RESILIENT GEOTECHNICAL ASSET MANAGEMENT

by

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Abstract

There is overwhelming evidence that the development of new, technically sound, engineered and fit-for-purpose critical physical infrastructure is vital for economic growth and stability. With many countries targeting significant levels of capital investment in energy, transport, communications, flood management and water and waste water infrastructure, there is a vital need for asset management frameworks that can provide both robust and resilient asset support.

Currently, asset management tools focus predominantly on data management, deterioration modelling, condition assessment, risk, as well as economic factors (such as whole-life costing and developing investment plans). Some also consider the vulnerabilities of a network to climate change and extreme weather events such as flooding. However, rather than taking a long term view, asset management strategies are often short term, typically five years or less. What is needed is a long-term approach, which will ensure assets are safe, secure and resilient to what the future may hold in 20, or even 50 years' time.

Developing such a holistic long-term approach will require adoption of robust, flexible and multifunctional solutions that not only suit the needs of the present but in addition are resilient to whatever the future may hold. This establishes a case for support to develop systems and frameworks that can enable asset owners, government organisation and other decision makers to make informed decisions for adopting such solutions that continue to perform even under changing conditions. The thesis describes the development of a 'Resilience Assessment Framework' which provides a platform to appraise resilience of geotechnical assets in the planning stage of asset management by considering how geotechnical assets (specifically for transport infrastructure) designed and built today will perform in the light of socio-economic, environmental, political, technological changes and shock events in the future. This framework intends to assist in strategic level decision-making by enabling long term planning and management of geotechnical assets and help future proof transport infrastructure. The proposed framework is validated using two real case studies to demonstrate its use and applicability in the field of geotechnical asset management.

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1. Introduction

1.1. Context

Much of the core infrastructure base in the UK is rapidly ageing and deteriorating. In today's dynamically changing world, there is overwhelming evidence that suggests a requirement to develop innovative and sustainable ways for driving growth and efficiency (HM treasury 2010, Armitt 2013). This results in growing dependency on developing new, technically sound, engineered, and fit-for-purpose critical physical infrastructure components that operate efficiently and are well maintained. The pressure for today's society is all the more increased due to reducing budgets (CIRIA-C677, 2009), ever increasing demands on the transport network (HM treasury, 2010 and DfT, 2012) along with the number of complex inter-dependencies between transportation assets. The core infrastructure areas in which many countries, including the UK, are specifically targeting their capital investment includes; Energy, Transportation, and Communications, Flood Management, Water and Waste infrastructure. There is a vital need for asset management systems that can provide both robust and resilient asset support (OECD, 2001). Hence asset owners worldwide are working towards improving their asset management processes by optimising resources, minimising risks and ensuring better level of service to the end-users (CSS, 2004 and ICE, 2009).

As such there is an imminent need to develop robust, flexible and multifunctional solutions that not only suit the needs of the present but also ensure that they are fit for purpose and resilient to what the future may hold.

Ultimately all infrastructure assets interact with the ground and their integrity relies substantially on the performance of geotechnical component of these assets. Hence this places geotechnical asset management at the critical starting point for any future-proofing of the infrastructure network in the UK.

1.2. Background to the Research

1.2.1. General Subject Area

Asset management, when undertaken correctly, can be a powerful tool in the maintenance of assets, and will produce long term solutions to the running and upkeep of the UK's ageing infrastructure networks. The key objectives of engineering asset management are to optimise the use and the lifespan of the asset, improve reliability, availability and safety, across a range of interdependent asset types. (CSS, 2004 and ICE 2009)

The ICE Manual of Highways Design and Management 2011 (Thorp, 2011) highlights that asset management is something that engineers do in their day-to-day jobs with their skill to determine the cost and the design life of an asset. Although, a large proportion of asset management includes the development of a strategic link between the service delivery and customer expectations, the manual argues that asset management should prioritise the future development in technology and innovation along with efficient service delivery based on cost, performance and risks. However, with changing future conditions future-proofing of the existing asset management systems is necessary. In order to address the changing conditions that are likely to be faced by the transportation industry, long-term planning and policymaking is essential for effective asset management.

HM Treasury's National Infrastructure Plan (2010) highlighted the UK government's approach towards infrastructure development, which aimed to keep a coherent view of the long-term needs for UK infrastructure by managing interdependency, building resilience and promoting engineering innovation. It emphasised that globalisation, increasing demands, climate change, interdependencies and obsolescence were the main future challenges that the infrastructure faced. UK infrastructure needs to keep pace with all of these in order to: give high returns on investments; economic growth and social development for future, that is both technologically enabled and customer focussed (HM Treasury National Infrastructure Plan, 2010).

Asset management strategies and policies prepared and adopted by various asset owners in the UK (e.g. Highways England, Network Rail and Local Authorities) are typically devised for the short-term period (i.e. five years). As such there is a need to consider how the decisions made today, based on these short-term strategies and policies, will affect the transportation assets of the future, say in 20 or 50 years. Changing times and robust long term policies, governance and investment strategies require that we build resilience ‘(for a broader discussion see Chapter 2 Section 2.4)’ into our infrastructure related systems. Resilience, for the purpose of this research, is defined as continued performance under changing conditions. In so doing we can take account of: natural and man-made threats, changing demands, changing demographics, urbanisation, climate change and limited resources (Cabinet Office, 2011, DfT, 2013 and Defra, 2012).

The widely differing nature of asset types found on any given infrastructure network requires effective management in order to keep them operational in a serviceable condition. As all infrastructure assets are founded directly or indirectly on geotechnical assets, effective implementation of geotechnical asset management is therefore crucial to the overall infrastructure management plan (Shah et al., 2014). Geotechnical asset management is currently being undertaken by UK asset owners such as Highways England, Network Rail and local authorities who have long maintained and managed transportation networks. Geotechnical asset management is utilised in the water and utilities sector, for example where excavating trenches on the transport network are regularly undertaken, a host of skills and analysis, not least geotechnical are required. This research aims to focus on the geotechnical assets found on infrastructure networks, mainly on roads. using this the work presented herein investigates how best to develop a decision support framework for assisting resilient geotechnical asset management of an overall infrastructure network, with the aim of making it fit for purpose in the light of changing future conditions.

1.3. Aims and Objectives of the study

The aim of the research is to produce a geotechnical asset management planning framework that allows assessment of the resilience of geotechnical solutions used on the road network in the light of changing future conditions over the long term.

The objectives of the research are enlisted below:

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 the long term planning needs and resilience assessment in asset management within the road transportation infrastructure (with focus on geotechnical) industry..

Objective 3: to study the ground structure interaction and determine the factors affecting the performance of the geotechnical assets including groundwater, seepage, soil properties, geology and hydrogeology.

Objective 4: To classify and evaluate the plausible future conditions relevant to the road transport network and the associated geotechnical assets.

Objective 5: To develop resilience based geotechnical asset management framework for use in the planning stage of an asset management lifecycle and to develop a tool to support these assessments**.**

Objective 6: to test the framework through case studies and validate the tool.

1.4. Justification and Scope of Research (Need for Research)

1.4.1. Changing Times require changing measures

The global population is predicted to increase to 9.6 billion by 2050 (United Nations, 2013).This will undoubtedly increase the demand for all types of infrastructure requirements. As such it becomes all the more important to effectively and efficiently manage infrastructure assets, not least because of the complex interdependencies that now exist. We live in a world where failure of one asset may directly (or indirectly) lead to the failure (or breakdown) of a set of surrounding assets, ultimately leading to failure of an entire section of a network. Thus the key question is: how resilient is the network in question and how does this relate to the future conditions (stresses) and their impact on the supporting asset base. Hudson et al (2012) argues that resilience of an asset can rarely (and should never) be considered in isolation; not least because it is typically part of an entire network with a host of external environmental influence. Hence assets interaction is a key element that cannot be neglected when considering resilience. With growing concerns related to increasing demands combined with reducing budgets (for maintaining and operating the transportation assets) coupled to an uncertain future, there is a need to develop robust asset management systems, where vulnerabilities can be explored and prepared for. Hence, it is vital to determine whether a given asset management system and practice (including design solutions provided today) for the remediation, maintenance and upkeep of transportation assets are applicable and fit for purpose within a range of future conditions.

A report on 'climate change risk assessment' prepared by Department of Food and Rural Affairs (DEFRA), in 2012, presents some of the major challenges faced by the transportation sector. These include changing demand resulting from population growth, changes in work patterns, and changes in social attitude and expectations. The reports envisages that technological changes are likely to shape the future of road transport which includes implementing measures to reduce carbon emissions, as transportation sector is responsible for a quarter of the overall emission produced in the UK (Defra, 2012).

This argument is strengthened when we consider that the infrastructure industry has developed over many centuries and what is built and being maintained today will provide a legacy for many centuries to come. Notwithstanding this we cannot forget that many (current) infrastructure assets are still in use, despite rapid changes in demographics, leading to changes in usage (sometimes (way) beyond design parameters) and operational purpose (Boyko et al. 2012). This means that the 'so-called' sustainable and technically efficient design solutions provided today may not guarantee sustainability and resilience over their intended design lives. For example, a parallel might be drawn with the current state of the housing industry. Various housing developments in the UK and US, which were designed to meet the limitations of the former housing conditions, became redundant before the end of their design life, due to the change in their usage and requirements (Wolfe 1981 and Bullock 2002). Therefore it is not surprising Boyko et al (2012) argue that designing and developing solutions now in what we presume to be a sustainable and robust way for the future even whilst carefully evading the errors made in the past (i.e. using hindsight in foresight), does not necessarily guarantee the long-term resilience of the environment is achieved.

The asset management framework presented here provides a methodological approach by which we can begin to *‘think’* beyond the traditional and *‘explore’* beyond what we know now. This is key to this methodological approach. In doing so, the framework contributes to extant knowledge on long term asset management requirements. However, it is important to note that the goal of any asset management framework is to be fully customer oriented, based on sound economic and engineering principles with long term sustainability as its core principal.

1.4.2. A requirement for long-term policies and investment

In order to address the changing conditions facing the transportation industry, long term planning and policymaking is essential for effective asset management. Asset management strategies and policies prepared and adopted by various asset owners, for example, in the UK (e.g. Highways England, Network Rail and Local Authorities) are typically devised for the short-term period (i.e. five years), and are directly linked to the nature of funding cycles and its associated influence from political change. However, to date there is limited work done through asset assessment frameworks for checking the robustness of these decisions for medium to long term (i.e. beyond five years). As such there is a need to consider how the decisions made today, based on these short-term strategies and policies, will affect the transportation assets of the future, say in 50 years. It is proposed that the asset management framework presented here takes cognisance of this and thus helps fill this key gap in the knowledge.

The key suggestions made at the ICE Infrastructure Conference on ‘UK Transport – Engine for Growth’ (2013), included the development of a national transport plan to clearly understand what is needed from the transportation infrastructure in the long-term. It suggested that long term planning (typically more than 30 years) will help address the issue of increasing demand and ageing assets and hence encouraged development of long-term decision making frameworks which considers the changing future for transportation network. Sir John Armitt, the former Olympic Delivery Authority Chairman (London 2012), in his review of the infrastructure plan, suggested developing a politically independent infrastructure service delivery organisation a so-called *‘National Infrastructure Commission’* that would provide advice to the government on infrastructure policies based on a long-term strategic planning, drawn from an evidence-based assessment of UK infrastructure needs over a 25-30 year horizon. The apolitical nature of the commission would result in a reduction in the impact of political changes over project delivery (Armitt, 2013). In an independent report by Management Consultancies Association (MCA), 2013, it was recommended that the National Infrastructure Plan should define the purpose of Infrastructure Services and provide a clear long-term vision of the economic and service environment desired for the UK. Recommendations suggested that the UK government should create an independent office for infrastructure, which could produce national infrastructure plans addressing a time horizon well beyond the 4-5 years political cycle and advise on projects that the government should take forward to fulfil its objectives by discussing the interactions between the project costs, timeframes and funding models.

