Angle	Construction Material Known, Materials Compliant with Current Design Standards Unknown Slope Angle	Construction Material Known, Materials Compliant with Current Design Standards Known Slope Angle
Impact Group			1	2	3	4	5
Construction Materials	Construction Materials Unknown	1	-	1	tie	tie	1
	Construction Material Known but Non-compliant with Current Design Standards Unknown Slope Angle	2	-	-	tie	2	2
	Construction Material Known but Non-compliant with Current Design Standards Known Slope Angle	3	-	-	-	3	3
	Construction Material Known, Materials Compliant with Current Design Standards Unknown Slope Angle	4	-	-	-	-	4
	Construction Material Known, Materials Compliant with Current Design Standards Known Slope Angle	5	-	-	-	-	-
	Pairwise Calculations	Count	4	3	2	1	0
		X	10				
		Weightages	40	30	20	10	0

	Impact Group	Condition Number (C) Y-Axis Primary	Maintenance History			
	Impact Element		Asset not been Inspected or Maintained within last 5 years	Asset has been Inspected, Minor Maintenance required with last 5 years	Asset has been Inspected, Major Maintenance required with last 5 years	Asset has been inspected, No defects, No maintenance
Impact Group			1	2	3	4
Maintenance History	Asset not been Inspected or Maintained within last 5 years	1	-	1	1	1
	Asset has been Inspected, Minor Maintenance required with last 5 years	2	-	-	2	2
	Asset has been Inspected, Major Maintenance required with last 5 years	3	-	-	-	3
	Asset has been inspected, No defects, No maintenance	4	-	-	-	-
	Pairwise Calculations	Count	3	2	1	0
		X	16.66666667			
		Weightages	50	33	17	0

	Impact Group	Condition Number (C) Y-Axis Primary	External Weathering			
	Impact Element		Water Scour	Wind Scour	Chemical Changes to Soil	None Visable
Impact Group			1	2	3	4
External Weathering	Water Scour	1	-	tie	1	1
	Wind Scour	2	-	-	2	2
	Chemical Changes to Soil	3	-	-	-	3
	None Visable	4	-	-	-	-
	Pairwise Calculations	Count	3	2	1	0
		X	16.66666667			
		Weightages	50	33	17	0

	Impact Group	Condition Number (C) Y-Axis Primary	Geotechnical Hazard Event	
	Impact Element		In Progress	None
Impact Group			1	2
Geotechnical Hazard Event	In Progress	1	-	1
	None	2	-	-
	Pairwise Calculations	Count	1	0
		X	100	
		Weightages	17	0

	Impact Group	Condition Number (C) Y-Axis Primary	Collision Trauma History Requiring Maintenance within the last 5 years? (Or Since last Principle Inspection?)	
	Impact Element		Yes	No
Impact Group			1	2
Collision Trauma History Requiring Maintenance within the last 5 years? (Or Since last Principle Inspection?)	Yes	1	-	1
	No	2	-	-
	Pairwise Calculations	Count	1	0
		X	100	
		Weightages	17	0

Pairwise Interviewee 2

Impact Group	Condition Number (C) Y-Axis Primary	Groundwater fluctuations	Change in Loading Conditions	Underlying Geology	Geographical Location	Age of Asset	Inter-network Node Point	Vegetation	Construction Materials	Maintenance History	External Weathering	Geotechnical Hazard Event	Collision Trauma History Requiring Maintenance within the last 5 years? (Or Since last Principle Inspection?)
		1	2	3	4	5	6	7	8	9	10	11	12
Groundwater fluctuations	1	-	1	1	1	1	1	1	1	1	1	1	1
Change in Loading Conditions	2	-	-	2	2	2	2	2	2	2	2	2	2
Underlying Geology	3	-	-	-	3	3	3	3	3	3	3	3	3
Geographical Location	4	-	-	-	-	4	4	4	4	4	4	4	4
Age of Asset	5	-	-	-	-	-	5	5	5	5	5	5	5
Inter-network Node Point	6	-	-	-	-	-	-	6	6	6	6	6	6
Vegetation	7	-	-	-	-	-	-	-	7	7	7	7	7
Construction Materials	8	-	-	-	-	-	-	-	-	8	8	8	8
Maintenance History	9	-	-	-	-	-	-	-	-	-	9	9	9
External Weathering	10	-	-	-	-	-	-	-	-	-	-	10	10
Geotechnical Hazard Event	11	-	-	-	-	-	-	-	-	-	-	-	11
Collision Trauma History Requiring Maintenance within the last 5 years? (Or Since last Principle Inspection?)	12	-	-	-	-	-	-	-	-	-	-	-	-
Pairwise Calculations	Count	11	10	9	8	7	6	5	4	3	2	1	0
	X	1.515151515											
	Weightages	17	15	14	12	11	9	8	6	5	3	2	0

Impact Group	Impact Element	Condition Number (C) Y-Axis Primary	Groundwater fluctuations							
			Unknown	Flooding Event	Damaged/ Blocked/ Inadequate Drainage	Drought	Excessive Rainfall	Frost/Thaw	Seasonal Fluctuations	None
Impact Group			1	2	3	4	5	6	7	8
Groundwater fluctuations	Unknown	1	-	2	3	tie	tie	1	1	1
	Flooding Event	2	-	-	2	2	2	2	2	2
	Damaged/Blocked/Inadequate Drainage	3	-	-	-	3	3	3	3	3
	Drought	4	-	-	-	-	tie	4	4	4
	Excessive Rainfall	5	-	-	-	-	-	5	5	5
	Frost/Thaw	6	-	-	-	-	-	-	6	6
	Seasonal Fluctuations	7	-	-	-	-	-	-	-	7
	None	8	-	-	-	-	-	-	-	-
	Pairwise Calculation	Count	4	7	5	4	3	2	1	0
		X	3.846153846							
		Weightages	15	27	19	15	12	8	4	0

	Impact Group	Condition Number (C) Y-Axis Primary	Change in Loading Conditions			
	Impact Element		Additional Material Added at Base or Top of Asset	Removal of Material at Base or Top of Asset	Subsidence Causing a Change in Loading Profile	No Change
Impact Group			1	2	3	4
Change in Loading Conditions	Additional Material Added at Base or Top of Asset	1	-	tie	tie	1
	Removal of Material at Base or Top of Asset	2	-	-	tie	2
	Subsidence Causing a Change in Loading Profile	3	-	-	-	3
	No Change	4	-	-	-	-
	Pairwise Calculations	Count	2	2	2	0
		X	16.66666667			
		Weightages	33	33	33	0

	Impact Group	Condition Number (C) Y-Axis Primary	Underlying Geology							
	Impact Element		Unknown	Organic Materials	Clays	Silts	Sands	Gravels/ Boulders/ Cobbles	Weak Rock	Rock
Impact Group			1	2	3	4	5	6	7	8
Underlying Geology	Unknown	1	-	2	1	tie	tie	1	1	1
	Organic Materials	2	-	-	2	2	2	2	2	2
	Clays	3	-	-	-	3	3	3	3	3
	Silts	4	-	-	-	-	4	4	4	4
	Sands	5	-	-	-	-	-	5	5	5
	Gravels/Boulders/Cobbles	6	-	-	-	-	-	-	6	6
	Weak Rock	7	-	-	-	-	-	-	-	7
	Rock	8	-	-	-	-	-	-	-	-
	Pairwise Calculations	Count	5	7	5	4	3	2	1	0
		X	3.703703704							
		Weightages	19	26	19	15	11	7	4	0

	Impact Group	Condition Number (C) Y-Axis Primary	Geographical Location				
	Impact Element		Site Previously Flooded (within 10 yrs)	Sited in Flood Plain	Critical Node Point	High Traffic Location (≥ 80 msa)	No Special Features
Impact Group			1	2	3	4	5
Geographical Location	Site Previously Flooded (within 10 yrs)	1	-	1	3	4	1
	Sited in Flood Plain	2	-	-	3	4	2
	Critical Node Point	3	-	-	-	3	3
	High Traffic Location (≥ 80 msa)	4	-	-	-	-	4
	No Special Features	5	-	-	-	-	-
	Pairwise Calculations	Count	2	1	4	3	0
		X	10				
		Weightages	20	10	40	30	0

	Impact Group	Condition Number (C) Y-Axis Primary	Age of Asset						
	Impact Element		Older than 1950	1950 - 1967	1968 - 1972	1973 - 1977	1978 - 1985	1986 - 1992	1993 - Present
Impact Group			1	2	3	4	5	6	7
Age of Asset	Older than 1950	1	-	1	1	1	1	1	1
	1950 - 1967	2	-	-	2	2	2	2	2
	1968 - 1972	3	-	-	-	3	3	3	3
	1973 - 1977	4	-	-	-	-	4	4	4
	1978 - 1985	5	-	-	-	-	-	5	5
	1986 - 1992	6	-	-	-	-	-	-	6
	1993 - Present	7	-	-	-	-	-	-	-
	Pairwise Calculations	Count	6	5	4	3	2	1	0
		X	4.761904762						
		Weightages	29	24	19	14	10	5	0

	Impact Group	Condition Number (C) Y-Axis Primary	Inter-network Node Point	
	Impact Element		Yes	No
Impact Group			1	2
Inter-network Node Point	Yes	1	-	1
	No	2	-	-
	Pairwise Calculations	Count	1	0
		X	100	
		Weightages	17	0

	Impact Group	Condition Number (C) Y-Axis Primary	Vegetation				
	Impact Element		Vegetation Removed	Grasses	Low Level Shrub	Trees	Mixed
Impact Group			1	2	3	4	5
Vegetation	Vegetation Removed	1	-	1	1	1	1
	Grasses	2	-	-	2	2	2
	Low Level Shrub	3	-	-	-	3	3
	Trees	4	-	-	-	-	4
	Mixed	5	-	-	-	-	-
	Pairwise Calculations	Count	4	3	2	1	0
		X	10				
		Weightages	40	30	20	10	0

	Impact Group		Construction Materials				
	Impact Element	Condition Number (C) Y-Axis Primary	Construction Materials Unknown	Construction Material Known but Non-compliant with Current Design Standards Unknown Slope Angle	Construction Material Known but Non-compliant with Current Design Standards Known Slope Angle	Construction Material Known, Materials Compliant with Current Design Standards Unknown Slope Angle	Construction Material Known, Materials Compliant with Current Design Standards Known Slope Angle
Impact Group			1	2	3	4	5
Construction Materials	Construction Materials Unknown	1	-	1	1	1	1
	Construction Material Known but Non-compliant with Current Design Standards Unknown Slope Angle	2	-	-	2	2	2
	Construction Material Known but Non-compliant with Current Design Standards Known Slope Angle	3	-	-	-	3	3
	Construction Material Known, Materials Compliant with Current Design Standards Unknown Slope Angle	4	-	-	-	-	4
	Construction Material Known, Materials Compliant with Current Design Standards Known Slope Angle	5	-	-	-	-	-
	Pairwise Calculations	Count	4	3	2	1	0
		X	10				
		Weightages	40	30	20	10	0