To deliver such a holistic long-term approach, there is an imminent need to develop robust, flexible and multifunctional solutions that suit the needs of present but also a offer resilience to whatever the future may hold. In itself this establishes a further need to develop systems and frameworks that can enable asset owners, government organisation and other decision makers to make informed decisions about the future. Whilst this research presents such a decision support framework, which tests the resilience of geotechnical design solutions in the light of changing socio-economic, technological, environmental and political conditions over the future, there is potential for it to be adapted and developed for a much broader transportation asset base.

1.4.3. Embedding resilience in designing asset solutions

Changing times and robust long term policies and investment require that we build ‘resilience’ into our systems and strategies. In so doing we can take account of: infrastructure vulnerabilities, natural and man-made threats, changing demands, changing demographics, urbanisation, climate change and limited resources. Resilience in the infrastructure industry implies that the network (e.g. road, rail, utilities, and water telecommunications) is up and running and continues to perform for its intended purpose even in harsh and unpredictable conditions that it may be exposed to at any given time.

One of the prime lessons learnt from the Sandy hurricane in the USA in 2012 was that we need to design both redundancy and flexibility into all infrastructure systems in order to create resilience (Lee, 2012). Lee (2012) highlighted that out of such natural disasters comes the opportunity to develop adaptive strategies for the future. Similarly, a number of recent events in the UK demonstrated the vulnerability of transportation networks and how this can cause substantial disruption across the whole country. For example, high flood levels in 2007, the unusually low temperatures in 2010, the eruption of the Eyjafjallajokull volcano in Iceland in 2010 and the winters of 2013, exposed the vulnerability in the UK’s national infrastructure to rapid breakdown and to some extent failure. The UK Cabinet Office (2011) highlighted that such events not only caused inconvenience to the public but incurred financial losses in the form of lost revenues, reputational damage and contractual fines and potential for legal action. For example, the 2007 floods alone cost the UK economy over £4 billion, and the damage specifically to critical infrastructure was valued at approximately £674 million (UK Cabinet Office, 2011). This substantial economic outlay reinforces a critical need for related organisations to manage and mitigate ‘risks’ and embed ‘resilience’ into their business processes (UK Cabinet Office, 2011). This justifies the need for a paradigm shift that places emphasis on designing in “Resilience” rather than designing in “Resistance” as is the case for many present solutions (Rogers et al., 2012).

Hudson et al., (2012), highlighted the need to engineer resilient infrastructure by exploring various examples of natural and man-made threats. For example, the fire explosion on M1 and M4 motorways in the UK in 2011 caused by human negligence closed major arterial routes for days - affecting the physical infrastructure and social activities. This was further illustrated by the nuclear power plant failure (caused by the devastating tsunami) in Japan in March 2011. This resulted in global consequences with some nations abandoning nuclear power could lead to less diverse alternative source of energy.

It is further argued that if a nation is to live a stable and buoyant life across the social, economic and environmental parameters both now and in to the future, there is a need to develop resilient infrastructure (Hudson, 2012). Therefore, enabling a nation to adequately develop methods (or design frameworks) for coping with the changes of an infrastructure base over (and sometimes beyond) its design-life are paramount. This echoes the Pitt review where it is stated that the driver for wider organisational resilience is the long-term commitment from the stakeholders to mitigate risks as a part of a continuous improvement cycle (Cabinet Office, 2010). Hence Governance (Policies) becomes a key driver in future-proofing the infrastructure and making it resilient. Thus, there is a clear need to embed resilience into planning and design is justified. This can be achieved by not only considering the changes in use and growing age of the infrastructure but also by the requirement to invest appropriately in infrastructure maintenance.

This is further reinforced by Department for Transport (DfT) report on the future of infrastructure, which specifically highlights the need to adapt to changes facing the road network and make it fit for purpose through embracing technology, meeting changing demands to reduce congestion and provision of a safe, green and socially connecting transportation network for motorists, cyclists and pedestrians (DfT, 2013).

1.4.4. Gap in knowledge

Existing asset management systems and tools predominantly focus on data management, deterioration modelling, condition assessment, risk assessment and investment planning to provide economical appraisal of projects in order to identify the whole life costing of the asset and identify optimum maintenance strategies. There is also a growing focus on developing decision support to identify the environmental, social and economic sustainability of projects. For e.g. Intelligent Transport Systems (TRL, http://www.trl.co.uk/solutions/intelligent-transport-systems/ accessed March 2013). In addition a number of current asset management framework (e.g. HM Government Climate Change Adaptation Framework, 2009) focus on developing risk management strategies through a better understanding of the vulnerabilities which exist on an infrastructure network particularly focussing on climate change and extreme weather events such as flooding. Yet, there exists the need to address long-term challenges across a broad spectrum of plausible futures comprising of social changes, economic agility, technological development, environmental changes and change in policies in a holistic and collective manner which can assist in strategic planning for transportation assets. The challenges faced by the transportation network are further discussed in section 1.4.2. The proposed research provides a decission support planning tool to enable accomplishing this need, in a pragmatic manner by encouraging early communications from stakeholders at a strategic level for individual projects.

Asset Management is undertaken by asset owners in the UK, based on available best practice guidance documents and standards (as discussed in section 2.6 and section 2.9). Asset management systems and tools on managing geotechnical assets are limited as compared to other assets (such as pavements or structures) and much of the geotechnical asset management is undertaken based on standards and/or guidance set out by asset owners such as Highways England and Network Rail or best practice guidance such as Construction Industry Research and Information Association (CIRIA). Much of the geotechnical asset risk assessment is based on sound engineering and experienced judgement. There is lack of available decision support tools that can predict the failure patterns and behaviour of geotechnical assets in the long term that is readily available in the public domain. This can be attributed to the diverse nature and unpredictability associated with natural ground material(s). As transportation networks face changing future condition(s), it is likely that additional interventions in managing and upgrading the transportation assets will be required, perhaps fundamentally changing the design of existing geotechnical assets and their use. Hence, if transportation assets are designed to be adaptable, to offer flexibility of use and multi-functionality the solutions can be more resilient to future changes and therefore less likely to require changes to the infrastructure network in the future which in turn can lead to an overall reduction in infrastructure improvement and maintenance costs. Whilst, it is not possible to make every aspect of the infrastructure network resilient at all times due to various constraints (such as budget, land take and risk of over design)at least knowing the likely vulnerabilities, and appreciating the fragility and the implications of the plausible future changes to the transportation network in the long term could significantly enhance asset management planning and designing.

Further details on how the research fulfils the research gap and contribution to knowledge through the proposed research is provided in section 1.4.5 and section 1.6 respectively.

1.4.5. How does the research fill this knowledge gap?

The process of assessing asset related solutions (proposed and used) in the real world today, requires a sound decision support framework that can help facilitate the process of translating resilience strategies in to tangible deliverables. This is a significant knowledge gap which the research presented herein helps to fill by describing in detail a step-wise methodology for assessing the resilience of geotechnical infrastructure assets within five stage framework.

The main focus of this research is development of a framework to facilitate the implementation, management and integration of resilience at the planning and designing levels. The hope is that such integration at a grass roots level will help promote wider uptake of the concept in the asset management industry. This requires a thorough understanding of the concepts of asset management related issues as well as drivers, benefits, challenges, barriers and enablers for achieving long term asset management. It also requires an examination of existing management frameworks and assimilation of case studies to establish critical factors geotechnical asset management. In addition there is a need to understand the requirements of strategic bodies that are involved in achieving long term asset management.

1.4.6. Contribution to knowledge through this research

Globally, government and private agencies involved in the development and maintenance of transport networks have called for asset solutions that are resilient to long-term changes in climate and other environmental factors (The Highways Agency Climate Change Risk Assessment, 2011, HM Treasury 2010, Cabinet Office, 2011, Pitt, 2008, DEFRA, 2012, Goulding et al., 2014). This research attempts to serve this need within the domain of infrastructural asset management by focusing on the long-term resilience planning of geotechnical assets. The objective of this work is to develop a novel resilience based geotechnical asset management framework to enable asset managers and stakeholders to appraise the resilience potential of existing geotechnical solutions provided on the road network in light of plausible changing future conditions. Mainly, this study contributes to existing knowledge in the following ways:

Development of a failure hypothesis model: Presently, asset management experts develop geotechnical failure hypotheses on the basis of their technical knowledge and experience, using guidance documents and by assessing the existing nature of the geotechnical asset. This information is then recorded and explained with the help of reports and graphs. However, a comprehensive framework that allows users to instantly identify and map the causes of failure in geotechnical assets and their inter-related effects has been hitherto unavailable. Model 1 in this study addresses this gap. The rose diagram (Model 1) helps demonstrate the potential (internal and external) causes of failure in geotechnical assets. Using this model enables asset managers to examine a geotechnical asset for triggered effects and then hypothesise the relevant internal or external critical factors that may have led to the failure. The strength of this model lies in its ability to improve the failure analysis of geotechnical assets, thus enabling more effective geotechnical design and maintenance. By helping users to identify the root causes of asset failure along with interaction of the various critical factors, the model facilitates ideation and development of appropriate long-term solutions.

Inter-linking of critical asset factors and future conditions: The objective of developing resilient solutions requires not only the generation of asset failure hypotheses but also an assessment of the plausible future conditions that are likely to affect the asset. Changes in the behaviour of an asset can be induced by a variety of factors, which include social, technological, economic, environmental and political. A resilient solution is one that anticipates the future conditions that are likely to affect a particular geotechnical asset and accounts for them judiciously. Model 2 developed in this research presents a visual summary of all future conditions along with their likely impact on the transportation network. It serves as a thought filter or a planning aid, allowing asset managers and planners to understand the effects of many changing future conditions on a geotechnical asset and the network, as a whole. This model maps the inter-relationships between the future conditions and the critical factors that they are likely to influence. For instance, future economic changes are unlikely to affect the physical characteristics of an asset such as its seepage properties. By linking future conditions and the critical asset factors, Model 2 paves the way for more comprehensive and intelligent resilience assessment of geotechnical asset solutions.

Long-term planning and resilience-assessment tool: The key contribution of this work lies in its unique conceptualisation of long-term resilience: an MS-Excel based resilience assessment tool. This tool allows for effective appraisal of potential geotechnical solutions in a methodical manner. Asset planners can use this tool to assess if a proposed geotechnical solution performs favourably in light of the interaction effects of the critical factors and the future conditions. That is, it enables stakeholders to carefully study the future conditions and critical factors in conjunction and explore the implications of their interactions on resilience management. By interpreting resilience as a score, arrived by rating every combination of a critical factor and a future condition, the tool allows for a comparison of multiple geotechnical solutions on a uniform basis. The weighting of future conditions and the use of an intuitive rating scale help users tailor the tool to the asset situation under consideration. The numerical output facilitates a clear understanding of the factors and conditions influencing resilience and directs further discussion on the solution design. The tool can be used at the planning stage of geotechnical asset management, where different options are evaluated and a feasibility analysis is undertaken to select the most technically sound, cost effective and sustainable solution. The tool is a sound platform for project planners and geotechnical asset managers to receive appropriate input from stakeholders and designers; it allows for collaborative knowledge sharing and discussing of the long-term perspective for geotechnical asset management.

The Figure 1.1 illustrates the research focus and data input to achieving the research aim.

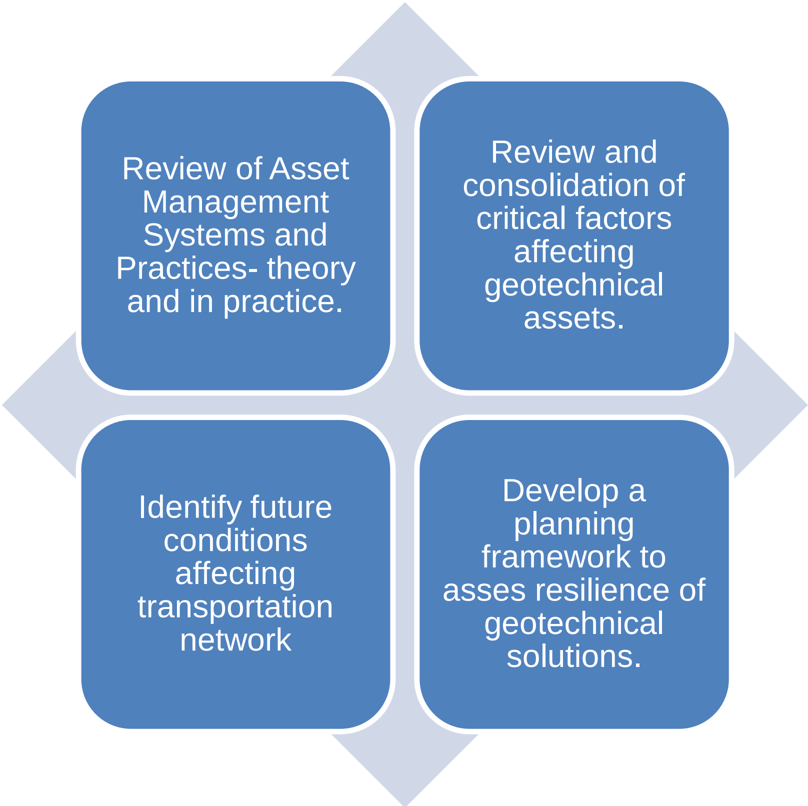


Figure 1.1: Research Focus and Data Input

1.4.7. Why Geotechnical asset Management? (with a key focus of UK highways network):

The UK has a considerable number of earthworks on both the rail and highway network(s). Whilst many rail network earthworks are over 100 years old as a direct result of the rising construction era in the 19th and 20th centuries whereas most of the highways earthworks, as a direct result of construction of UK motorways in the 50's, are about 50 to 60 years old (Wilks,2010). Network Rail is responsible for managing, operating and maintaining the railway network and Highways England is responsible for managing and maintain the strategic and trunk roads network in UK. Highways England was formerly known as the Highways Agency. In April, 2015 the Highways Agency became a government owned company known as ‘Highways England’. Network rail has over 16000km of network of which there are 5000km of embankments and 5000km of cutting slopes and Highways England (formerly known as the Highways Agency) manages approximately 10500 km of earthworks of which 3500 km is located in cuttings and 3500 km is on embankment (Wilks, 2010). Geotechnical assets are the foundations upon which any transportation asset and the overall infrastructure network will depend. Thus, long-term planning and resilience of a geotechnical asset management can be considered as a key starting point in embedding resilience in overall transportation system.

The proposed research’s case studies are based on two real projects on UK’s highways network. The reason for focussing on highways network in this research is based on permitted access to highways database and identification of a clear potential within the existing geotechnical asset management plan on highways network where the proposed framework can be integrated to add value. This is demonstrated through the use of case studies used in this research to validate the tool.

Highways England (formerly known as the Highways Agency) improves, operates and maintains strategic road networks (motorways and major trunk roads) in England from a central asset management office which provides asset management systems and processes for managing the highways network across England resulting in a consistent asset management approach for managing highways assets. The existing asset management systems for maintaining and improving the road network comprises of an end-to-end service delivery for all assets. For example: implementation of geotechnical asset management includes asset inspection, asset data collection and recording on a central GIS based database, development of asset management plans, options feasibility analysis, developing prioritised forward works programme along with design and delivery of geotechnical solutions. Within the existing asset management process, there is a clear potential for integrating the proposed resilient assessment framework during the planning stage(s).

Following a conversation with subject matter expert (Technical Director Railways, Amey) it came to light that the asset management systems adopted on the railway network are dependent on different geographic areas and railway routes. Although the Network Rail strategies are developed centrally, the asset management systems and practices are specific to different routes and areas. The asset management implementation plans for managing and maintaining assets are not centralised and are dependent on different asset types, scope of work and is not likely to follow an end to end asset management framework. There are various types of contracts from signalisation to new platform extension to electrification and earthworks examination, which are spread across entire railway network in the country.

The asset database for highways network (which is The Highways Agency Geotechnical Data Management systems) (HD41/15) is accessible to the managing agents and service providers and as such has kindly granted permission to use and access the database for this research. In contrast this level of unfettered access could not have been facilitated by Network Rail due to confidentiality. This was the key reason for choosing to validate the 'resilient geotechnical asset management framework' using data for geotechnical assets on the highways network.

Similarly for local authorities, the asset management frameworks for maintaining and managing their local roads (if present) are highly variable in quality depending on the authorities being looked at. Similarly, the quality of geotechnical asset database is likely to be varying and less likely to be comprehensive. The local authorities can use the proposed framework and incorporate the same within their planning processes.

Although geotechnical assets and their end-use are similar on both highways and railway network, there are certain differences in terms of key factors affecting their performance. Within the given time frame of a PhD, it was considered feasible only to focus on the highways network. The framework has the potential to be adapted for geotechnical assets on the railway transportation network and similarly for other assets on the transportation network.

Hence the research is developed based on literature from archival sources, industrial experience, interviews and personal communications with industry experts (geotechnical asset management and designers).

1.4.8. Summary

The proposed ‘resilient asset management framework’ provides a systematic approach to assist in asset management planning and strategic decision making for geotechnical assets on the highways network. The framework considers how geotechnical assets provided today, will perform in the light of changing future conditions and helps evaluate their impacts on the use of the geotechnical asset on the transportation network within the assets’ projected design life. The research does not aim to replace conventional asset management planning tools and systems and/or economic and risk mitigation tools. It is rather a tool which enables us to see the behaviour of geotechnical assets in the long term spanning 30-50 years i.e. within their expected design life which for geotechnical assets is considered to be more than at least 60 years. Thereby, allowing long term asset management planning, although currently for geotechnical assets alone, to be considered more effectively. In doing so, the research provides a methodology which can stimulate such long term planning and holistic futures based decision making towards providing a measure of future-proofing to the transportation industry.

1.5. Research Road Map

The road-map of the research is shown in Table 1.1 below.

Table 1.1: Research Road Map

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 transportation network in UK and around the world including geotechnical assets	Review of current literature for transportation asset management including geotechnical assets adopted in UK and across the world	Literature Review
2	To examine the long term planning needs and resilience assessment within the road transportation	Review of literature on resilience, futures research and long term planning needs of road transportation network.	Literature Review

Table 1.1: Research Road Map			
Objective No.	**Objectives of the Research**	**Methodology to achieve the Objectives**	**Research Output**
	network (with focus on geotechnical) industry.		
3	To study the ground structure interaction and determine the factors affecting the performance of the geotechnical assets including ground water, seepage, soil properties, geology and hydrogeology.	Determining the critical factors affecting the performance of geotechnical assets and their inter-relationships.	A list of critical factors and the interrelation between the same. Output: Model 1.
4	To classify and evaluate the plausible future conditions relevant to the road transport network and the associated geotechnical assets	Review the existing literature on future scenarios work and in various strategic documents in relation to transportation network. Determine key likely conditions of the future (i.e. future conditions) Identify the correlation between the critical factors and the future conditions	List of Future Conditions and the inter-relationship between the future conditions and critical factors. Output: Model 2 Resilience Assessment Framework
5	To develop resilience based geotechnical asset management framework for use in the planning stage of an asset management life cycle and to develop a tool to support these assessments.	Develop a framework typically consisting of a matrix of critical factors and drivers of change.	Report highlighting validated outcome of the research i.e. Resilience Framework
6	To test the framework through case studies and validate the tool.	Validate the resilience framework and the methodology; using pilot projects i.e. case studies and personal interaction with industry experts. Integrate feedback from the validation stage and develop the framework as a finished tool.	Resilience Assessment Tool

1.6. Structure of the Thesis

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

Chapter 1 – provides an introduction to the research. It provides the aims and objectives, background and need for to the research.

Chapter 2 – reviews current and previous literature related to the topic in hand, this includes collation of archival information and exemplification though industrial examples. An exploration into the detailed aspects of asset management, resilience, not least in geotechnical asset management, is provided.

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 Resilience Assessment Tool. The various iterations undertaken to develop the resilience assessment framework are included.

Chapter 5 – discusses the research findings and provides detailed description of the resilience assessment framework supported by the tool and its elements with the help of examples. It also showcases two real case studies that have been used to 'validate' the use of the tool. This chapter contains the discussion of the research and it and limitations of the tool

Chapter 6 – This chapter includes conclusion and a summary of the research undertaken and provides thoughtful insight into possible future work that might be considered.

2. Literature Review

2.1. Introduction

Through a thorough critical review of the literature this chapter aims to develop a common definition for asset management and identify various components of an effective asset management system. The literature review chapter aims to provide a holistic view of the theoretical asset management systems and highlights the current implementation of asset management systems and tools adopted in the transportation industry. The chapter highlights the benefits of incorporating an asset management approach and ultimately its implementation in the geotechnical sphere of infrastructure industry.

2.2. Asset Management Definitions

ISO 55000 defines Asset Management as the "co-ordinated activities of an organisation to realise value from assets". 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*". A common objective is to minimise the whole life cost of assets but there may be other critical factors such as risk or business continuity to be considered objectively in the decision making process. (Institute of Asset Management, https://theiam.org/what-asset-management, accessed November 2012). ICE (2001) highlights that asset management is "*fundamental to the way in which we design, specify and replace but it also includes strategic links to the customer.*"

Of the several definitions that exist for asset management, the definition provided in the guidance documents published by County Surveyors Society (CSS) and Organisation of Economic Co-operation and Development (OECD) are considered most applicable to infrastructure asset management systems:

CSS (2004) defines it as the "*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*."

OECD (2001) defines asset management as a "*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*".

The definition of asset management for the purpose of this research is:

'*A systematic process of planning and designing solutions for constructing, maintaining, upgrading and operating physical assets on the transportation network through effective utilisation of resources in order to provide a better level of service to the customer'.*

The definitions therefore suggest that asset management requires attention to certain key details like existing and aspired levels of service, option feasibility and financial implications. These are based on sound asset knowledge and therefore having an adequate and reliable asset database is vital for an effective asset management process.

Infrastructure asset management can operate over a range of different levels, within both national and local networks. For most infrastructure authorities, it is a key area of development; however the methodologies differ vastly, from sophisticated integrated data warehouses, with incorporated condition modelling and decision support tools; to basic spreadsheets containing local maintenance and renewal programmes. In both cases, the chosen method should appropriately support the level at which the authority is working and the size of the network. The reason for this is that asset management is focused on organisational strategy and policy. With a strong, defined asset management strategy and supporting policies, an organisation can deliver an asset management approach to long-term maintenance. (PAS 55 2008, ICE 2001 and OECD 2001).

2.3. Theoretical treatment of asset management in terms of management functions

In their seminal work on asset management of roads, Snaith et al., (1998) divided the management functions into four categories: planning, programming, preparation and operations. The planning stage involves an overarching analysis of the entire road network system. It covers the development of long-term strategic plans, expenditure estimation and maintenance of the network under various funding levels. The key stakeholders at this stage are policy makers, planners, economists, analysts and senior decision makers. In a nutshell, the planning stage establishes the long-term approach to management within the whole life cycle of the infrastructural asset management. The programming stage focuses on the identification of maintenance-related requirements and the allocation of budgets to maintenance efforts. One of the key features of this stage is maximizing the value of the constrained budgets by identifying works that need critical intervention. This stage typically sees the involvement of managers from road planning and/or maintenance companies. The preparation stage covers short-term plans for implementation. Specific activities such as the design of the road works or repair or modification of the assets are crystallized at this stage. Detailed contracts and costing plans are worked out, and the junior engineers and technical experts from road agencies are entrusted with carrying out these responsibilities. The final stage of operations covers the day-to-day activities conducted on the field by labourers, engineers and managers. Equipment, materials, scheduling and such other modalities are worked out at this final stage. In terms of time horizons, these four functions are arranged in a descending order, with the planning stage responsible for the long-term vision and the operations stage spelling out everyday schedules.