	Impact Group		Maintenance History			
	Impact Element	Condition Number (C) Y-Axis Primary	Asset not been Inspected or Maintained within last 5 years	Asset has been Inspected, Minor Maintenance required with last 5 years	Asset has been Inspected, Major Maintenance required with last 5 years	Asset has been inspected, No defects, No maintenance
Impact Group			1	2	3	4
Maintenance History	Asset not been Inspected or Maintained within last 5 years	1	-	1	1	1
	Asset has been Inspected, Minor Maintenance required with last 5 years	2	-	-	2	2
	Asset has been Inspected, Major Maintenance required with last 5 years	3	-	-	-	3
	Asset has been inspected, No defects, No maintenance	4	-	-	-	-
	Pairwise Calculations	Count	3	2	1	0
		X	16.66666667			
		Weightages	50	33	17	0

	Impact Group	Condition Number (C) Y-Axis Primary	External Weathering			
	Impact Element		Water Scour	Wind Scour	Chemical Changes to Soil	None Visable
Impact Group			1	2	3	4
External Weathering	Water Scour	1	-	1	1	1
	Wind Scour	2	-	-	2	2
	Chemical Changes to Soil	3	-	-	-	3
	None Visable	4	-	-	-	-
	Pairwise Calculations	Count	3	2	1	0
		X	16.66666667			
		Weightages	50	33	17	0

	Impact Group	Condition Number (C) Y-Axis Primary	Geotechnical Hazard Event	
	Impact Element		In Progress	None
Impact Group			1	2
Geotechnical Hazard Event	In Progress	1	-	1
	None	2	-	-
	Pairwise Calculations	Count	1	0
		X	100	
		Weightages	17	0

	Impact Group	Condition Number (C) Y-Axis Primary	Collision Trauma History Requiring Maintenance within the last 5 years? (Or Since last Principle Inspection?)	
	Impact Element		Yes	No
Impact Group			1	2
Collision Trauma History Requiring Maintenance within the last 5 years? (Or Since last Principle Inspection?)	Yes	1	-	1
	No	2	-	-
	Pairwise Calculations	Count	1	0
		X	100	
		Weightages	17	0

Pairwise Interviewee 3

Impact Group	Condition Number (C) Y-Axis Primary	Groundwater fluctuations	Change in Loading Conditions	Underlying Geology	Geographical Location	Age of Asset	Inter-network Node Point	Vegetation	Construction Materials	Maintenance History	External Weathering	Geotechnical Hazard Event	Collision Trauma History Requiring Maintenance within the last 5 years? (Or Since last Principle Inspection?)
		1	2	3	4	5	6	7	8	9	10	11	12
Groundwater fluctuations	1	-	1	1	1	1	1	1	1	1	1	1	1
Change in Loading Conditions	2	-	-	2	2	2	2	2	2	2	2	2	2
Underlying Geology	3	-	-	-	3	3	3	3	3	3	3	3	3
Geographical Location	4	-	-	-	-	4	4	4	4	4	4	4	4
Age of Asset	5	-	-	-	-	-	5	5	5	5	5	5	5
Inter-network Node Point	6	-	-	-	-	-	-	6	6	6	6	6	6
Vegetation	7	-	-	-	-	-	-	-	7	7	7	7	7
Construction Materials	8	-	-	-	-	-	-	-	-	8	8	8	8
Maintenance History	9	-	-	-	-	-	-	-	-	-	9	9	9
External Weathering	10	-	-	-	-	-	-	-	-	-	-	10	10
Geotechnical Hazard Event	11	-	-	-	-	-	-	-	-	-	-	-	11
Collision Trauma History Requiring Maintenance within the last 5 years? (Or Since last Principle Inspection?)	12	-	-	-	-	-	-	-	-	-	-	-	-
Pairwise Calculations	Count	11	10	9	8	7	6	5	4	3	2	1	0
	X	1.515151515											
	Weightages	17	15	14	12	11	9	8	6	5	3	2	0

Impact Group	Impact Element	Condition Number (C) Y-Axis Primary	Unknown	Flooding Event	Damaged/ Blocked/ Inadequate Drainage	Drought	Excessive Rainfall	Frost/Thaw	Seasonal Fluctuations	None
	Impact Group		Groundwater fluctuations							
			1	2	3	4	5	6	7	8
Groundwater fluctuations	Unknown	1	-	2	3	tie	tie	1	1	1
	Flooding Event	2	-	-	2	2	2	2	2	2
	Damaged/Blocked/Inadequate Drainage	3	-	-	-	3	3	3	3	3
	Drought	4	-	-	-	-	tie	4	4	4
	Excessive Rainfall	5	-	-	-	-	-	5	5	5
	Frost/Thaw	6	-	-	-	-	-	-	6	6
	Seasonal Fluctuations	7	-	-	-	-	-	-	-	7
	None	8	-	-	-	-	-	-	-	-
	Pairwise Calculation	Count	4	7	5	4	3	2	1	0
		X	3.846153846							
		Weightages	15	27	19	15	12	8	4	0

Impact Group	Impact Element	Condition Number (C) Y-Axis Primary	Change in Loading Conditions			
			Additional Material Added at Base or Top of Asset	Removal of Material at Base or Top of Asset	Subsidence Causing a Change in Loading Profile	No Change
Impact Group			1	2	3	4
Change in Loading Conditions	Additional Material Added at Base or Top of Asset	1	-	tie	tie	1
	Removal of Material at Base or Top of Asset	2	-	-	tie	2
	Subsidence Causing a Change in Loading Profile	3	-	-	-	3
	No Change	4	-	-	-	-
	Pairwise Calculations	Count	2	2	2	0
		X	16.66666667			
		Weightages	33	33	33	0

Impact Group	Impact Element	Condition Number (C) Y-Axis Primary	Underlying Geology							
			Unknown	Organic Materials	Clays	Silts	Sands	Gravels/ Boulders/ Cobbles	Weak Rock	Rock
Impact Group			1	2	3	4	5	6	7	8
Underlying Geology	Unknown	1	-	2	1	tie	tie	1	1	1
	Organic Materials	2	-	-	2	2	2	2	2	2
	Clays	3	-	-	-	3	3	3	3	3
	Silts	4	-	-	-	-	4	4	4	4
	Sands	5	-	-	-	-	-	5	5	5
	Gravels/Boulders/Cobbles	6	-	-	-	-	-	-	6	6
	Weak Rock	7	-	-	-	-	-	-	-	7
	Rock	8	-	-	-	-	-	-	-	-
	Pairwise Calculations	Count	5	7	5	4	3	2	1	0
		X	3.703703704							
		Weightages	19	26	19	15	11	7	4	0

Impact Group	Impact Element	Condition Number (C) Y-Axis Primary	Geographical Location				
			Site Previously Flooded (within 10 yrs)	Sited in Flood Plain	Critical Node Point	High Traffic Location (≥ 80 msa)	No Special Features
Impact Group			1	2	3	4	5
Geographical Location	Site Previously Flooded (within 10 yrs)	1	-	1	3	4	1
	Sited in Flood Plain	2	-	-	3	4	2
	Critical Node Point	3	-	-	-	3	3
	High Traffic Location (≥ 80 msa)	4	-	-	-	-	4
	No Special Features	5	-	-	-	-	-
	Pairwise Calculations	Count	2	1	4	3	0
		X	10				
		Weightages	20	10	40	30	0

Impact Group	Impact Element	Condition Number (C) Y-Axis Primary	Age of Asset						
			Older than 1950	1950 - 1967	1968 - 1972	1973 - 1977	1978 - 1985	1986 - 1992	1993 - Present
Impact Group			1	2	3	4	5	6	7
Age of Asset	Older than 1950	1	-	1	1	1	1	1	1
	1950 - 1967	2	-	-	2	2	2	2	2
	1968 - 1972	3	-	-	-	3	3	3	3
	1973 - 1977	4	-	-	-	-	4	4	4
	1978 - 1985	5	-	-	-	-	-	5	5
	1986 - 1992	6	-	-	-	-	-	-	6
	1993 - Present	7	-	-	-	-	-	-	-
	Pairwise Calculations	Count	6	5	4	3	2	1	0
		X	4.761904762						
		Weightages	29	24	19	14	10	5	0

Impact Group	Impact Element	Condition Number (C) Y-Axis Primary	Inter-network Node Point	
			Yes	No
Impact Group			1	2
Inter-network Node Point	Yes	1	-	1
	No	2	-	-
	Pairwise Calculations	Count	1	0
		X	100	
		Weightages	17	0

Impact Group	Impact Element	Condition Number (C) Y-Axis Primary	Vegetation				
			Vegetation Removed	Grasses	Low Level Shrub	Trees	Mixed
Impact Group			1	2	3	4	5
Vegetation	Vegetation Removed	1	-	1	1	1	1
	Grasses	2	-	-	2	2	2
	Low Level Shrub	3	-	-	-	3	3
	Trees	4	-	-	-	-	4
	Mixed	5	-	-	-	-	-
	Pairwise Calculations	Count	4	3	2	1	0
		X	10				
		Weightages	40	30	20	10	0

Impact Group	Impact Element	Condition Number (C) Y-Axis Primary	Construction Materials				
			Construction Materials Unknown	Construction Material Known but Non-compliant with Current Design Standards Unknown Slope Angle	Construction Material Known but Non-compliant with Current Design Standards Known Slope Angle	Construction Material Known, Materials Compliant with Current Design Standards Unknown Slope Angle	Construction Material Known, Materials Compliant with Current Design Standards Known Slope Angle
Impact Group			1	2	3	4	5
Construction Materials	Construction Materials Unknown	1	-	1	1	1	1
	Construction Material Known but Non-compliant with Current Design Standards Unknown Slope Angle	2	-	-	2	2	2
	Construction Material Known but Non-compliant with Current Design Standards Known Slope Angle	3	-	-	-	3	3
	Construction Material Known, Materials Compliant with Current Design Standards Unknown Slope Angle	4	-	-	-	-	4
	Construction Material Known, Materials Compliant with Current Design Standards Known Slope Angle	5	-	-	-	-	-
	Pairwise Calculations	Count	4	3	2	1	0
		X	10				
		Weightages	40	30	20	10	0

Impact Group	Impact Element	Condition Number (C) Y-Axis Primary	Maintenance History			
			Asset not been Inspected or Maintained within last 5 years	Asset has been Inspected, Minor Maintenance required with last 5 years	Asset has been Inspected, Major Maintenance required with last 5 years	Asset has been inspected, No defects, No maintenance
Impact Group			1	2	3	4
Maintenance History	Asset not been Inspected or Maintained within last 5 years	1	-	1	1	1
	Asset has been Inspected, Minor Maintenance required with last 5 years	2	-	-	2	2
	Asset has been Inspected, Major Maintenance required with last 5 years	3	-	-	-	3
	Asset has been inspected, No defects, No maintenance	4	-	-	-	-
	Pairwise Calculations	Count	3	2	1	0
		X	16.66666667			
		Weightages	50	33	17	0