This goal of this research is two-fold: (1) to understand the behaviour of geotechnical assets on roads by exploring the critical factors that determine asset performance or failure and (2) to develop a resilience assessment framework that allows asset managers to select the most resilient geotechnical solutions after assessing the long-term future conditions that may impact the critical factors. The emphasis on long-term maintenance, selection of a strategic and resilient geotechnical solution and the involvement of planners and asset management experts in the selection of the geotechnical solution are three key factors that embed this work in the planning domain of asset management literature.

2.4. Asset management planning tools, systems and approaches in highways transportation sector

The document on 'Asset Management for Road Sector' published by Organisation of Economic Co-Operation and Development (OECD) (2001) highlights effectively that in most countries the road network is the principal component of public assets. Roads are owned by the government, and it is their responsibility to operate, maintain and improve them. Roads and the highway network constitute one of the most vital infrastructure assets because their role is central to the economic, social and environmental health of the citizens (Kendrick & Taggart, 2006).

Drawing on the theoretical and conceptual literature on asset management, numerous scholars, authorities and private organisations have devised models, tools or systems that contain guidance and practical management measures relevant to a specific project or asset or to all assets under the same class. These are presented as decision-support tools, lifecycle planning methods, data-driven prediction models, risk assessment systems, best practices frameworks or even a combination of the above. While some of these are dynamic and can be adapted to different assets, others are tailored for use on a specific project. As the tool developed in this work focuses on long-term planning of geotechnical assets, below we review some of the existing asset management planning systems from the transport sector.

2.4.1. Highway Development and Management Tool (HDM-4)

The Highway Development and Management Tool (HDM-4) is viewed as the one of the important instruments available for the management of roads. Built on the theoretical approaches proposed by Snaith et al., (1998) and the Highway Design and Maintenance Standards Model (HDM-III), the tool can be used estimate the behaviour of a road pavement over its life span of 15–40 years (Kerali, 2000) in terms of road deterioration, road work effects and road user effects.

Aligned with the four functions of asset management proposed by Snaith et al., (1998), the tool consists of applications for project-level analysis, road work programming under constrained budgets, and for strategic planning of long-term network performance and expenditure needs. By inputting data related to traffic loading, environmental conditions, pavement types and pavement conditions, senior managers can use HDM-4 to anticipate the long-term requirements of the road network and accordingly direct their funding sources. It serves as a good decision support tool that can (1) reliably predict the changes in the road network in response to environmental and interactions, traffic, construction standards and maintenance standards; (2) analyse the effects of road management policies on the life cycle costs of road pavements; (3) offer a mechanism for empirical selection of the optimum investment alternative in the roads sector (Kerali, 2003).

Strategic planning in this tool includes looking at the long term performance and maintenance of road networks determining the funding needs for road network development and maintenance. This includes determining the performance of road networks and the subsequent effect on road users by considering the impact of various budget scenarios estimated together with the asset value of the network. HDM 4 can be used to compare funding policies for competing needs and the impacts of policy changes over energy consumption and impact of load limits and pavement maintenance and rehabilitation standards. (http://www.hdmglobal.com/, accessed September 2014).

2.4.2. Pavement Management System (PMS)

PMS are commonly adopted asset management tool for pavements. It includes a broad spectrum of tasks ranging from planning or programming of investments, pavement design, construction and maintenance and assessment of performance and deterioration. Basic components of a PMS is a centralised database, performance models, analysis tools and reporting mechanisms (Dewan, 2004). PMS involves the evaluation of alternative strategies over a specified period of intervals (e.g. yearly) comparing pavement performance using key performance measures and considering boundary conditions/limitations. PMS includes also a feedback loop in the system to record the performance achievements and the corresponding key performance measures considered for the analysis (Dewan, 2004).

2.4.3. UK Pavement Management System (UKPMS)

UKPMS is the national standard for pavement management systems for assessing the conditions of local roads and for planning the maintenance and capital investment on paved areas of roads, kerbs, and footways. This standard provides 'best value indicators' on local roads that is required by the government and is recommended best practice in the code of good practice for maintenance management (www.UKPMS.com). UKPMS provides location and referencing of highways, inventory of maintainable assets, record of condition data based on historic deterioration and engineering models based on designs, type of construction and pavement life, selection of type of works and associated typical costs. It analyses budgetary needs and maintenance requirements for road networks based on the above information and prioritises works based on condition and using economic principles (http://www.ukpms.com/about/intro.asp). UKPMS uses conditions survey data from Surface Condition Assessment of the National Network of Roads (SCANNER) surveys, deflectographs, Sideway-Force Coefficient Routine Investigation (SCRIM) and detailed visual inspections. The primary use of UKPMS is to assist local authorities in planning of maintenance on their local road network using systematic collection and analysing of data. The use of PMS accredited to UKPMS specification is required to produce national performance indicators (NI) for local roads. The Pavement Condition Information Systems (PCIS) provide general information UKPMS and SCANNER surveys used on pavement network (http://www.pcis.org.uk/index.php?p=2/3/0).

2.4.4. Stochastic Modelling using Risk-Based Approaches in Asset Management

Costello et al., (2005) developed a planning methodology targeted at senior maintenance managers and administrators responsible for pavement management that involves the use of stochastic modelling. Because the researchers were particularly interested in the 'development of long term, or strategic, estimates of road maintenance expenditure and road condition forecasts under various budgetary scenarios', they developed algorithms for simulating pavement deterioration using

Markovian processes as against the traditionally used regression models and tested their model with the help of a case study in Central Europe. The model allowed for prediction of changes in the future condition of the road network in response to changes in budgets. Further, it also helped in estimating the total budget needed to maintain the road network in future on the basis of the current funding and policy status. Such methods that involve the prediction of risk of asset failure or change in asset performance as known are risk-based approaches to asset management.

Mian, et al., (2011) also presented a risk-based framework for infrastructure asset management by outlining a four-step process to analysing risks which include ‘hazard identification’, ‘risk estimation’, ‘risk evaluation’ and implementing ‘risk based investment decision’. The authors suggest using cross asset interaction, asset criticality and asset vulnerability as key variables in the risk based framework. The authors suggest that within asset management planning, risk matrices are more frequently considered to be suitable tools than sophisticated modelling tools in terms of the level of information available for asset groups. The authors argue that a risk-based view is essential for timely intervention and to ensure that the most low-cost solution is not the default choice of the decision makers.

Leviäkangas et al., (2014) also used a cost-benefit analysis to estimate the impact of extreme weather and climate risks on infrastructure assets in Europe. While their study mainly focussed on the financial effects of the weather risks, it also served to the highlight the vital role played by local factors in the maintenance of an asset. In acknowledging the lack of systems to measuring weather risks, the authors explained that weather conditions/risks vary substantially across countries within the European Union and should be considered for any long-term asset planning efforts.

Many decision-support support tools do not have an explicit risk assessment component. Although lifecycle-planning tools attempt to anticipate future changes, a clear estimation of risks of asset failure and the future costs of different maintenance solutions is not always required. Interestingly, Costello et al., (2011) note that most of the existing stochastic or deterministic approaches cannot be applied to the lifecycle planning of ancillary highway assets because of the problems associated with determining the current state of an asset and with simulating deterioration. In their work, they accounted for present-day deterioration in the highway assets by collecting data in the form video footage and walked surveys. Subsequently, they solicited expert opinion on asset lives and developed them into probability matrices on the strength of simplistic assumptions. The authors believe that visual estimation of deterioration can be used as approach for ancillary highway assets owing to their homogeneity.

Some of the widely used asset management planning guidance and approaches on the highways network are discussed below.

2.4.5. Highways Maintenance Efficiency Programme – Asset Management Guidance

Within the UK, the Highways Maintenance Efficiency Programme (HMEP), funded by the Department of Transport (DfT), is one the leading initiatives started for promotion and preservation of the highway network. The latest documentation released by the HMEP is the Highway Infrastructure Asset Management Guidance Document (UK Road Liaison Group, 2013), a report commissioned by the DfT that offers comprehensive advice on the management of the highway assets. Interestingly, the report urges authorities to replace the traditional ‘worst-first’ approach to asset management with preventive maintenance and underscores the importance of long-term maintenance planning. The guidance document aims to:

- establish a framework to enable development of asset management;
- provide advice for authorities to interpret the requirements of asset management;
- promote good practice through a common framework for highway infrastructure asset management;
- support efficiency in the delivery of highway maintenance;
- embed the learning from practical application of asset management; and
- enable quick and consistent progress to be made (pg. 3).

Accordingly, the report lists 14 recommendations as the minimum requirements for achieving a reasonable level of benefit from asset management. These include the (1) development of a robust asset management framework, (2) setting and assessing of performance, (3) careful and appropriate management of asset data, (4) lifecycle plans to support decision making and justify allocation of funds, (5) risk assessment to anticipate and mitigate future threats to the asset and (6) benchmarking to continuously evolve the asset management framework. These recommendations are contained within a broader highway infrastructure asset management framework, which is categorized into three themes: context, asset management planning and enablers. The centrality of the planning functions to the framework is evident from the fact that the majority of the recommendations are covered under the planning theme.

Targeted at local authorities in charge of managing their highways network, the asset management framework provided in the guidance document is divided into three parts: context, asset management planning and asset management enablers. The asset management planning provides key information on how to undertake effective asset management planning. This includes defining a clear organisation-level policy and strategy towards transportation asset planning. The strategy should encompass the long-term vision of the organisation and the level of service expected from the network. Life cycle planning explains the rationale behind considering the long-term needs of the assets while maintaining assets through their whole life cycle. In order to undertake life cycle planning, it is imperative to assess the current asset condition, identify performance gaps and determine an effective and optimal maintenance intervention strategy. Life cycle planning is undertaken by stakeholders to identify long-term investments, predict future performances for different level of investments and support decision-making while identifying the impact of different funding scenarios. The framework demonstrates the role of asset management enablers in developing and deploying efficient asset management systems through effective leadership and commitment, appropriate risk management strategies, asset management training, benchmarking and performance monitoring.

2.4.6. Highways Maintenance Efficiency Programme – Life Cycle Planning Toolkits

Going a step beyond modelling, the HMEP has developed three toolkits that can serve as ready-to-use decision support systems for highway asset managers. These include ancillary assets toolkit, carriageway toolkit and the footway toolkit. Each asset-specific toolkit is available as a downloadable excel file and serves as a strategic decision-making and planning instrument for local authorities. It enables decision-makers to select prudent investment alternatives after accounting for the entire lifetime of an asset. It also helps deliver timely maintenance interventions so as to ensure long-term performance of the assets and optimal budget prioritizing. According to HMEP, these toolkits facilitate long-term strategic planning because they:

- Examine the impact of funding on asset performance and maintenance requirements
- Indicate the present and future funds needed
- Identify the funds needed for effective maintenance (HMEP, 2014)

On the spectrum of readiness for use, toolkits represent one end as they are readily usable and specific to the asset while frameworks are closer to the other end as they are more generic and adaptable. However, when scouring for best practices in asset management globally, it is easier to use the latter as benchmark rather than the former.

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

Taggart (2014) discusses Highways Infrastructure Asset Management code of practice (COP) supported by UKRLG for asset management, which offers three codes of practice to enable local authorities in UK to make best possible use of resources and adopt better asset management practices. The three codes of practice are ‘Well Maintained Highways’ for highways maintenance management, ‘Well-Lit Highways’ for maintaining highways lighting and ‘Well-Maintained Highways Structure’ for effectively maintaining highways structures. Although there is no statutory requirement for adopting the approach laid out in this guidance, this is among the few standards that provide guidance on delivering effective asset management. The codes of practice provide guidance to highway authorities and council members on efficient, effective and economic delivery of highway maintenance services while contributing to wider local authority objectives.

2.5. Asset management systems and tools used by railway and ports

Asset-specific guidance and assessment models are also available outside the domain of highways transportation. For instance, Burrow et al., (2009) devised a probability-based planning model to help railway authorities study the effects of budget constraints on the maintenance of the railway network. The study focused on presenting network-level benefits of maintenance in an easy-to-understand manner so as to justify funding and policy formulation linked to maintenance. A similar research objective was pursued by Lai and Barkan (2011) who aimed to assist corporations looking to optimize their capital investments on railway capacity. The authors worked on a comprehensive decision-support framework that consisted of three discrete tools: an 'alternatives generator', which presented the cost vs. capacity trade-off of the options considered; an 'investment selection model', which helped identify the railway network sections that needed capacity-specific improvements; and an 'impact analysis module', which evaluated the trade-off between capital investment and delay cost.