	Impact Group	Condition Number (C) Y-Axis Primary	External Weathering			
	Impact Element		Water Scour	Wind Scour	Chemical Changes to Soil	None Visable
Impact Group			1	2	3	4
External Weathering	Water Scour	1	-	1	1	1
	Wind Scour	2	-	-	2	2
	Chemical Changes to Soil	3	-	-	-	3
	None Visable	4	-	-	-	-
	Pairwise Calculations	Count	3	2	1	0
		X	16.66666667			
		Weightages	50	33	17	0

	Impact Group	Condition Number (C) Y-Axis Primary	Geotechnical Hazard Event	
	Impact Element		In Progress	None
Impact Group			1	2
Geotechnical Hazard Event	In Progress	1	-	1
	None	2	-	-
	Pairwise Calculations	Count	1	0
		X	100	
		Weightages	17	0

	Impact Group	Condition Number (C) Y-Axis Primary	Collision Trauma History Requiring Maintenance within the last 5 years? (Or Since last Principle Inspection?)	
	Impact Element		Yes	No
Impact Group			1	2
Collision Trauma History Requiring Maintenance within the last 5 years? (Or Since last Principle Inspection?)	Yes	1	-	1
	No	2	-	-
	Pairwise Calculations	Count	1	0
		X	100	
		Weightages	17	0

Pairwise Interviewee 4

Impact Group	Condition Number (C) Y-Axis Primary	Groundwater fluctuations	Change in Loading Conditions	Underlying Geology	Geographical Location	Age of Asset	Inter-network Node Point	Vegetation	Construction Materials	Maintenance History	External Weathering	Geotechnical Hazard Event	Collision Trauma History Requiring Maintenance within the last 5 years? (Or Since last Principle Inspection?)
		1	2	3	4	5	6	7	8	9	10	11	12
Groundwater fluctuations	1	-	1	1	1	1	1	1	1	1	1	1	1
Change in Loading Conditions	2	-	-	2	2	2	2	2	2	2	2	2	2
Underlying Geology	3	-	-	-	3	3	3	3	3	3	3	3	3
Geographical Location	4	-	-	-	-	4	4	4	4	4	4	4	4
Age of Asset	5	-	-	-	-	-	5	5	5	5	5	5	5
Inter-network Node Point	6	-	-	-	-	-	-	6	6	6	6	6	6
Vegetation	7	-	-	-	-	-	-	-	7	7	7	7	7
Construction Materials	8	-	-	-	-	-	-	-	-	8	8	8	8
Maintenance History	9	-	-	-	-	-	-	-	-	-	9	9	9
External Weathering	10	-	-	-	-	-	-	-	-	-	-	10	10
Geotechnical Hazard Event	11	-	-	-	-	-	-	-	-	-	-	-	11
Collision Trauma History Requiring Maintenance within the last 5 years? (Or Since last Principle Inspection?)	12	-	-	-	-	-	-	-	-	-	-	-	-
Pairwise Calculations	Count	11	10	9	8	7	6	5	4	3	2	1	0
	X	1.515151515											
	Weightages	17	15	14	12	11	9	8	6	5	3	2	0

Impact Group	Impact Group / Impact Element	Condition Number (C) Y-Axis Primary	Unknown	Flooding Event	Damaged/ Blocked/ Inadequate Drainage	Drought	Excessive Rainfall	Frost/Thaw	Seasonal Fluctuations	None
			Groundwater fluctuations							
Impact Group			1	2	3	4	5	6	7	8
Groundwater fluctuations	Unknown	1	-	2	3	tie	tie	1	1	1
	Flooding Event	2	-	-	2	2	2	2	2	2
	Damaged/Blocked/Inadequate Drainage	3	-	-	-	3	3	3	3	3
	Drought	4	-	-	-	-	tie	4	4	4
	Excessive Rainfall	5	-	-	-	-	-	5	5	5
	Frost/Thaw	6	-	-	-	-	-	-	6	6
	Seasonal Fluctuations	7	-	-	-	-	-	-	-	7
	None	8	-	-	-	-	-	-	-	-
	Pairwise Calculation	Count	4	7	5	4	3	2	1	0
		X	3.846153846							
		Weightages	15	27	19	15	12	8	4	0

	Impact Group		Change in Loading Conditions

Impact Group	Impact Element	Condition Number (C) Y-Axis Primary	Additional Material Added at Base or Top of Asset	Removal of Material at Base or Top of Asset	Subsidence Causing a Change in Loading Profile	No Change
			1	2	3	4
Change in Loading Conditions	Additional Material Added at Base or Top of Asset	1	-	tie	tie	1
	Removal of Material at Base or Top of Asset	2	-	-	tie	2
	Subsidence Causing a Change in Loading Profile	3	-	-	-	3
	No Change	4	-	-	-	-
	Pairwise Calculations	Count	2	2	2	0
		X	16.66666667			
		Weightages	33	33	33	0

Impact Group	Impact Element	Condition Number (C) Y-Axis Primary	Underlying Geology							
			Unknown	Organic Materials	Clays	Silts	Sands	Gravels/ Boulders/ Cobbles	Weak Rock	Rock
			1	2	3	4	5	6	7	8
Underlying Geology	Unknown	1	-	2	1	tie	tie	1	1	1
	Organic Materials	2	-	-	2	2	2	2	2	2
	Clays	3	-	-	-	3	3	3	3	3
	Silts	4	-	-	-	-	4	4	4	4
	Sands	5	-	-	-	-	-	5	5	5
	Gravels/Boulders/Cobbles	6	-	-	-	-	-	-	6	6
	Weak Rock	7	-	-	-	-	-	-	-	7
	Rock	8	-	-	-	-	-	-	-	-
	Pairwise Calculations	Count	5	7	5	4	3	2	1	0
		X	3.703703704							
		Weightages	19	26	19	15	11	7	4	0

Impact Group	Impact Element	Condition Number (C) Y-Axis Primary	Geographical Location				
			Site Previously Flooded (within 10 yrs)	Sited in Flood Plain	Critical Node Point	High Traffic Location (≥ 80 msa)	No Special Features
			1	2	3	4	5
Geographical Location	Site Previously Flooded (within 10 yrs)	1	-	1	3	4	1
	Sited in Flood Plain	2	-	-	3	4	2
	Critical Node Point	3	-	-	-	3	3
	High Traffic Location (≥ 80 msa)	4	-	-	-	-	4
	No Special Features	5	-	-	-	-	-
	Pairwise Calculations	Count	2	1	4	3	0
		X	10				
		Weightages	20	10	40	30	0

Impact Group	Impact Element	Condition Number (C) Y-Axis	Age of Asset						
			Older than 1950	1950 - 1967	1968 - 1972	1973 - 1977	1978 - 1985	1986 - 1992	1993 - Present

Impact Group		Primary	1	2	3	4	5	6	7
Age of Asset	Older than 1950	1	-	1	1	1	1	1	1
	1950 - 1967	2	-	-	2	2	2	2	2
	1968 - 1972	3	-	-	-	3	3	3	3
	1973 - 1977	4	-	-	-	-	4	4	4
	1978 - 1985	5	-	-	-	-	-	5	5
	1986 - 1992	6	-	-	-	-	-	-	6
	1993 - Present	7	-	-	-	-	-	-	-
	Pairwise Calculations	Count	6	5	4	3	2	1	0
		X	4.761904762						
		Weightages	29	24	19	14	10	5	0

	Impact Group	Condition Number (C) Y-Axis Primary	Inter-network Node Point	
	Impact Element		Yes	No
Impact Group			1	2
Inter-network Node Point	Yes	1	-	1
	No	2	-	-
	Pairwise Calculations	Count	1	0
		X	100	
		Weightages	17	0

	Impact Group	Condition Number (C) Y-Axis Primary	Vegetation				
	Impact Element		Vegetation Removed	Grasses	Low Level Shrub	Trees	Mixed
Impact Group			1	2	3	4	5
Vegetation	Vegetation Removed	1	-	1	1	1	1
	Grasses	2	-	-	2	2	2
	Low Level Shrub	3	-	-	-	3	3
	Trees	4	-	-	-	-	4
	Mixed	5	-	-	-	-	-
	Pairwise Calculations	Count	4	3	2	1	0
		X	10				
		Weightages	40	30	20	10	0

	Impact Group	Condition Number (C) Y-Axis Primary	Construction Materials				
	Impact Element		Construction Materials Unknown	Construction Material Known but Non-compliant with Current Design Standards Unknown Slope Angle	Construction Material Known but Non-compliant with Current Design Standards Known Slope Angle	Construction Material Known, Materials Compliant with Current Design Standards Unknown Slope Angle	Construction Material Known, Materials Compliant with Current Design Standards Known Slope Angle
Impact Group			1	2	3	4	5
Construction Materials	Construction Materials Unknown	1	-	1	1	1	1
	Construction Material Known but Non-compliant with Current Design Standards Unknown Slope Angle	2	-	-	2	2	2
	Construction Material Known but Non-compliant with Current Design Standards Known Slope Angle	3	-	-	-	3	3
	Construction Material Known, Materials Compliant with Current Design Standards Unknown Slope Angle	4	-	-	-	-	4
	Construction Material Known, Materials Compliant with Current Design Standards Known Slope Angle	5	-	-	-	-	-
	Pairwise Calculations	Count	4	3	2	1	0
		X	10				
		Weightages	40	30	20	10	0

	Impact Group	Condition Number (C) Y-Axis Primary	Maintenance History			
	Impact Element		Asset not been Inspected or Maintained within last 5 years	Asset has been Inspected, Minor Maintenance required with last 5 years	Asset has been Inspected, Major Maintenance required with last 5 years	Asset has been inspected, No defects, No maintenance
Impact Group			1	2	3	4
Maintenance History	Asset not been Inspected or Maintained within last 5 years	1	-	1	1	1
	Asset has been Inspected, Minor Maintenance required with last 5 years	2	-	-	2	2
	Asset has been Inspected, Major Maintenance required with last 5 years	3	-	-	-	3
	Asset has been inspected, No defects, No maintenance	4	-	-	-	-
	Pairwise Calculations	Count	3	2	1	0
		X	16.66666667			
		Weightages	50	33	17	0

	Impact Group	Condition Number (C) Y-Axis Primary	External Weathering			
	Impact Element		Water Scour	Wind Scour	Chemical Changes to Soil	None Visable
Impact Group			1	2	3	4
External Weathering	Water Scour	1	-	1	1	1
	Wind Scour	2	-	-	2	2
	Chemical Changes to Soil	3	-	-	-	3
	None Visable	4	-	-	-	-
	Pairwise Calculations	Count	3	2	1	0
		X	16.66666667			
		Weightages	50	33	17	0

	Impact Group	Condition Number (C) Y-Axis Primary	Geotechnical Hazard Event	
	Impact Element		In Progress	None
Impact Group			1	2
Geotechnical Hazard Event	In Progress	1	-	1
	None	2	-	-
	Pairwise Calculations	Count	1	0
		X	100	
		Weightages	17	0

	Impact Group	Condition Number (C) Y-Axis Primary	Collision Trauma History Requiring Maintenance within the last 5 years? (Or Since last Principle Inspection?)	
	Impact Element		Yes	No
Impact Group			1	2
Collision Trauma History Requiring Maintenance within the last 5 years? (Or Since last Principle Inspection?)	Yes	1	-	1
	No	2	-	-
	Pairwise Calculations	Count	1	0
		X	100	
		Weightages	17	0

Pairwise Interviewee 5

Impact Group	Condition Number (C) Y-Axis Primary	Groundwater fluctuations	Change in Loading Conditions	Underlying Geology	Geographical Location	Age of Asset	Inter-network Node Point	Vegetation	Construction Materials	Maintenance History	External Weathering	Geotechnical Hazard Event	Collision Trauma History Requiring Maintenance within the last 5 years? (Or Since last Principle Inspection?)
		1	2	3	4	5	6	7	8	9	10	11	12
Groundwater fluctuations	1	-	1	1	1	1	1	1	1	1	1	1	1
Change in Loading Conditions	2	-	-	2	2	2	2	2	2	2	2	2	2
Underlying Geology	3	-	-	-	3	3	3	3	3	3	3	3	3
Geographical Location	4	-	-	-	-	4	4	4	4	4	4	4	4
Age of Asset	5	-	-	-	-	-	5	5	5	5	5	5	5
Inter-network Node Point	6	-	-	-	-	-	-	6	6	6	6	6	6
Vegetation	7	-	-	-	-	-	-	-	7	7	7	7	7
Construction Materials	8	-	-	-	-	-	-	-	-	8	8	8	8
Maintenance History	9	-	-	-	-	-	-	-	-	-	9	9	9
External Weathering	10	-	-	-	-	-	-	-	-	-	-	10	10
Geotechnical Hazard Event	11	-	-	-	-	-	-	-	-	-	-	-	11
Collision Trauma History Requiring Maintenance within the last 5 years? (Or Since last Principle Inspection?)	12	-	-	-	-	-	-	-	-	-	-	-	-
Pairwise Calculations	Count	11	10	9	8	7	6	5	4	3	2	1	0
	X	1.515151515											
	Weightages	17	15	14	12	11	9	8	6	5	3	2	0

	Impact Group		Groundwater fluctuations							
	Impact Element	Condition Number (C) Y-Axis Primary	Unknown	Flooding Event	Damaged/ Blocked/ Inadequate Drainage	Drought	Excessive Rainfall	Frost/Thaw	Seasonal Fluctuations	None
Impact Group			1	2	3	4	5	6	7	8
Groundwater fluctuations	Unknown	1	-	2	3	tie	tie	1	1	1
	Flooding Event	2	-	-	2	2	2	2	2	2
	Damaged/Blocked/Inadequate Drainage	3	-	-	-	3	3	3	3	3
	Drought	4	-	-	-	-	tie	4	4	4
	Excessive Rainfall	5	-	-	-	-	-	5	5	5
	Frost/Thaw	6	-	-	-	-	-	-	6	6
	Seasonal Fluctuations	7	-	-	-	-	-	-	-	7
	None	8	-	-	-	-	-	-	-	-
	Pairwise Calculation	Count	4	7	5	4	3	2	1	0
		X	3.846153846							
		Weightages	15	27	19	15	12	8	4	0

Impact Group	Impact Element	Condition Number (C) Y-Axis Primary	Change in Loading Conditions			
			Additional Material Added at Base or Top of Asset	Removal of Material at Base or Top of Asset	Subsidence Causing a Change in Loading Profile	No Change
Impact Group			1	2	3	4
Change in Loading Conditions	Additional Material Added at Base or Top of Asset	1	-	tie	tie	1
	Removal of Material at Base or Top of Asset	2	-	-	tie	2
	Subsidence Causing a Change in Loading Profile	3	-	-	-	3
	No Change	4	-	-	-	-
	Pairwise Calculations	Count	2	2	2	0
		X	16.66666667			
		Weightages	33	33	33	0

Impact Group	Impact Element	Condition Number (C) Y-Axis Primary	Underlying Geology							
			Unknown	Organic Materials	Clays	Silts	Sands	Gravels/ Boulders/ Cobbles	Weak Rock	Rock
Impact Group			1	2	3	4	5	6	7	8
Underlying Geology	Unknown	1	-	2	1	tie	tie	1	1	1
	Organic Materials	2	-	-	2	2	2	2	2	2
	Clays	3	-	-	-	3	3	3	3	3
	Silts	4	-	-	-	-	4	4	4	4
	Sands	5	-	-	-	-	-	5	5	5
	Gravels/Boulders/Cobbles	6	-	-	-	-	-	-	6	6
	Weak Rock	7	-	-	-	-	-	-	-	7
	Rock	8	-	-	-	-	-	-	-	-
	Pairwise Calculations	Count	5	7	5	4	3	2	1	0
		X	3.703703704							
		Weightages	19	26	19	15	11	7	4	0

Impact Group	Impact Element	Condition Number (C) Y-Axis Primary	Geographical Location				
			Site Previously Flooded (within 10 yrs)	Sited in Flood Plain	Critical Node Point	High Traffic Location (≥ 80 msa)	No Special Features
Impact Group			1	2	3	4	5
Geographical Location	Site Previously Flooded (within 10 yrs)	1	-	1	3	4	1
	Sited in Flood Plain	2	-	-	3	4	2
	Critical Node Point	3	-	-	-	3	3
	High Traffic Location (≥ 80 msa)	4	-	-	-	-	4
	No Special Features	5	-	-	-	-	-
	Pairwise Calculations	Count	2	1	4	3	0
		X	10				
		Weightages	20	10	40	30	0

Impact Group	Impact Element	Condition Number (C) Y-Axis Primary	Age of Asset						
			Older than 1950	1950 - 1967	1968 - 1972	1973 - 1977	1978 - 1985	1986 - 1992	1993 - Present
			1	2	3	4	5	6	7
Age of Asset	Older than 1950	1	-	1	1	1	1	1	1
	1950 - 1967	2	-	-	2	2	2	2	2
	1968 - 1972	3	-	-	-	3	3	3	3
	1973 - 1977	4	-	-	-	-	4	4	4
	1978 - 1985	5	-	-	-	-	-	5	5
	1986 - 1992	6	-	-	-	-	-	-	6
	1993 - Present	7	-	-	-	-	-	-	-
	Pairwise Calculations	Count	6	5	4	3	2	1	0
		X	4.761904762						
		Weightages	29	24	19	14	10	5	0

Impact Group	Impact Element	Condition Number (C) Y-Axis Primary	Inter-network Node Point	
			Yes	No
			1	2
Inter-network Node Point	Yes	1	-	1
	No	2	-	-
	Pairwise Calculations	Count	1	0
		X	100	
		Weightages	17	0

Impact Group	Impact Element	Condition Number (C) Y-Axis Primary	Vegetation				
			Vegetation Removed	Grasses	Low Level Shrub	Trees	Mixed
			1	2	3	4	5
Vegetation	Vegetation Removed	1	-	1	1	1	1
	Grasses	2	-	-	2	2	2
	Low Level Shrub	3	-	-	-	3	3
	Trees	4	-	-	-	-	4
	Mixed	5	-	-	-	-	-
	Pairwise Calculations	Count	4	3	2	1	0
		X	10				
		Weightages	40	30	20	10	0

Impact Group	Impact Group / Impact Element	Condition Number (C) Y-Axis Primary	Construction Materials				
			Construction Materials Unknown	Construction Material Known but Non-compliant with Current Design Standards Unknown Slope Angle	Construction Material Known but Non-compliant with Current Design Standards Known Slope Angle	Construction Material Known, Materials Compliant with Current Design Standards Unknown Slope Angle	Construction Material Known, Materials Compliant with Current Design Standards Known Slope Angle
Impact Group			1	2	3	4	5
Construction Materials	Construction Materials Unknown	1	-	1	1	1	1
	Construction Material Known but Non-compliant with Current Design Standards Unknown Slope Angle	2	-	-	2	2	2
	Construction Material Known but Non-compliant with Current Design Standards Known Slope Angle	3	-	-	-	3	3
	Construction Material Known, Materials Compliant with Current Design Standards Unknown Slope Angle	4	-	-	-	-	4
	Construction Material Known, Materials Compliant with Current Design Standards Known Slope Angle	5	-	-	-	-	-
	Pairwise Calculations	Count	4	3	2	1	0
		X	10				
		Weightages	40	30	20	10	0

Impact Group	Impact Group / Impact Element	Condition Number (C) Y-Axis Primary	Maintenance History			
			Asset not been Inspected or Maintained within last 5 years	Asset has been Inspected, Minor Maintenance required with last 5 years	Asset has been Inspected, Major Maintenance required with last 5 years	Asset has been inspected, No defects, No maintenance
Impact Group			1	2	3	4
Maintenance History	Asset not been Inspected or Maintained within last 5 years	1	-	1	1	1
	Asset has been Inspected, Minor Maintenance required with last 5 years	2	-	-	2	2
	Asset has been Inspected, Major Maintenance required with last 5 years	3	-	-	-	3
	Asset has been inspected, No defects, No maintenance	4	-	-	-	-
	Pairwise Calculations	Count	3	2	1	0
		X	16.66666667			
		Weightages	50	33	17	0

Impact Group	Impact Group / Impact Element	Condition Number (C) Y-Axis Primary	External Weathering			
			Water Scour	Wind Scour	Chemical Changes to Soil	None Visable
			1	2	3	4
External Weathering	Water Scour	1	-	1	1	1
	Wind Scour	2	-	-	2	2
	Chemical Changes to Soil	3	-	-	-	3
	None Visable	4	-	-	-	-
	Pairwise Calculations	Count	3	2	1	0
		X	16.66666667			
		Weightages	50	33	17	0

Impact Group	Impact Group / Impact Element	Condition Number (C) Y-Axis Primary	Geotechnical Hazard Event	
			In Progress	None
			1	2
Geotechnical Hazard Event	In Progress	1	-	1
	None	2	-	-
	Pairwise Calculations	Count	1	0
		X	100	
		Weightages	17	0

Impact Group	Impact Group / Impact Element	Condition Number (C) Y-Axis Primary	Collision Trauma History Requiring Maintenance within the last 5 years? (Or Since last Principle Inspection?)	
			Yes	No
			1	2
Collision Trauma History Requiring Maintenance within the last 5 years? (Or Since last Principle Inspection?)	Yes	1	-	1
	No	2	-	-
	Pairwise Calculations	Count	1	0
		X	100	
		Weightages	17	0