For the evaluation of ports and waterfront assets, a manual was developed by a committee formed by the American Society of Civil Engineers and COPRI Ports Harbours Committee (Heffron, 2013). The document outlines the processes and procedures for inspecting assets both above and under water such as anchoring systems, piers, seawalls, relieving platforms, gravity block walls, marine railways and floating structures. It covers eight types of inspections: routine inspection; structural repair or upgrade inspection; new construction inspection; baseline inspection; due diligence inspection; special inspection; repair construction inspection; and post-event inspection. Advice is also provided to owners and caretakers on the type of inspection suited to each asset or project and on combining inspection types if needed. The manual is a step towards standardizing the maintenance of ports and waterfront assets and lengthening their lifetime. Because port assets face significant stress from air and marine environments, the Port of Melbourne Corporation (PoMC) has adopted a strategic asset management programme for estimating the total lifecycle cost of its assets (Lo Bianco et al., 2010). The programme uses a 4-step approach to ensure that their asset investments yield the maximum benefits: renewals modelling; risk management; optimized decision making and lifecycle planning. The framework particularly focuses on renewals and details the techniques to be used under each step.

Brooke (2015) notes that climate change is bound to affect the existing and proposed developments of port, harbour and inland waterway infrastructure, especially those located in the environmentally sensitive areas. Climate adaptation reports (ABP 2011, MHPA 2011 and Brooke, 2015) suggest that certain marine structures are at significant risk of flooding owing to climate change factors. Modern marine structures have a typical design life ranging from 20 to 100 years (Brooke, 2015). Recreational facilities are another component of marine infrastructure that is vulnerable to the risk of flooding, temperature fluctuations, erosion and sediment transport. In addition, coastal habitats, which are already suffering from degradation, are likely to become more vulnerable because of changes in water temperature (Brooke, 2015; Maselink et al., 2013 and Simpson, 2013). Hanson et al., (2011) and Nicholls et al., (2008) highlight the need for 'adaptation planning' by developing a national-level 'toolbox' that includes adaption measures for coastal infrastructure such as modifying, reinforcing or replacing existing structures and developing increased opportunities to identify future vulnerabilities and ideas to future proof new developments. Some other suggestions for effective management and future proofing these assets include changes in vegetation management, resolving structural integrity, developing innovative technology especially for bank protection and regular monitoring and generating adequate data for determining intervention strategies. While the authors highlight interesting challenges in asset management for ports and other marine structures especially due to changing environmental conditions there is no asset management planning framework which can assess the resilience of coastal solutions across a broad range of future conditions which can assist in determining coastal solutions' adaptability in the light of future events.

2.6. Asset management systems used in water and power and distribution industry

While water and power distribution networks do not fall into the transportation domain, these assets are definitely part of the broader infrastructural umbrella. Scholars have developed inclusive frameworks that cover not just maintenance but also new construction and rebuilding. Abuzayan et al., (2014) have proposed an overarching asset-management framework for infrastructure facilities in high-alter or disaster- or conflict-hit countries. Using Libya, Egypt, and Tunisia as study sites, the authors aim to develop a framework that covers techniques related to economic evaluation, asset management and change management of civil assets that are flexible to withstand adverse situations. A recurring theme in the literature on asset management tools and approaches is the concept of life-cycle management, which explores the longevity or the actual lifetime of an asset. Naturally, those in charge of managing assets are interested in lengthening asset performance and activities of planning, prediction, maintenance and management are organized around this objective. Ruitenburg et al. (2014) developed a multi-perspective model that uses both qualitative and quantitative data to build a lifetime impact report of the asset. The model evaluates the impact of trends or events from technical, economic compliancy and other commercial perspectives, thus providing an all-round insight into the asset lifetime. The model yielded robust results when it was tested on an asset (switchgear) of a Netherlands-based electricity and gas distribution network; data collection was done through interview sessions with experts who represented the different perspectives. While the researchers used the model for assessing intermediate (<5 years) and long-term life impacts, the time span covered under long-term scenarios has not been clearly defined. Given that most geotechnical assets are known to have a lifetime of up to 120 years, the applicability of this model for studying the long-term resilience of such assets is uncertain.

2.7. A review of asset management standards and specifications particularly in relation to planning

Theoretical guidance and detailed frameworks for the maintenance and management of roadways have been developed by many governmental and independent bodies, researchers and industry experts specialised in the field of asset management. Some of the most well-known works pertaining to asset management of roadways and infrastructure asset management at large are summarized below.

2.7.1. PAS 55

The most highly regarded and internationally recognized standard for the management of any kind of asset is Publicly Available Specification 55 (PAS 55, 2008). Published by British Standards Institution (BSI), it is now the default global standard for asset management. PAS 55 covers 28 parameters of effective asset management, from lifecycle strategy to everyday maintenance (cost/risk/performance). It combines all the aspects of an asset lifecycle: from the recognition of a need to design, acquisition, construction, commissioning, utilisation or operation to maintenance, renewal, modification and/or ultimate disposal. The standard not only defines key terms, constructs, responsibilities and roles but also offers practical advice for senior managers and organisations committed to maintaining the quality and ensuring efficient management of their asset. Part 1 of the standard contains a checklist of the requirements that organisations should fulfil to comply with the standard, and part 2 contains detailed information on how the requirements of part 1 can be met. Because of its focus on the planning functions of asset management, which are common to all asset management across sectors, PAS 55 has found wide applications in diverse industry sectors – from water distribution networks (Ugarelli et al., 2009) to the development of information management (Ouertani et al., 2008).

2.7.2. ISO 55000

Complying with the specifications of PAS 55 is viewed as a stepping stone to acquiring the ISO 55000 certification for asset management. In fact the BSI has been instrumental in the formulation and adoption of these international standards for asset management. ISO 55000, 55001 and 55002 pertain to different aspects of the asset management functions: the first covers the principles underlying asset management and the relevant terminology, the second delineates the requirements of a robust asset management system and the third explains how such a system can be implemented. As with PAS 55, the standards highlight the importance of long-term planning as a vital approach to asset management.

PAS 55 covers all physical assets and is not confined to any type or class of asset. However, the ISO 55000 suite focuses only on transportation assets and was developed from PAS 55, 2008, after industry consultation and expert advice from asset management practitioners. The most important features of PAS 55, 2008, have been incorporated and comprehensively explained in the suite of ISO 55000. These cover asset management strategies, objectives plans and day-to-day activates. The ISO suite acknowledges the importance of considering the whole life cycle of assets, undertaking cross-disciplinary collaboration for asset management and adopting a risk-based decision making approach to implementing asset management. However, the style and structure of ISO 55000 suite is different from that of PAS 55. For instance, PAS 55 focuses on optimisation between cost risk performance and between short-term and long-term needs and impacts whereas ISO 55000 standards focus on well-documented evidence-based methods and decision making, along with identifying the stakeholder needs and defining the ‘value’ to best balance conflicting objectives. Risk management details are limited in ISO55501 but are detailed in ISO31000 risk management standard. Moreover, ISO 55001 highlights the requirements for auditing and documenting (Woodhouse, 2014). This feature is likely to encourage the regulators to adopt and ensure compliance with the ISO standards within the physical infrastructure environment (Moodley, 2014)

2.7.3. Asset Management for the Roads Sector (2001)

This document is published by the Organisation of Economic Co-operation and Development (OECD) and aims to address some of the key issues in undertaking an asset management approach within the infrastructure sector. It delivers comprehension around the key focuses of infrastructure asset management; however, it is limited by its international remit. Whilst OECD is a multi-national economic forum that has provided substantial Asset Management guidance via its specifically assigned Asset Management Working Group (OECD, 2001) the working group strives to develop a common understanding of the goals, scope and definition of asset management strategies for implementation across the world. The international members include Australia, Belgium, Canada, Denmark, France, Sweden, Switzerland, Turkey, UK and USA.

2.7.4. International Infrastructure Management Manual (2011)

Published by New Zealand Asset Management Support (NAMS). This manual was developed by a consortium of companies and bodies delivering asset management in New Zealand and Australia. Infrastructure asset management has been practiced in New Zealand since 1995, and encompasses a wide range of publically owned physical assets.

2.7.5. Framework for Highway Asset Management (2004)

Published by the County Surveyors Society (CSS). A general purpose guide largely aimed at Local Authorities in UK. This document has a significant emphasis on Highway Asset Management.

2.7.6. Manual of Highway Design and Management (2011)

Published by the Institute of Civil Engineers (ICE). A further general purpose guide, updated to incorporate current thinking on asset management provision. Useful for both local and national highway authorities.

2.7.7. C667 Whole-life Infrastructure Asset Management, A good practice guide for civil infrastructure (2009)

Published by Construction Industry Research and Information Association (CIRIA). This is a general guidance provided for maintaining physical assets on the infrastructure network in the UK. CIRIA document shares information and best practice on undertaking asset management for physical assets while ensuring skills are retained for delivering challenging and innovative solutions.

2.7.8. Rail Safety and Standards Board (RSSB)

RSSB publishes asset management standards and guidance for railway network in the UK. It provides guidance on risk analysis and improving safety on railways along with improving industry practice.

2.7.9. Asset management guidance from asset owners in the UK

Asset owners like the Highways England (formerly called Highways Agency), Network Rail and local authorities in the UK produce their own asset management guidance documents in line with the standards and best practice guidance documents discussed above which provide recommendations on implementing effective asset management practices on their transportation network. These can include asset management frameworks to provide an insight how asset management activities will deliver the authority's business plan objectives. For example, Highways England, in association with the Department for Transport and other UK motorway and truck road authorities, produce the Design Manual for Roads and Bridges (DMRB), in which volume 4 specifically sets out standards for the design and maintenance of geotechnical and drainage assets. Of particular interest, in terms of geotechnical asset management, are HD 41 (2015) 'Maintenance of Highway Geotechnical Assets' and HD 22 (2008) 'Managing Geotechnical Risk', both of which define a set of principles specifically design to manage the Highway England's geotechnical assets on the network.

Similarly asset owners produce their asset management plans and policies and strategies which sets out their implementation plan to delivery effective asset management services on their transport network.

2.8. Asset management planning tools utilised by industry internationally

In a study aimed at identifying the asset management approaches used in Canada, England, New Zealand and Australia, US-based researchers Geiger et al., (2005) found that most countries relied on lifecycle costing as their basic approach to asset management. Asset management authorities of all the countries undertook risk assessment, in some form or the other, especially by local governments achieving a trade-off among different budget allocations. However, in such analyses, the nature of the risks considered tended to vary depending on the stakeholders involved and the asset category. The researchers explain that ‘the risk assessment associated with a concessionaire’s participation in a public-private partnership related to factors that affected revenue generation, while that for public services tended to relate to safety, public support, and customer service factors’. Finally, asset management programs that received the backing of professional organizations and user groups were found to be more impressive than the rest. In England and New Zealand, researchers found that the local governments made active efforts to engage the public in asset management decision making by forming associations and working groups. The research team concluded that top-down involvement, formation of a committee for widespread information distribution, creation of asset-management toolkits, and research on the topics vital to transportation programs are needed for capital investment in asset renewal and preservation.

2.8.1. Resilient Communities Planning Framework – Canada

The concept of resilience although not new has attracted considerable interest since Hurricane Sandy which devastated the northeast coast in USA (Hay et al., 2015). In brief, infrastructure is designed to serve a purpose, and resilience is the study of how the infrastructure will continue to serve that purpose (Hay et al., 2015 and Holling 1973).