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Impact Group	Condition Number (C) Y-Axis Primary	Groundwater fluctuations	Change in Loading Conditions	Underlying Geology	Geographical Location	Age of Asset	Inter-network Node Point	Vegetation	Construction Materials	Maintenance History	External Weathering	Geotechnical Hazard Event	Collision Trauma History Requiring Maintenance within the last 5 years? (Or Since last Principle Inspection?)
		1	2	3	4	5	6	7	8	9	10	11	12
Groundwater fluctuations	1	-	1	1	1	1	1	1	1	1	1	1	1
Change in Loading Conditions	2	-	-	2	2	2	2	2	2	2	2	2	2
Underlying Geology	3	-	-	-	3	3	3	3	3	3	3	3	3
Geographical Location	4	-	-	-	-	4	4	4	4	4	4	4	4
Age of Asset	5	-	-	-	-	-	5	5	5	5	5	5	5
Inter-network Node Point	6	-	-	-	-	-	-	6	6	6	6	6	6
Vegetation	7	-	-	-	-	-	-	-	7	7	7	7	7
Construction Materials	8	-	-	-	-	-	-	-	-	8	8	8	8
Maintenance History	9	-	-	-	-	-	-	-	-	-	9	9	9
External Weathering	10	-	-	-	-	-	-	-	-	-	-	10	10
Geotechnical Hazard Event	11	-	-	-	-	-	-	-	-	-	-	-	11
Collision Trauma History Requiring Maintenance within the last 5 years? (Or Since last Principle Inspection?)	12	-	-	-	-	-	-	-	-	-	-	-	-
Pairwise Calculations	Count	11	10	9	8	7	6	5	4	3	2	1	0
	X	1.515151515											
	Weightages	17	15	14	12	11	9	8	6	5	3	2	0

	Impact Group	Condition Number (C) Y-Axis Primary	Groundwater fluctuations							
	Impact Element		Unknown	Flooding Event	Damaged/ Blocked/ Inadequate Drainage	Drought	Excessive Rainfall	Frost/Thaw	Seasonal Fluctuations	None
Impact Group			1	2	3	4	5	6	7	8
Groundwater fluctuations	Unknown	1	-	2	3	tie	tie	1	1	1
	Flooding Event	2	-	-	2	2	2	2	2	2
	Damaged/Blocked/Inadequate Drainage	3	-	-	-	3	3	3	3	3
	Drought	4	-	-	-	-	tie	4	4	4
	Excessive Rainfall	5	-	-	-	-	-	5	5	5
	Frost/Thaw	6	-	-	-	-	-	-	6	6
	Seasonal Fluctuations	7	-	-	-	-	-	-	-	7
	None	8	-	-	-	-	-	-	-	-
	Pairwise Calculation	Count	4	7	5	4	3	2	1	0
		X	3.846153846							
		Weightages	15	27	19	15	12	8	4	0

Impact Group	Impact Element	Condition Number (C) Y-Axis Primary	Change in Loading Conditions			
			Additional Material Added at Base or Top of Asset	Removal of Material at Base or Top of Asset	Subsidence Causing a Change in Loading Profile	No Change
Impact Group			1	2	3	4
Change in Loading Conditions	Additional Material Added at Base or Top of Asset	1	-	tie	tie	1
	Removal of Material at Base or Top of Asset	2	-	-	tie	2
	Subsidence Causing a Change in Loading Profile	3	-	-	-	3
	No Change	4	-	-	-	-
	Pairwise Calculations	Count	2	2	2	0
		X	16.66666667			
		Weightages	33	33	33	0

Impact Group	Impact Element	Condition Number (C) Y-Axis Primary	Underlying Geology							
			Unknown	Organic Materials	Clays	Silts	Sands	Gravels/ Boulders/ Cobbles	Weak Rock	Rock
Impact Group			1	2	3	4	5	6	7	8
Underlying Geology	Unknown	1	-	2	1	tie	tie	1	1	1
	Organic Materials	2	-	-	2	2	2	2	2	2
	Clays	3	-	-	-	3	3	3	3	3
	Silts	4	-	-	-	-	4	4	4	4
	Sands	5	-	-	-	-	-	5	5	5
	Gravels/Boulders/Cobbles	6	-	-	-	-	-	-	6	6
	Weak Rock	7	-	-	-	-	-	-	-	7
	Rock	8	-	-	-	-	-	-	-	-
	Pairwise Calculations	Count	5	7	5	4	3	2	1	0
		X	3.703703704							
		Weightages	19	26	19	15	11	7	4	0

Impact Group	Impact Element	Condition Number (C) Y-Axis Primary	Geographical Location				
			Site Previously Flooded (within 10 yrs)	Sited in Flood Plain	Critical Node Point	High Traffic Location (≥ 80 msa)	No Special Features
Impact Group			1	2	3	4	5
Geographical Location	Site Previously Flooded (within 10 yrs)	1	-	1	3	4	1
	Sited in Flood Plain	2	-	-	3	4	2
	Critical Node Point	3	-	-	-	3	3
	High Traffic Location (≥ 80 msa)	4	-	-	-	-	4
	No Special Features	5	-	-	-	-	-
	Pairwise Calculations	Count	2	1	4	3	0
		X	10				
		Weightages	20	10	40	30	0

Impact Group	Impact Group	Condition Number (C) Y-Axis Primary	Age of Asset						
	Impact Element		Older than 1950	1950 - 1967	1968 - 1972	1973 - 1977	1978 - 1985	1986 - 1992	1993 - Present
			1	2	3	4	5	6	7
Age of Asset	Older than 1950	1	-	1	1	1	1	1	1
	1950 - 1967	2	-	-	2	2	2	2	2
	1968 - 1972	3	-	-	-	3	3	3	3
	1973 - 1977	4	-	-	-	-	4	4	4
	1978 - 1985	5	-	-	-	-	-	5	5
	1986 - 1992	6	-	-	-	-	-	-	6
	1993 - Present	7	-	-	-	-	-	-	-
	Pairwise Calculations	Count	6	5	4	3	2	1	0
		X	4.761904762						
		Weightages	29	24	19	14	10	5	0

Impact Group	Impact Group	Condition Number (C) Y-Axis Primary	Inter-network Node Point	
	Impact Element		Yes	No
			1	2
Inter-network Node Point	Yes	1	-	1
	No	2	-	-
	Pairwise Calculations	Count	1	0
		X	100	
		Weightages	17	0

Impact Group	Impact Group	Condition Number (C) Y-Axis Primary	Vegetation				
	Impact Element		Vegetation Removed	Grasses	Low Level Shrub	Trees	Mixed
			1	2	3	4	5
Vegetation	Vegetation Removed	1	-	1	1	1	1
	Grasses	2	-	-	2	2	2
	Low Level Shrub	3	-	-	-	3	3
	Trees	4	-	-	-	-	4
	Mixed	5	-	-	-	-	-
	Pairwise Calculations	Count	4	3	2	1	0
		X	10				
		Weightages	40	30	20	10	0

Impact Group	Impact Group	Condition Number (C) Y-Axis Primary	Construction Materials				
	Impact Element		Construction Materials Unknown	Construction Material Known but Non-compliant with Current Design Standards Unknown Slope Angle	Construction Material Known but Non-compliant with Current Design Standards Known Slope Angle	Construction Material Known, Materials Compliant with Current Design Standards Unknown Slope Angle	Construction Material Known, Materials Compliant with Current Design Standards Known Slope Angle
Impact Group			1	2	3	4	5
Construction Materials	Construction Materials Unknown	1	-	1	1	1	1
	Construction Material Known but Non-compliant with Current Design Standards Unknown Slope Angle	2	-	-	2	2	2
	Construction Material Known but Non-compliant with Current Design Standards Known Slope Angle	3	-	-	-	3	3
	Construction Material Known, Materials Compliant with Current Design Standards Unknown Slope Angle	4	-	-	-	-	4
	Construction Material Known, Materials Compliant with Current Design Standards Known Slope Angle	5	-	-	-	-	-
	Pairwise Calculations	Count	4	3	2	1	0
		X	10				
		Weightages	40	30	20	10	0

Impact Group	Impact Group	Condition Number (C) Y-Axis Primary	Maintenance History			
	Impact Element		Asset not been Inspected or Maintained within last 5 years	Asset has been Inspected, Minor Maintenance required with last 5 years	Asset has been Inspected, Major Maintenance required with last 5 years	Asset has been inspected, No defects, No maintenance
Impact Group			1	2	3	4
Maintenance History	Asset not been Inspected or Maintained within last 5 years	1	-	1	1	1
	Asset has been Inspected, Minor Maintenance required with last 5 years	2	-	-	2	2
	Asset has been Inspected, Major Maintenance required with last 5 years	3	-	-	-	3
	Asset has been inspected, No defects, No maintenance	4	-	-	-	-
	Pairwise Calculations	Count	3	2	1	0
		X	16.66666667			
		Weightages	50	33	17	0

	Impact Group	Condition Number (C) Y-Axis Primary	External Weathering			
	Impact Element		Water Scour	Wind Scour	Chemical Changes to Soil	None Visable
Impact Group			1	2	3	4
External Weathering	Water Scour	1	-	1	1	1
	Wind Scour	2	-	-	2	2
	Chemical Changes to Soil	3	-	-	-	3
	None Visable	4	-	-	-	-
	Pairwise Calculations	Count	3	2	1	0
		X	16.66666667			
		Weightages	50	33	17	0

	Impact Group	Condition Number (C) Y-Axis Primary	Geotechnical Hazard Event	
	Impact Element		In Progress	None
Impact Group			1	2
Geotechnical Hazard Event	In Progress	1	-	1
	None	2	-	-
	Pairwise Calculations	Count	1	0
		X	100	
		Weightages	17	0

	Impact Group	Condition Number (C) Y-Axis Primary	Collision Trauma History Requiring Maintenance within the last 5 years? (Or Since last Principle Inspection?)	
	Impact Element		Yes	No
Impact Group			1	2
Collision Trauma History Requiring Maintenance within the last 5 years? (Or Since last Principle Inspection?)	Yes	1	-	1
	No	2	-	-
	Pairwise Calculations	Count	1	0
		X	100	
		Weightages	17	0

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Impact Group	Condition Number (C) Y-Axis Primary	Groundwater fluctuations	Change in Loading Conditions	Underlying Geology	Geographical Location	Age of Asset	Inter-network Node Point	Vegetation	Construction Materials	Maintenance History	External Weathering	Geotechnical Hazard Event	Collision Trauma History Requiring Maintenance within the last 5 years? (Or Since last Principle Inspection?)
		1	2	3	4	5	6	7	8	9	10	11	12
Groundwater fluctuations	1	-	1	1	1	1	1	1	1	1	1	1	1
Change in Loading Conditions	2	-	-	2	2	2	2	2	2	2	2	2	2
Underlying Geology	3	-	-	-	3	3	3	3	3	3	3	3	3
Geographical Location	4	-	-	-	-	4	4	4	4	4	4	4	4
Age of Asset	5	-	-	-	-	-	5	5	5	5	5	5	5
Inter-network Node Point	6	-	-	-	-	-	-	6	6	6	6	6	6
Vegetation	7	-	-	-	-	-	-	-	7	7	7	7	7
Construction Materials	8	-	-	-	-	-	-	-	-	8	8	8	8
Maintenance History	9	-	-	-	-	-	-	-	-	-	9	9	9
External Weathering	10	-	-	-	-	-	-	-	-	-	-	10	10
Geotechnical Hazard Event	11	-	-	-	-	-	-	-	-	-	-	-	11
Collision Trauma History Requiring Maintenance within the last 5 years? (Or Since last Principle Inspection?)	12	-	-	-	-	-	-	-	-	-	-	-	-
Pairwise Calculations	Count	11	10	9	8	7	6	5	4	3	2	1	0
	X	1.515151515											
	Weightages	17	15	14	12	11	9	8	6	5	3	2	0