Canada has a ‘Resilient Communities Planning Framework’, which identifies the ‘influences’ that affect a city’s vulnerability and ability to perform during a shock event. The framework outlines the scope, analysis, resilience goals and the planning of resilience strategies. It helps a user identify a community’s strengths and focus areas and sets out ‘indicators of need relative to resilience’ and determines their dependencies and relationships. Hay et al., 2015 research focusses on community resilience i.e. the factors such as ‘livelihood and continued prosperity of the community’ which affect people and supportive community operations (and not just infrastructure) are therefore at the centre of resilience planning in their research. Their planning framework is used to identify risks which are present in the current state with the objective to determine all pathways of exposure to those risks. It also identifies the dependencies of the community on various factors which may be affected by these risks.

Although, the context of developing a resilience based planning framework is similar to the proposed study, there exists key differences in the research outcomes. For example, the researcher's tool is specific for geotechnical assets (and therefore resilience in the context of transportation network is the domain of study with community well being targeted through one of the future condition i.e. Social whereas Hay et al., (2015) research focusses on community as the prime focus and transportation as a subsidiary for continued wellbeing through access to travel, leisure etc. and hence the focus of identifying critical factors affecting resilience are significantly different to one another). The proposed research focusses on changes in future conditions which are likely to affect the geotechnical assets on the road network and therefore assesses how flexible, adaptable and fit for purpose are the solutions in order to be resilient. The planning framework providers a numerical score as a comparator followed by qualitative assessment of the asset information. Whereas, Hay's research focusses on risks in the present times (and no reference to the future) and identifies how dependant is the community to certain factors which may be subject to certain risks. The frameworks in both the studies are based on similar principles of resilience but different aim to serve different objectives i.e. community function and transport continuity.

Another resilience framework proposed by the University of Toronto Centre for Resilience for Critical Infrastructure (CRCI) focuses on the issues related to investment and funding for critical infrastructure by studying the inter-relationships and dependency between the community and the infrastructure. It begins with identifying low-cost measures, which are mainly 'organisational' and 'procedural', and then progresses to the more cost-intensive measures such as resource adaptation, identifying alternative energy supplies and infrastructure changes and modification. The investments are recovered through life savings and risk minimisation (Hay et al., 2015).

2.8.2. Systems Resilience Planning – Toronto

In 2012, the City of Toronto Environment Office undertook a resilience assessment project to determine the dependency of critical infrastructure and develop a resilience planning tool for stakeholders to share and communicate their views on extreme events. The tool contributes to the broader goal of improving urban resilience by developing and analysing core dependencies. It provides a methodological platform to link critical elements of infrastructural interdependencies to urban planning. The tool presents a city-specific list of critical interdependencies and indicates the ability of the city to respond and adapt to shock events with minimal damage. A combination of concept mapping, expert consultation and data is deployed to establish correlations between the various components related to system resilience and urban infrastructure. While the tool provides a method of implementing system resilience, it does not provide a framework for identifying the future conditions and their impact on the critical factors of geotechnical assets. The tool enables 'dependency mapping' for operational resilience planning using a hierarchal approach instead of focusing on individual elements of a city. Expert consultation is an integral part of this process as knowledge and expert opinions from various communities are needed to understand the resilience of complex human systems. The City of Toronto Environment Office is one of many organisations that are turning their attention to resilience in the urban environment. Other resilience-based initiatives include the Rockfeller Foundation's 100 Cities Challenge; the annual ICLEI Global Forum on Resilient Cities and Global Collaboration on Urban Resilience, which includes global bodies such as United Nations and World Bank; and the C40 Cities Climate Leadership Group (APA, 2013, C40 2014 and Bristow, 2015).

2.8.3. Decision-Support Tools for Municipal Maintenance and Capital Projects – United States of America

Giokas et al., (2008) discusses a unique decision tool that can be used for planning capital improvement of municipal infrastructure projects in the USA. Called the 'Capital Improvement Planning Tool (CASS: CIP), it assess the current condition of municipal assets using datasets and can predict the deterioration of each asset base for a certain number of years based on factors such as material and age. The unique feature of the tool is that it utilises not only physical asset data but also capacity information from flow analysis based on evidence from historical incidents of overflow. Thus, it can be used to predict social cost in the event of an asset failure such as with pipes. The tool can incorporate data from long-term capital plans, which can aid in the process of decision-making. That is, the tool can identify the current state of the asset and depending on the required level of service run different models to demonstrate the level of service expected using a range of cost and time options and provide a capital plan for each option. It helps justify prioritisation and funding of municipal projects and enables decision makers to understand the time and cost intervention options.

While the tool allows users to envision the impact of time and budget decisions on the service level of an asset over time, it does not highlight the impact of other anthropogenic factors, such as technology, and policy-based shock events, that can influence the nature of capital and maintenance projects. It provides answers in terms of what the nature of the asset will be if a certain amount of money is spent over a certain period of time but without considering the impact of other future conditions that are likely to influence the behaviour of the asset For example, while it utilises the data of historical overflow it does not anticipate the change in infrastructure that may be required to cater to increased or decreased use and change in demand patterns. Thus, it serves as a sophisticated deterioration modelling and capital planning tool from an economic perspective but does not act as a resilience assessment planning tool as it does not consider change in use and continual performance under a variety of aforementioned changing factors.

Michele et al., (2011) discuss key elements for developing decision-support tools for municipal assets such as sewers, pipes and streets. The authors note that given the rate of urbanisation, economic constraints, globalisation and increasing competition between cities across the world, it is important to develop decision support tools for the maintenance of these assets within set timeframes and budgets. The modern decision support tools should integrate computerised maintenance management systems, whole life cycle management systems and geographic information systems and consider elements such as interactions between assets and their inter-relationships along with social factors such as change in the nature of demand. Vernier (1998) developed a decision-support tool ‘computerised maintenance management system’ for technical and economic decision-making in asset maintenance. It is available in a wide variety of software programmes which enable the users to identify maintenance strategies for different service periods or for a single asset throughout its life cycle. These tools typically provide data inventory and programmed maintenance plans. Condition Assessment Survey System (CASS) is a decision-support tool that uses benchmarks to compare infrastructure elements of the same type or a single infrastructure network during different time periods. The CASS tool identifies the deficiency in the system, the need for undertaking repairing works and cost estimates for repair solutions (Michele et al., 2011 and Wernsing et al., 2004).

The spatial decision-support system (SDS) relies on the geographic information system (GIS) for spatial and non-spatial information about specific infrastructure. This tool provides a platform for combining technical data, user knowledge and software inputs to provide a simple vision of the complex interface between different elements of infrastructure. The spatial decision-support tool provides geographical information along with the asset information on a common platform so that users can visualise the asset system as a whole and not just single elements of an asset. (Michelle et al., 2011).

The AWARE-P planning software is a decision-support tool used for water and wastewater utilities in Portugal (Alegre et al., 2013). The tool is based on a planning approach proposed by the Institute of Asset Management (2012). The approach focuses on diagnosing and assessing the condition of the water supply network over a planning horizon and draws from a wide range of models for evaluating risk, cost and performance such as system statistics and network simulation. The AWARE-P planning software assesses planning alternatives for water supply and sewer systems and compares them on the basis of cost, risk and performance criteria (Alegre, 2013). Although the tool is suited for long-term planning, (the authors do not mention any specific time frame), it does not cover the aspect of ‘resilience’ where the performance of water supply and sewer systems assets are predicted over a range of changing future conditions.

Piayatrapoomi et al., (2004) provide a framework for investment decision-making considering risks and uncertainties. The authors note that many countries such as Australia, UK, France and Germany utilise scenario planning to identify risks and uncertainties, which are based on data, forecasting errors and modelling. The authors explain that ‘probability based risk assessment’ techniques can be used for maintenance/rehabilitation and capital works using HDM 4 software. Alternative scenarios are employed while undertaking a cost-benefit analysis for major infrastructure projects such as those funded by the World Bank, which mandates a risk assessment as part of project appraisals.

Apart from the tools discussed above, there are other propriety tools available internationally, such as Computer Aided Rehabilitation for Water Networks aka CARE-W (Saegrov, 2005) Another example is the Sustainable Infrastructure Management Program or SIMPLE (Sneesby, 2010) which can be used in the planning stage of asset management to consider the cost, risk and performance aspects of an asset throughout its life cycle. It yields valuable information in terms of deterioration models and expected level of service for a range of time and cost options. However, there are no planning tools, which cater to the needs of assessing the resilience i.e. ‘continual performance under changing condition’ at a strategic level such as that provided by the researcher.

2.9. Risk management techniques

Risk management and planning is a powerful exercise when carried out in an effective manner. It is used to synthesise information and provide valuable insights in an asset management context. In the USA, through the introduction of a new bill ‘Moving Ahead for Progress in the 21st Century’, published by FHWA (2012) highlighted the importance of developing risk-based asset management plan, to be deployed not just at the project level but throughout the project programme and at the enterprise level. The 2012 Transportation bill requires transportation departments to share a formal risk management plan whose purpose is to minimise inherent risk while making the most of available resources. The risk management plan should ensure that the department’s mission and objectives are met and to communicate the identified risk and mitigation measures at all levels of operation within an organisation. In addition to risk analysts, senior decision makers play a role in defining acceptable risks and risk thresholds.

In adopting mitigation measures, senior decision makers should apply the principle of proportionality, especially when developing transportation asset management plans, as it tends to provide more efficient and cost-effective solutions. While risk management can be proactive or reactive, it emphasises collaboration between designers, analysts and planners. At a project level, analysts typically address risks such as delay in project duration, timely completion and cost overruns, whereas senior decision makers are likely to focus on organisational and societal risks.

However, for risks to be identified, managed and communicated, adequate data, systems and commitment is considered essential. Subject to availability of adequate and accurate data, the advances in technology have made sophisticated risk management systems more accurate and reliable than expert judgement which relies on assessment by individuals. Although expert judgement is considered effective in decision making especially where data is crude (Mian et al., 2011), it may have certain limitations like personal biases and subjectivity.

Risk management techniques can range from qualitative methods to quantitative techniques (Hubbard, 2009). One such quantitative risk management techniques is ‘actuarial risk management’, which combines the use of statistics and data analytics (Boadi et al., 2009). This technique uses historical data to estimate the likelihood of the occurrence of future events. Such sophisticated techniques are widely adopted in industries such as defence, energy and health. In industries where such data are not readily or accurately available, experienced judgments and/or the use of qualitative techniques are relied upon. Amendola (2001) argues that in situations where the emphasis is on distinguishing between significant and non-significant risks, probabilistic studies are not needed; an expert-based risk assessment can prove to be very informative.

According to ISO 33000, risk management involves establishing the context, which includes recognising the risk in the industry; identifying stakeholders and those who are likely to be affected; identifying the risks, analysing the risks and ascertaining the treatment of the risks. Many risk management techniques are adopted for determining and mitigating risks within the infrastructure asset management industry. Authors have highlighted the importance of integrating risk management within decision-making tools and frameworks to make the asset management approach more holistic and effective. Computational techniques and dynamic risk modelling techniques using Markovian Chain and associated deterioration models are typically used for determining optimal portfolio strategies (Leccadito et al., 2007 and Duan et al., 2003). They are also used to identify and quantify the risk value of an asset especially within dynamic operational research background. Other methods used for assessing dynamic risk measures include the policy iteration and value iterations methods and Newton's Method (Ruszczyn'ski, 2009). FHWA (2012) provides a framework for assessing 'enterprise risk management'. The framework covers the type of risk, responsibilities and mitigation measures applicable at different levels, ranging from a project to a portfolio and to overall organisation.

Some other risk management techniques widely used in the asset management industry include the Monte Carlo Simulation and Failure Mode and Effects Analysis (FMEA). In Monte Carlo Simulation, risk assessment is performed using probabilistic modelling, where uncertainty is determined using statistical models. It allows decision makers to anticipate a range of uncertainties and their probabilities along with the possible outcomes (Schuhmacher, 2001; Cohen et al., 1996). FMEA is a systematic method of identifying potential causes of failure before they occur in reality. It is used through the project life cycle—from project planning state to deployment. Given the growing need to ensure reliability in product output, companies across sectors—from manufacturing to infrastructure—are looking to anticipate risks and eliminating their occurrence (if possible) beforehand to save valuable time, resources and reputation. FMEA assigns a risk priority number (RPN) by multiplying severity, occurrence and probability. Each of these parameters is determined using linguistic expressions and a rating scale from 1 (minimum) to 10 (maximum). The 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 some have even modified the technique to best fit their risk assessments. However risk assessment and modelling are not within the scope of the research and hence this is not discussed in any more detail.

2.10. Transport Asset Management in UK

In most countries including UK, road network encompass the principal portion of public assets, which are largely owned by the government, who are responsible to operate, maintain and improve them (OECD, 2011). HM Treasury Autumn Statement (2011) highlights effectively that asset management service objectives need to be met within the constrained budget and growing scrutiny from the taxpayer who pay and use the road network and demand a better level of service in terms of safety, reliability and comfort with minimum environmental impact. In the statement, there is a clear focus for the government and its service providers to improve infrastructure network performance whilst ensuring value for money for network users and for UK taxpayers. The Autumn Statement (2011) further highlights making 'smarter' use of existing infrastructure by improving capacity and connectivity on highways network which provided a programme of targeted investments (referred to as the 'pinch point' programme') to provide workable solutions to alleviate congestion at busy parts of the highway network, and supported by a strong programme of asset management across the rest of the network. The 'pinch point' programme was included as a part of the governments growth strategy in order to improve the strategic junctions of the road network in order to help stimulate growth and development in the local economy while alleviating congestion and improving safety. The Highways England (formerly known as Highways Agency) was initially allocated a total budget of £317 million during the period 2012 to 2015 for undertaking the pinch point projects comprising of 123 schemes across the network. A fundamental aspect of the pinch point program was to facilitate stakeholder engagement between the Highways England, local authorities and local enterprise partnerships. Collectively this allowed them to use their knowledge and understanding of growth priorities to drive pinch point projects. (http://www.highways.gov.uk/our-road-network/managing-our-roads/improving-our-network/pinch-point-programme/, accessed September 2014)

In 2010-11 the Highways England (formerly called Highways Agency) was allocated a budget of £7,869M (HA 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 Highways England's government funding is spent on maintenance, it is only right that HM treasury demanded a not insignificant amount of evidence for works to be carried out to achieve a level of certainty (and so dispel uncertainty) regarding the Highways England's investment strategy.

2.11. Asset management systems

Guidance for the development and implementation of an effective asset management system can be found in the guidance documents described in section 2.7. These guidance documents highlight the benefits of implementing an effective asset management and Enunciate its key elements. Adopting and modifying the processes laid out in guidance documents CSS (2004) and PAS 55, (2008), a generic theoretical asset management system for implementing highways asset management is provided in figure 2.1 and the process is described below.

An effective asset management system initiates with a clear idea of the goals and objectives of the organisation which is coherent and aligned with the transport authority's policies and strategies for effectively managing their assets. The next step is to identify asset data i.e. location, inspection history and condition of the assets. Subsequently identifying the level of service which can be delivered by the transport network based on its' asset performance. Gap analysis of this asset data can enable identifying the difference between existing asset performance and expected performance from the asset and to fill this gap effective decision making is required.

Life cycle plans can help identify maintenance intervention strategies for the required asset performance and budget implications. The next stage is options evaluation which includes undertaking feasibility studies to compare asset management solutions based on the whole life cycle of the asset. The asset management system enables breaking bigger tasks into smaller work packages thereby ensuring a clear programme of works is prepared. The asset management process should be monitored and reported for continual improvement.

Organisational of Economic Co-operation and Development (OECD) (2004) along with other guidance bodies coherently suggests that for an effective asset management implementation a clear idea of the goals and objectives of the organisation is required, not least in terms of the type of network and types of assets. Modelling the condition of the assets therein and determining their performance in order to develop implementation strategies with adequate feasibility analysis is required in order to determine the selection criteria of a project and finally to allocate appropriate funds and budget for its implementation. These are the essential elements that underpin and ultimately steer an asset management process.

Figure 2.1: Generic Asset Management System

It can be inferred that the principles and key elements of an asset management systems discussed in relevant guidance documents are broadly similar with only minor differences occurring depending on the background of the guidance body. For example, PAS 55 (2008) is a generic asset management specification for all physical asset types, and not infrastructure specific, hence it is more macroscopic in nature. Whereas the asset management system shown in CSS (2004) was drafted by several local highway authorities and city council bodies and hence details every stage of asset management that is specific to maintaining highways. Hence, asset management concepts are based on common principles on which an effective and uniform asset management system can be based. Therefore, a standardised asset management system, applicable for all types of transportation network, should follow the stages outlined in Figure 2.1, in order to provide a consistent framework for maintaining and managing physical assets on the transportation network.

2.11.1. Key elements of a theoretical asset management system

In order, to put a systematic framework in place, it is paramount to understand the various components and inherent implications of an asset management system. For example, County Surveyors Society 'Framework for Highway Asset Management' (CSS, 2004) suggests that the asset management should be established to focus on taking a long term approach for management of assets considering a 10 year cycle of renewal and at the very least a whole life cycle for all assets. The need for optimising resources and processes is highlighted so as to maximise benefits and suitable resource allocation based on and assessed for the needs of the customer. The Institute of Civil Engineer's 'Manual of Highways Design and Management' (ICE, 2011) compares asset management to a skeletal 'jigsaw' that that links together a wide range of activities in a logical manner. It is a series of interrelated activities that serve to enhance and improve management systems. Figure 2.2 shows the various components for whole life cycle management of Assets.

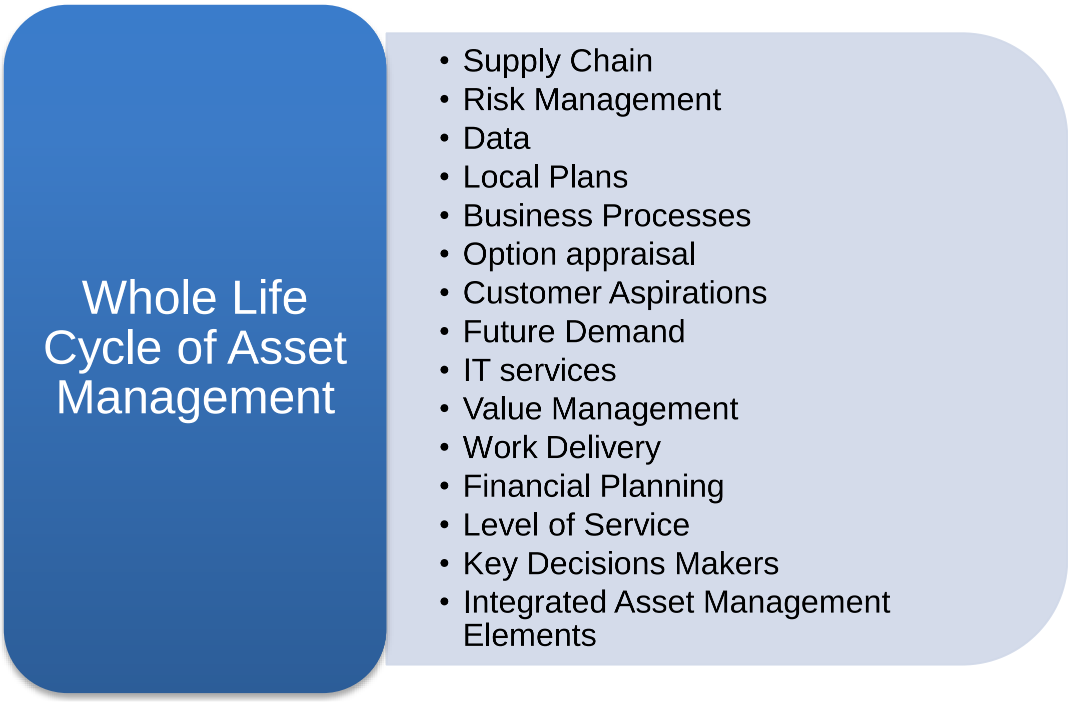


Figure 2.2: Components of Asset Management (ICE, 2011)

2.11.1.1 Data Management

There is an emphasis in all of the cited guidance documentation for the importance that data has to an organisation practicing asset management. Elements include the amount of data, how it is held, who has access to it and how it is managed. These are all fundamental to achieving optimal performance of the asset and the management team within an infrastructure maintenance environment. Data are critical to the maintenance of Infrastructure assets, hence accurate and up-to-date data sets are required within any asset management programme. Faiz, et al., (2009) recommend increasing the confidence threshold within all reliable data management systems which are tasked with keeping assets up and running for a longer period of time.

Typically, data sets may be housed in a number of different ways; however all should be managed with a similar set of policies, which rigorously address the following (Faiz, et al., 2009):

- Network Location Data – with GPS mapping, 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 improved, if not assured. Moreover, decision support systems provide evidentiary support for the selection of project, and can be invaluable when submitting bids at the beginning of funding cycles.

Further, the datasets can be used to understand the trends 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.

2.11.1.2 Level of Service

County Surveyors Society 'Framework for Highway Asset Management' (CSS, 2004) defines level of service as the quality of service for the asset for the benefit of the customer. The level of service is governed by safety, accessibility, reliability and availability of the infrastructure assets (CSS, 2004 and ICE, 2011)

The Institute of Civil Engineers 'Manual of Highways Design and Management' (ICE, 2011) highlights the factors that will influence the effective level of service; 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. It suggests that the levels of service can aid in the 'rational evaluation of services vs. cost trade-offs' by keeping the customer as the central focal point. OECD (2001) highlights that performance indicators are used around the world to assess and monitor this kind of performance. In facilitating this process further The Institute of Civil Engineers 'Manual of Highways Design and Management' (ICE, 2011) recommends public opinion surveys should be undertaken to determine current opinions on condition, safety, availability and the environmental implications that an asset has on the overall level of network service.

The Institute of Civil Engineers ‘Manual of Highways Design and Management’ (ICE, 2011) suggests that the level of service should consider the entire service of the network, not just for an individual asset, thereby promoting an integrated asset management system.

2.11.1.3 Integrating Asset Management

Integrated asset management as an ethos aims to provide a plan for managing the infrastructure system as a whole, and not individual assets, thereby providing robust solutions that are economically an technically well-optimised and more sustainable for the whole-life cycle period of the asset system. As such Integrated Asset Management systems facilitate understanding of the interface between different asset types and their performance within a particular network.

OECD (2001) highlights that integrated asset management system aids in an “improved budget analysis and decision making, increases operational efficiencies and strategic planning and increased productivity on road administration due to reduced information fragmentation” thereby giving best value for the service.