	Impact Group		Groundwater fluctuations							
	Impact Element	Condition Number (C) Y-Axis Primary	Unknown	Flooding Event	Damaged/ Blocked/ Inadequate Drainage	Drought	Excessive Rainfall	Frost/Thaw	Seasonal Fluctuations	None
Impact Group			1	2	3	4	5	6	7	8
Groundwater fluctuations	Unknown	1	-	2	3	tie	tie	1	1	1
	Flooding Event	2	-	-	2	2	2	2	2	2
	Damaged/Blocked/Inadequate Drainage	3	-	-	-	3	3	3	3	3
	Drought	4	-	-	-	-	tie	4	4	4
	Excessive Rainfall	5	-	-	-	-	-	5	5	5
	Frost/Thaw	6	-	-	-	-	-	-	6	6
	Seasonal Fluctuations	7	-	-	-	-	-	-	-	7
	None	8	-	-	-	-	-	-	-	-
	Pairwise Calculation	Count	4	7	5	4	3	2	1	0
		X	3.846153846							
		Weightages	15	27	19	15	12	8	4	0

Impact Group	Impact Element	Condition Number (C) Y-Axis Primary	Change in Loading Conditions			
			Additional Material Added at Base or Top of Asset	Removal of Material at Base or Top of Asset	Subsidence Causing a Change in Loading Profile	No Change
Impact Group			1	2	3	4
Change in Loading Conditions	Additional Material Added at Base or Top of Asset	1	-	tie	tie	1
	Removal of Material at Base or Top of Asset	2	-	-	tie	2
	Subsidence Causing a Change in Loading Profile	3	-	-	-	3
	No Change	4	-	-	-	-
	Pairwise Calculations	Count	2	2	2	0
		X	16.66666667			
		Weightages	33	33	33	0

Impact Group	Impact Element	Condition Number (C) Y-Axis Primary	Underlying Geology							
			Unknown	Organic Materials	Clays	Silts	Sands	Gravels/ Boulders/ Cobbles	Weak Rock	Rock
Impact Group			1	2	3	4	5	6	7	8
Underlying Geology	Unknown	1	-	2	1	tie	tie	1	1	1
	Organic Materials	2	-	-	2	2	2	2	2	2
	Clays	3	-	-	-	3	3	3	3	3
	Silts	4	-	-	-	-	4	4	4	4
	Sands	5	-	-	-	-	-	5	5	5
	Gravels/Boulders/Cobbles	6	-	-	-	-	-	-	6	6
	Weak Rock	7	-	-	-	-	-	-	-	7
	Rock	8	-	-	-	-	-	-	-	-
	Pairwise Calculations	Count	5	7	5	4	3	2	1	0
		X	3.703703704							
		Weightages	19	26	19	15	11	7	4	0

Impact Group	Impact Element	Condition Number (C) Y-Axis Primary	Geographical Location				
			Site Previously Flooded (within 10 yrs)	Sited in Flood Plain	Critical Node Point	High Traffic Location (≥ 80 msa)	No Special Features
Impact Group			1	2	3	4	5
Geographical Location	Site Previously Flooded (within 10 yrs)	1	-	1	3	4	1
	Sited in Flood Plain	2	-	-	3	4	2
	Critical Node Point	3	-	-	-	3	3
	High Traffic Location (≥ 80 msa)	4	-	-	-	-	4
	No Special Features	5	-	-	-	-	-
	Pairwise Calculations	Count	2	1	4	3	0
		X	10				
		Weightages	20	10	40	30	0

Impact Group	Impact Element	Condition Number (C) Y-Axis Primary	Age of Asset						
			Older than 1950	1950 - 1967	1968 - 1972	1973 - 1977	1978 - 1985	1986 - 1992	1993 - Present
Impact Group			1	2	3	4	5	6	7
Age of Asset	Older than 1950	1	-	1	1	1	1	1	1
	1950 - 1967	2	-	-	2	2	2	2	2
	1968 - 1972	3	-	-	-	3	3	3	3
	1973 - 1977	4	-	-	-	-	4	4	4
	1978 - 1985	5	-	-	-	-	-	5	5
	1986 - 1992	6	-	-	-	-	-	-	6
	1993 - Present	7	-	-	-	-	-	-	-
	Pairwise Calculations	Count	6	5	4	3	2	1	0
		X	4.761904762						
		Weightages	29	24	19	14	10	5	0

Impact Group	Impact Element	Condition Number (C) Y-Axis Primary	Inter-network Node Point	
			Yes	No
Impact Group			1	2
Inter-network Node Point	Yes	1	-	1
	No	2	-	-
	Pairwise Calculations	Count	1	0
		X	100	
		Weightages	17	0

Impact Group	Impact Element	Condition Number (C) Y-Axis Primary	Vegetation				
			Vegetation Removed	Grasses	Low Level Shrub	Trees	Mixed
Impact Group			1	2	3	4	5
Vegetation	Vegetation Removed	1	-	1	1	1	1
	Grasses	2	-	-	2	2	2
	Low Level Shrub	3	-	-	-	3	3
	Trees	4	-	-	-	-	4
	Mixed	5	-	-	-	-	-
	Pairwise Calculations	Count	4	3	2	1	0
		X	10				
		Weightages	40	30	20	10	0

Impact Group	Impact Element	Condition Number (C) Y-Axis Primary	Construction Materials				
			Construction Materials Unknown	Construction Material Known but Non-compliant with Current Design Standards Unknown Slope Angle	Construction Material Known but Non-compliant with Current Design Standards Known Slope Angle	Construction Material Known, Materials Compliant with Current Design Standards Unknown Slope Angle	Construction Material Known, Materials Compliant with Current Design Standards Known Slope Angle
Impact Group			1	2	3	4	5
Construction Materials	Construction Materials Unknown	1	-	1	1	1	1
	Construction Material Known but Non-compliant with Current Design Standards Unknown Slope Angle	2	-	-	2	2	2
	Construction Material Known but Non-compliant with Current Design Standards Known Slope Angle	3	-	-	-	3	3
	Construction Material Known, Materials Compliant with Current Design Standards Unknown Slope Angle	4	-	-	-	-	4
	Construction Material Known, Materials Compliant with Current Design Standards Known Slope Angle	5	-	-	-	-	-
	Pairwise Calculations	Count	4	3	2	1	0
		X	10				
		Weightages	40	30	20	10	0

Impact Group	Impact Element	Condition Number (C) Y-Axis Primary	Maintenance History			
			Asset not been Inspected or Maintained within last 5 years	Asset has been Inspected, Minor Maintenance required with last 5 years	Asset has been Inspected, Major Maintenance required with last 5 years	Asset has been inspected, No defects, No maintenance
Impact Group			1	2	3	4
Maintenance History	Asset not been Inspected or Maintained within last 5 years	1	-	1	1	1
	Asset has been Inspected, Minor Maintenance required with last 5 years	2	-	-	2	2
	Asset has been Inspected, Major Maintenance required with last 5 years	3	-	-	-	3
	Asset has been inspected, No defects, No maintenance	4	-	-	-	-
	Pairwise Calculations	Count	3	2	1	0
		X	16.66666667			
		Weightages	50	33	17	0

	Impact Group	Condition Number (C) Y-Axis Primary	External Weathering			
	Impact Element		Water Scour	Wind Scour	Chemical Changes to Soil	None Visable
Impact Group			1	2	3	4
External Weathering	Water Scour	1	-	1	1	1
	Wind Scour	2	-	-	2	2
	Chemical Changes to Soil	3	-	-	-	3
	None Visable	4	-	-	-	-
	Pairwise Calculations	Count	3	2	1	0
		X	16.66666667			
		Weightages	50	33	17	0

	Impact Group	Condition Number (C) Y-Axis Primary	Geotechnical Hazard Event	
	Impact Element		In Progress	None
Impact Group			1	2
Geotechnical Hazard Event	In Progress	1	-	1
	None	2	-	-
	Pairwise Calculations	Count	1	0
		X	100	
		Weightages	17	0

	Impact Group	Condition Number (C) Y-Axis Primary	Collision Trauma History Requiring Maintenance within the last 5 years? (Or Since last Principle Inspection?)	
	Impact Element		Yes	No
Impact Group			1	2
Collision Trauma History Requiring Maintenance within the last 5 years? (Or Since last Principle Inspection?)	Yes	1	-	1
	No	2	-	-
	Pairwise Calculations	Count	1	0
		X	100	
		Weightages	17	0

Pairwise Interviewee 8

Impact Group	Condition Number (C) Y-Axis Primary	Groundwater fluctuations	Change in Loading Conditions	Underlying Geology	Geographical Location	Age of Asset	Inter-network Node Point	Vegetation	Construction Materials	Maintenance History	External Weathering	Geotechnical Hazard Event	Collision Trauma History Requiring Maintenance within the last 5 years? (Or Since last Principle Inspection?)
		1	2	3	4	5	6	7	8	9	10	11	12
Groundwater fluctuations	1	-	1	1	1	1	1	1	1	1	1	1	1
Change in Loading Conditions	2	-	-	2	2	2	2	2	2	2	2	2	2
Underlying Geology	3	-	-	-	3	3	3	3	3	3	3	3	3
Geographical Location	4	-	-	-	-	4	4	4	4	4	4	4	4
Age of Asset	5	-	-	-	-	-	5	5	5	5	5	5	5
Inter-network Node Point	6	-	-	-	-	-	-	6	6	6	6	6	6
Vegetation	7	-	-	-	-	-	-	-	7	7	7	7	7
Construction Materials	8	-	-	-	-	-	-	-	-	8	8	8	8
Maintenance History	9	-	-	-	-	-	-	-	-	-	9	9	9
External Weathering	10	-	-	-	-	-	-	-	-	-	-	10	10
Geotechnical Hazard Event	11	-	-	-	-	-	-	-	-	-	-	-	11
Collision Trauma History Requiring Maintenance within the last 5 years? (Or Since last Principle Inspection?)	12	-	-	-	-	-	-	-	-	-	-	-	-
Pairwise Calculations	Count	11	10	9	8	7	6	5	4	3	2	1	0
	X	1.515151515											
	Weightages	17	15	14	12	11	9	8	6	5	3	2	0

Impact Group	Impact Element	Condition Number (C) Y-Axis Primary	Groundwater fluctuations							
			Unknown	Flooding Event	Damaged/ Blocked/ Inadequate Drainage	Drought	Excessive Rainfall	Frost/Thaw	Seasonal Fluctuations	None
			1	2	3	4	5	6	7	8
Groundwater fluctuations	Unknown	1	-	2	3	tie	tie	1	1	1
	Flooding Event	2	-	-	2	2	2	2	2	2
	Damaged/Blocked/Inadequate Drainage	3	-	-	-	3	3	3	3	3
	Drought	4	-	-	-	-	tie	4	4	4
	Excessive Rainfall	5	-	-	-	-	-	5	5	5
	Frost/Thaw	6	-	-	-	-	-	-	6	6
	Seasonal Fluctuations	7	-	-	-	-	-	-	-	7
	None	8	-	-	-	-	-	-	-	-
	Pairwise Calculation	Count	4	7	5	4	3	2	1	0
		X	3.846153846							
		Weightages	15	27	19	15	12	8	4	0

	Impact Group	Condition Number (C) Y-Axis Primary	Change in Loading Conditions			
	Impact Element		Additional Material Added at Base or Top of Asset	Removal of Material at Base or Top of Asset	Subsidence Causing a Change in Loading Profile	No Change
Impact Group			1	2	3	4
Change in Loading Conditions	Additional Material Added at Base or Top of Asset	1	-	tie	tie	1
	Removal of Material at Base or Top of Asset	2	-	-	tie	2
	Subsidence Causing a Change in Loading Profile	3	-	-	-	3
	No Change	4	-	-	-	-
	Pairwise Calculations	Count	2	2	2	0
		X	16.66666667			
		Weightages	33	33	33	0

	Impact Group	Condition Number (C) Y-Axis Primary	Underlying Geology							
	Impact Element		Unknown	Organic Materials	Clays	Silts	Sands	Gravels/ Boulders/ Cobbles	Weak Rock	Rock
Impact Group			1	2	3	4	5	6	7	8
Underlying Geology	Unknown	1	-	2	1	tie	tie	1	1	1
	Organic Materials	2	-	-	2	2	2	2	2	2
	Clays	3	-	-	-	3	3	3	3	3
	Silts	4	-	-	-	-	4	4	4	4
	Sands	5	-	-	-	-	-	5	5	5
	Gravels/Boulders/Cobbles	6	-	-	-	-	-	-	6	6
	Weak Rock	7	-	-	-	-	-	-	-	7
	Rock	8	-	-	-	-	-	-	-	-
	Pairwise Calculations	Count	5	7	5	4	3	2	1	0
		X	3.703703704							
		Weightages	19	26	19	15	11	7	4	0

	Impact Group	Condition Number (C) Y-Axis Primary	Geographical Location				
	Impact Element		Site Previously Flooded (within 10 yrs)	Sited in Flood Plain	Critical Node Point	High Traffic Location (≥ 80 msa)	No Special Features
Impact Group			1	2	3	4	5
Geographical Location	Site Previously Flooded (within 10 yrs)	1	-	1	3	4	1
	Sited in Flood Plain	2	-	-	3	4	2
	Critical Node Point	3	-	-	-	3	3
	High Traffic Location (≥ 80 msa)	4	-	-	-	-	4
	No Special Features	5	-	-	-	-	-
	Pairwise Calculations	Count	2	1	4	3	0
		X	10				
		Weightages	20	10	40	30	0

	Impact Group	Condition Number (C) Y-Axis Primary	Age of Asset						
	Impact Element		Older than 1950	1950 - 1967	1968 - 1972	1973 - 1977	1978 - 1985	1986 - 1992	1993 - Present
Impact Group			1	2	3	4	5	6	7
Age of Asset	Older than 1950	1	-	1	1	1	1	1	1
	1950 - 1967	2	-	-	2	2	2	2	2
	1968 - 1972	3	-	-	-	3	3	3	3
	1973 - 1977	4	-	-	-	-	4	4	4
	1978 - 1985	5	-	-	-	-	-	5	5
	1986 - 1992	6	-	-	-	-	-	-	6
	1993 - Present	7	-	-	-	-	-	-	-
	Pairwise Calculations	Count	6	5	4	3	2	1	0
		X	4.761904762						
		Weightages	29	24	19	14	10	5	0

	Impact Group	Condition Number (C) Y-Axis Primary	Inter-network Node Point	
	Impact Element		Yes	No
Impact Group			1	2
Inter-network Node Point	Yes	1	-	1
	No	2	-	-
	Pairwise Calculations	Count	1	0
		X	100	
		Weightages	17	0

	Impact Group	Condition Number (C) Y-Axis Primary	Vegetation				
	Impact Element		Vegetation Removed	Grasses	Low Level Shrub	Trees	Mixed
Impact Group			1	2	3	4	5
Vegetation	Vegetation Removed	1	-	1	1	1	1
	Grasses	2	-	-	2	2	2
	Low Level Shrub	3	-	-	-	3	3
	Trees	4	-	-	-	-	4
	Mixed	5	-	-	-	-	-
	Pairwise Calculations	Count	4	3	2	1	0
		X	10				
		Weightages	40	30	20	10	0

	Impact Group		Construction Materials				
	Impact Element	Condition Number (C) Y-Axis Primary	Construction Materials Unknown	Construction Material Known but Non-compliant with Current Design Standards Unknown Slope Angle	Construction Material Known but Non-compliant with Current Design Standards Known Slope Angle	Construction Material Known, Materials Compliant with Current Design Standards Unknown Slope Angle	Construction Material Known, Materials Compliant with Current Design Standards Known Slope Angle
Impact Group			1	2	3	4	5
Construction Materials	Construction Materials Unknown	1	-	1	1	1	1
	Construction Material Known but Non-compliant with Current Design Standards Unknown Slope Angle	2	-	-	2	2	2
	Construction Material Known but Non-compliant with Current Design Standards Known Slope Angle	3	-	-	-	3	3
	Construction Material Known, Materials Compliant with Current Design Standards Unknown Slope Angle	4	-	-	-	-	4
	Construction Material Known, Materials Compliant with Current Design Standards Known Slope Angle	5	-	-	-	-	-
	Pairwise Calculations	Count	4	3	2	1	0
		X	10				
		Weightages	40	30	20	10	0

	Impact Group		Maintenance History			
	Impact Element	Condition Number (C) Y-Axis Primary	Asset not been Inspected or Maintained within last 5 years	Asset has been Inspected, Minor Maintenance required with last 5 years	Asset has been Inspected, Major Maintenance required with last 5 years	Asset has been inspected, No defects, No maintenance
Impact Group			1	2	3	4
Maintenance History	Asset not been Inspected or Maintained within last 5 years	1	-	1	1	1
	Asset has been Inspected, Minor Maintenance required with last 5 years	2	-	-	2	2
	Asset has been Inspected, Major Maintenance required with last 5 years	3	-	-	-	3
	Asset has been inspected, No defects, No maintenance	4	-	-	-	-
	Pairwise Calculations	Count	3	2	1	0
		X	16.66666667			
		Weightages	50	33	17	0

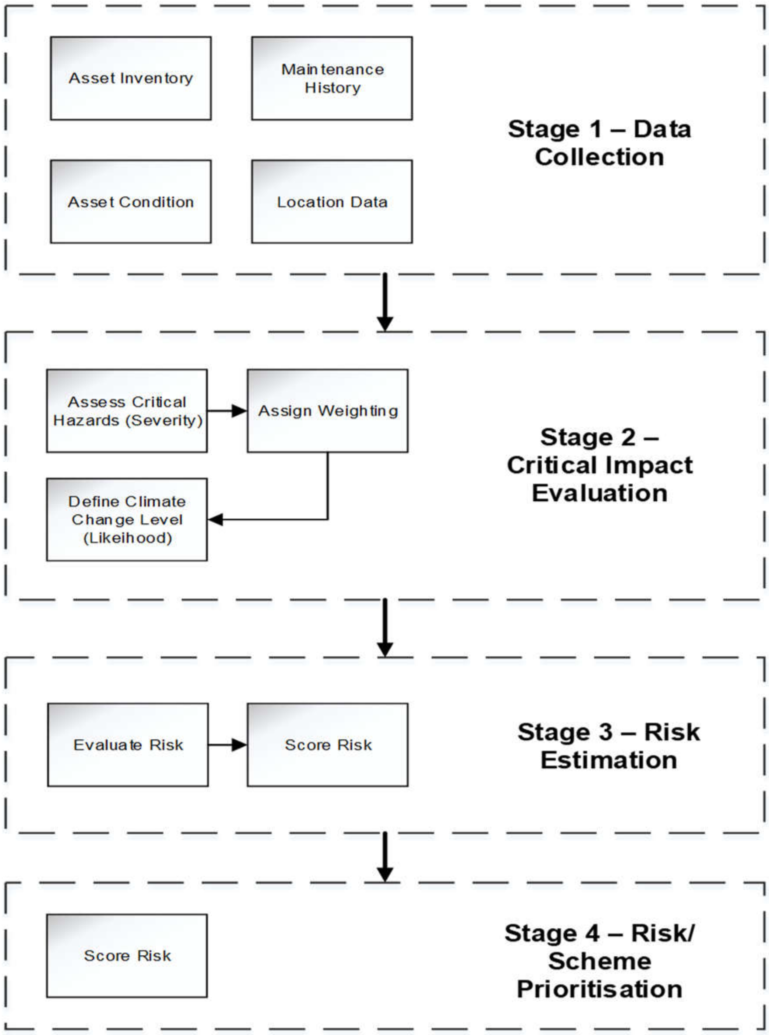
	Impact Group	Condition Number (C) Y-Axis Primary	External Weathering			
	Impact Element		Water Scour	Wind Scour	Chemical Changes to Soil	None Visable
Impact Group			1	2	3	4
External Weathering	Water Scour	1	-	1	1	1
	Wind Scour	2	-	-	2	2
	Chemical Changes to Soil	3	-	-	-	3
	None Visable	4	-	-	-	-
	Pairwise Calculations	Count	3	2	1	0
		X	16.66666667			
		Weightages	50	33	17	0

	Impact Group	Condition Number (C) Y-Axis Primary	Geotechnical Hazard Event	
	Impact Element		In Progress	None
Impact Group			1	2
Geotechnical Hazard Event	In Progress	1	-	1
	None	2	-	-
	Pairwise Calculations	Count	1	0
		X	100	
		Weightages	17	0

	Impact Group	Condition Number (C) Y-Axis Primary	Collision Trauma History Requiring Maintenance within the last 5 years? (Or Since last Principle Inspection?)	
	Impact Element		Yes	No
Impact Group			1	2
Collision Trauma History Requiring Maintenance within the last 5 years? (Or Since last Principle Inspection?)	Yes	1	-	1
	No	2	-	-
	Pairwise Calculations	Count	1	0
		X	100	
		Weightages	17	0

8.3 Appendix C – Case Study Detail

Case Study Approach



Project Cover Sheet

PROJECT NAME

Project Ref Document Ref Revision Date Prepared By Checked By Authorised By	

Project Lead Project Manager Organisation Client	

Project Descriptor	

Project Stakeholders	

Project Start Northing	Project Start Easting
Project End Northing	Project End Easting

Project Start Date	Project End Date
DD/MM/YYYY	DD/MM/YYYY
SCAR Stage	

Assumptions/Other Information

Asset Information Sheet

PROJECT NAME

Insert Additional Asset Information Here

Date of last Inspection	
Type of Inspection	

Inspector	

Initial Feature Grade	

Subsequent Feature Grade	

Additional Inspection Notes	

Maintenance/Scheme History

PROJECT NAME

Scheme Ref	
Asset Ref	
Scheme Type	
Scheme Action	
Full Scheme Description	
Geotechnnical Asset Specific	
Duration	
Completion Date	
Cost	
Comments	

USER NOTE:

Insert All known scheme and maintenance works here.

Copy and Paste as required

For provisional/potential works schemes, please

Scheme Ref	
Asset Ref	
Scheme Type	
Scheme Action	
Full Scheme Description	
Geotechnnical Asset Specific	
Duration	
Completion Date	
Cost	
Comments	

Scheme Ref	
Asset Ref	
Scheme Type	
Scheme Action	
Full Scheme Description	
Geotechnnical Asset Specific	
Duration	
Completion Date	
Cost	
Comments	

Geotechnical Risk Assessment Tool

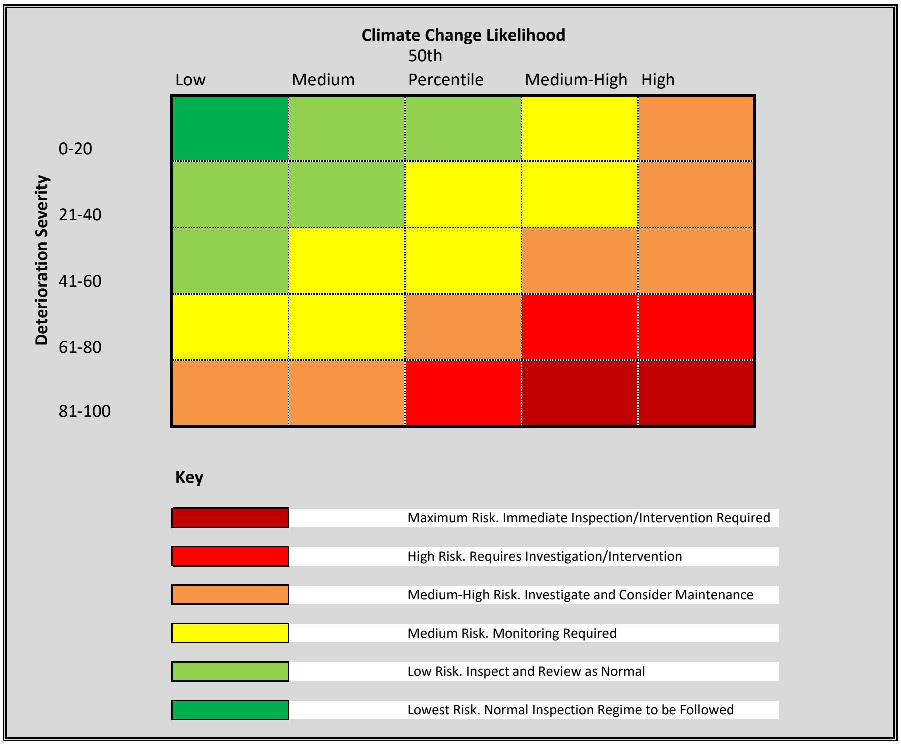
Impact Factor	Outcome	CASE STUDY 1 Weighted Score	CASE STUDY 2 Weighted Score	CASE STUDY 3 Weighted Score
Groundwater Fluctuations	Damaged/Blocked/Inadequate Drainage	14.0	12.8	15.0
Change In Loading Conditions	No Change	0.0	0.0	0.0
Underlying Geology	Rock	0.0	0.0	0.0
Geographical Location	No Special Features	0.0	0.0	0.0
Age of Asset	1993 - resent	0.0	0.0	0.0
Inter-network Node Point	No	0.0	0.0	0.0
Vegetation	Mixed	0.0	0.0	0.0
Construction Materials	Construction Material Known, Materials Compliant with Current Design Standards Known Slope Angle	0.0	0.0	0.0
Maintenance History	Asset has been inspected, No defects, No maintenance	0.0	0.0	0.0
External Weathering	None Visable	0.0	0.0	0.0
Geotechnical Hazard Event	None	0.0	0.0	0.0
Collision Trauma History within the last 5 years?	No	0.0	0.0	0.0
	TOTAL SCORE	14.0	12.8	15.0

Likelihood Scorecard

PROJECT NAME

Select Region:	Climate Change Risk Profile
CHOOSE:	

Risk Score



Climate Change Likelihood
Low
Medium
50th Percentile
Medium-High
High
Deterioration Severity
0-20
21-40
41-60
61-80
81-100
Key
Maximum Risk. Immediate Inspection/Intervention Required
High Risk. Requires Investigation/Intervention
Medium-High Risk. Investigate and Consider Maintenance
Medium Risk. Monitoring Required
Low Risk. Inspect and Review as Normal
Lowest Risk. Normal Inspection Regime to be Followed

										CASE STUDY 2			CASE STUDY 3		
		CASE STUDY 1													
Impact Group	Impact Element	Element Weighting (within Group)	Mean Weight	Mean Element Weighting (within Total)	Mean Total Score	Conservative Weight	Conservative Element Weighting	Conservative Mean Score	Final Score	Group Weighting	Element Weighting	Final Score	Group Weighting	Element Weighting	Final Score
	Unknown	25		2.083			5		20.0		3	12.8		2	9
	Flooding Event	22.5		1.875			4.5		18.0		4	17.0		4	18
	Damaged/Blocked/Inadequate Drainage	17.5		1.458			3.5		14.0		3	12.8		4	15
Groundwater fluctuations	Drought	10		0.833	8.333	20	2		8.0		3	12.8		3	10.5
	Excessive Rainfall	10		0.833			2		8.0		2	8.5		3	10.5
	Frost/Thaw	7.5		0.625			1.5		6.0		1	4.3		1	6
	Seasonal Fluctuations	7.5		0.625			1.5		6.0		1	4.3		1	3
	None	0		0.000			0	20	0.0	17	0	0.0	18	0	0
	Additional Material Added at Base or Top of Asset	33.3		2.775			4.995		15.0		5	15.0		4	13
Change in Loading Conditions	Removal of Material at Base or Top of Asset	33.3		2.775	8.325	15	4.995		15.0		5	15.0		4	13
	Subsidence Causing a Change in Loading Profile	33.3		2.775			4.995		15.0		5	15.0		4	13
	No Change	0		0.000			0	15	0.0	15	0	0.0	13	0	0
	Unknown	25		2.083			3.125		12.5		3	10.5		2	10
	Organic Materials	25		2.083			3.125		12.5		4	14.0		3	12
	Clays	20		1.667			2.5		10.0		3	10.5		2	10
Underlying Geology	Silts	15		1.250	8.333	12.5	1.875		7.5		2	7.0		2	8
	Sands	8		0.667			1		4.0		2	7.0		1	6
	Gravels/Boulders/Cobbles	5		0.417			0.625		2.5		1	3.5		1	4
	Weak Rock	2		0.167			0.25		1.0		1	3.5		0	2
	Rock	0		0.000			0	12.5	0.0	14	0	0.0	12	0	0
	Site Previously Flooded (within 10 yrs)	25		2.083			3.125		12.5		2	4.8		2	5
	Sited in Flood Plain	25		2.083			3.125		12.5		1	2.4		1	2.5
Geographical Location	Critical Node Point	25		2.083	8.333	12.5	3.125		12.5		5	12.0		4	10
	High Traffic Location (≥ 80 msa)	25		2.083			3.125		12.5		4	9.6		3	7.5
	No Special Features	0		0.000			0	12.5	0.0	12	0	0.0	10	0	0
	Older than 1950	31		2.583			1.55		5.0		3	11.0		2	6
	1950 - 1967	24		2.000			1.2		3.9		3	11.0		3	10
	1968 - 1972	18		1.500			0.9		2.9		2	7.3		2	7
Age of Asset	1973 - 1977	14		1.167	8.333	5	0.7		2.3		2	7.3		2	6
	1978 - 1985	9	8.333	0.750			0.45		1.5		1	3.7		1	4
	1986 - 1992	4		0.333			0.2		0.6		1	3.7		1	2
	1993 - resent	0		0.000			0	5	0.0	11	0	0.0	10	0	0
Inter-network Node Point	Yes	100		8.333	8.333	5	5		5.0		3	9.0		9	9
	No	0		0.000			0	5	0.0	9	0	0.0	9	0	0
	Vegetation Removed	40		3.333			1		2.5		3	8.0		2	6
	Grasses	30		2.500			0.75		1.9		2	5.3		2	4.5
Vegetation	Low Level Shrub	20		1.667	8.333	2.5	0.5		1.3		2	5.3		1	3
	Trees	10		0.833			0.25		0.6		1	2.7		1	1.5
	Mixed	0		0.000			0	2.5	0.0	8	0	0.0	6	0	0
	Construction Materials Unknown	40		3.333			3		7.5		3	6.0		1	4
	Construction Material Known but Non-compliant with Current Design Standards Unknown Slope Angle	30		2.500			2.25		5.6		2	4.0		1	3
Construction Materials	Construction Material Known but Non-compliant with Current Design Standards Known Slope Angle	20		1.667	8.333	7.5	1.5		3.8		2	4.0		1	4
	Construction Material Known, Materials Compliant with Current Design Standards Unknown Slope Angle	10		0.833			0.75		1.9		1	2.0		0	1
	Construction Material Known, Materials Compliant with Current Design Standards Known Slope Angle	0		0.000			0	7.5	0.0	6	0	0.0	4	0	0
	Asset not been Inspected or Maintained within last 5 years	50		4.167			3.75		7.5		2	5.0		1	3
Maintenance History	Asset has been Inspected, Minor Maintenance required with last 5 years	25		2.083	8.333	7.5	1.875		3.8		2	5.0		0	0
	Asset has been Inspected, Major Maintenance required with last 5 years	25		2.083			1.875		3.8		1	2.5		1	2
	Asset has been inspected, No defects, No maintenance	0		0.000			0	7.5	0.0	5	0	0.0	3	0	0
	Water Scour	33.3		2.775			0.8325		2.5		2	3.0		1	1
External Weathering	Wind Scour	33.3		2.775	8.325	2.5	0.8325		2.5		1	1.5		1	1
	Chemical Changes to Soil	33.3		2.775			0.8325		2.5		1	1.5		0	0
	None Visable	0		0.000			0	2.5	0.0	3	0	0.0	1	0	0
Geotechnical Hazard Event	In Progress	100		8.333	8.333	2.5	2.5		2.5		3	2.0		13	13
	None	0		0.000			0	2.5	0.0	2	0	0.0	13	0	0
Collision Trauma History Requiring Maintenance within the last 5 years? (Or Since last Principle Inspection?)	Yes	100		8.333	8.333	7.5	7.5		7.5		3	0.0		0	0
	No	0		0.000			0	7.5	0.0	0	0	0.0	0	0	0
					99.98			99.9825							