2.11.1.4 Gap Analysis

County Surveyors Society ‘Framework for Highway Asset Management’ (CSS, 2004) defines gap analysis as the comparison of current and desired practices and quantifying the activities required to change current practices to desired practices as represented in Figure 2.3. This shows that undertaking gap analysis incorporates several stages

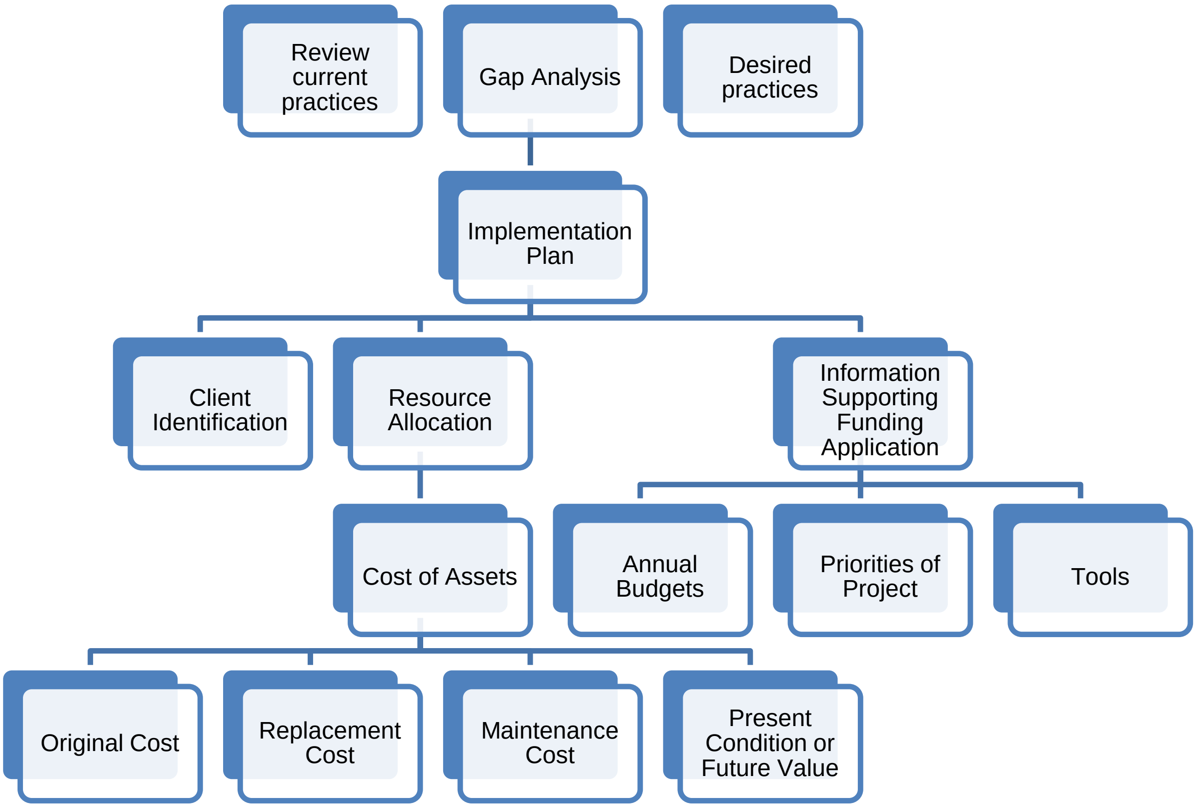


Figure 2.3: Gap Analysis and Implementation of Asset Management Plan (adapted from CSS, 2004)

In addition the guidance indicates looming key questions within what is a logistically complex process, this includes; determining the cost of bridging the gap, understanding the benefits achieved from the same, and setting a hierarchy for different criteria and allocation of required resources. CSS (2004) highlights that a gap can exist in many places, for example, it could be on the part of expectations and performance noting the difference between what the actual customer expectations are and what the management perceives them to be. It could also imply questions around the performance standards of the asset; what they should be and what they are.

The Institute of Civil Engineers ‘Manual of Highways Design and Management’ (ICE, 2011) suggests that a Gap Analysis should identify ‘what is there and what should be there’, in terms of understanding the asset; this could mean data, performance metrics, maintenance, organisational or even staffing needs. In essence it should provide an improvement plan that highlights the list of actions with indication to the resources it will require.

2.11.1.5 Risk Assessment

County Surveyors Society 'Framework for Highway Asset Management' (CSS, 2004) suggests undertaking risk analysis is of paramount importance for developed asset management system. Risk analysis should involve determining the consequence of the impact and its likelihood of occurrence. There are alternative analysis measures as well, which consider undertaking qualitative and quantitative analysis of the perceived risks.

Asset management strategy and risk management from The Institute of Civil Engineers 'Manual of Highways Design and Management' (ICE, 2011) highlights that steps to consider for risk management include adopting appropriate skills, corporate risk strategy, identifying existing and historic risk registers. 'Risk' within this document is considered as a unit for prioritising works and investments plans that enable mitigation systems and appropriate documentation. There is also acknowledgement that risk registers should be available to relevant bodies. A much detailed section on risk assessment is provided in section 2.16 of this chapter.

2.11.2. Challenges of Implementing Asset Management Systems (Theory)

Current systems of managing assets pose several challenges to its implementation. Asset management in itself is not a completely new concept, it has always been implemented at some level or other in various organisations, but in general there is a lack of any integrated, network-wide approach to maintaining and managing activities on the infrastructure network (CSS, 2004 and ICE, 2011). In addition there is a lack of standardisation in asset management system within different areas of infrastructure asset management. Having a standardised asset management system for an infrastructure network provides uniformity in processes and avoids the inconsistencies and consequent ineffectiveness in the existing maintenance and renewal processes.

The following sub-sections discuss key challenges in effective adoption of asset management systems in practice.

2.11.2.1 Data Referencing and Management

ICE (2011) further highlights that, the inventory of data maybe either (or both) inadequate or obsolete in terms of the condition data. One cannot underemphasise the role of adequate and accurate data in implementing effective asset management system. Hence undertaking gap analysis based on inaccurate data could result in an overall redundant asset management system due to a cacophony of errors, resulting from lack of understanding and inaccurate analysis of asset condition and therefore inappropriate decision-making. ICE (2011) suggests that most of the current data management systems and practices are often referenced to separate network models, rather than defining them within a single referencing model, which is in accordance with CSS (2004) which stipulates that any data should be referenced to National Grid Co-ordinates and National Streets Gazetteer.

The Institute of Civil Engineers 'Manual of Highways Design and Management' (ICE, 2011) highlights some of the biggest challenges in asset management can often be found in data management; 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. It classifies the challenges in Asset Management as:

- *Inventory*: Questions like what, where condition, value, performance, significance and Impact on the network are important.
- *Impacts*: Short term, long term and medium term? Are the objectives deliverable cost effectively?
- *Utilisation*: An important element to assess and evaluate current state of the asset and how they are utilised or used.

2.11.2.2 Organisational Behaviour

Asset management works best when the emphasis is placed largely on change management, where employees of the appropriate competence and seniority are taught how to properly manage the assets within their remit and actively take responsibility for them (ICE, 2011). However this requires care as Kellick (2010) recognises problems, not least where development and initiation of implementing asset management systems in an organisation has become a responsibility of all, ending up being a responsibility of none, resulting in a lack of ownership of any set actions and non-uniformity in approach. Therefore it is evident that ownership, accountability and responsibility remain key factors of the successful implementation of asset management for any organisation.

Both The Institute of Civil Engineers 'Manual of Highways Design and Management' (ICE, 2011) and Kellick (2010) suggest that getting the commitment from the organisation and its senior management is essential for the asset management practice to get an initial start. Kellick (2010) also highlights that involvement of senior management in formulation of asset management system right from the early stages will initiate and enable accessibility of financial and human resources. Both The Institute of Civil Engineers 'Manual of Highways Design and Management' (ICE, 2011) and Kellick (2010) agree that there should be an asset management steering group or a working group, which will focus the direction of work to business and industry objectives, whilst ensuring the interaction of different departments to exchange knowledge and resources through effective communications

2.12. Benefits of adopting an asset management system.

An asset management system, when tailored to the needs of the industry and adopted in a proactive manner, may provide multiple benefits to an infrastructure asset owner, including the provision of a 'better-informed' decision tool, improved results and outcome from the modelling process and an organised strategy for delivery. County Surveyors Society 'Framework for Highway Asset Management' (CSS, 2004) highlights areas where a well-defined asset management system provides specific benefits including:

- Reduced Life Cycle Costs
- Defined level of Service

- Ability to track performance
- Improved transparency in decision making
- Predicting consequences of funding decision
- Decreased financial, operational and legal risk
- Ability to discharge to financial reporting responsibilities and statutory valuation

In addition, the framework highlights that a process with on-going monitoring and review must be set up, thus focusing the maintenance strategy by aiding the transition to need-based funding. Thereby, streamlining the process for resource allocation and therefore, ensuring that funding bids are submitted with an explicit asset need stipulated and evaluation and risk profile detailed. By requesting this level of detail from the outset, and by ensuring that delivery agents understand the need for comprehensive bids to be submitted, a 'cradle-to-grave' project evaluation process is established, which aids the asset maintenance process through efficient and effective decision-making. County Surveyors Society 'Framework for Highway Asset Management' (CSS, 2004) further states that a benefit occurs when a customer receives an improved level of service for the resource available. The asset management systems help to establish a process between the various elements of the system and incorporate some new elements that fulfil the needs of the current socio-economic climate.

Therefore Asset management removes the emphasis on each individual asset towards a more optimised approach that considers both the asset and the impacts on other surrounding assets of the same and differing nature. It also aims to deliver a more financially accountable maintenance approach, which can be used in support of decisions and as evidence for spending reviews, given that much of the funding for Infrastructure networks, which are, by and large, owned by the state; is acquired from governmental budgets.

In the UK, a lot of decision support tools look at providing condition assessment and performance monitoring which enables deterioration modelling by forecasting the performance of asset in the light of changing maintenance patterns/schedules, budget restrictions and user demand. Some of the asset management systems and strategies are discussed in the next section.

2.13. Limitations of current asset management systems

Some of the limitations of current decision support tools are that they commonly cater for optimising single criterion problems only (Faiz et al., 2009). For example, certain tools aim to provide the deterioration modelling for an asset based on its historic records and current condition but it does not show how the asset will perform in the light of changing conditions i.e. if the demand on the asset changes or environmental factors may affect its performance in the long term. Or the tool may highlight the economic viability of preferred solutions to optimise resources for maintaining and managing the assets, but it may not consider the likely impact of change in use of the assets. However, a lot of new tools are being developed to cater for multiple goals and employ multi-criteria decision analysis to look at the aspects of cost, risk and performance of assets. These are considered as most important factors within the industry. However, the current tools do not fully consider the asset's performance in terms of flexibility towards change in condition and user pattern etc. in the long term governing the usefulness of the asset in its design life. Therefore there are strong arguments to support the proposed research to develop a decision support framework which considers multi-criteria analysis and can cater for multiple goals considerations related to organisational objectives.

Michele (2011) argues that asset management has significant influence on the use and growth of infrastructure development. However, the author points out that without understanding the broader impacts of technological and social evolution, and the associated complexity and diversity it brings, the system will invariably waste economic, social, cultural and environmental resources. Lemer (1998) and Michele (2011) both highlight the growing challenges in urban infrastructure management when trying to relate reduced funds, higher user's interest and attention to such things as: the quality of service; increasing interest in public health and safety; enhanced focus on water and air quality and green spaces; reduction in vehicle traffic and noise; ageing population; and consequent difficulties in accessing the town and cities services and obsolescence of structures as a result of town growth.

In the light of the aforementioned issues, the authors suggest it is necessary to develop operational tools which can improve the effectiveness of the decision-making process by enhancing the capacity of preferred prediction methodologies by considering short and long term approaches as well as evaluating technical, economic and financial factors considering the urban body as one unit. This builds a strong case for developing a framework which considers the long-term impacts in a holistic way. Similarly, Lemer (1998) highlights asset management systems should take into account the wide picture of what asset value is and how decision makers should consider the full 'value" or "cost" of the infrastructure and the returnable attributes provided by the infrastructure. Lemer (1998) suggests that the future of asset management is where an embodied version of the capital value can consider the significance of cultural, economic, environmental, political and social dynamics relating to an infrastructure asset. However, the author highlights that there is still more work needed in order to develop asset management systems in order to review the impact of plausible changing socio-economic, environmental and regulatory influences, rather the economic implications. The proposed research framework aims to address these changes and enable effective decision-making for long term asset management.

2.14. Theoretical approach on decision support tools and data management systems.

From the theory of asset management as discussed in the previous sections, there are some key aspects that are of primary importance to an asset manager in practice which are based on the concept of knowing what are the assets (location and condition), what is its value (cost and replacement) and what remaining service life exists (or could be achievable at lowest investment cost). For an asset manager, knowing the existing level of service and the expected level of service is crucial to identify the gap in the performance and develop maintenance strategy to bridge the gap and improve asset service life by carefully evading the risk along with improving the long-term affordability and sustainability. In summary, all asset management systems aim to identify and undertake to ensure the following tasks are achieved (Prescott et al., 2013, Faiz et al., 2009, FHWA, 2005):

- Provide an inventory of assets and their ownership.
- Obtain information relating to the current condition of the assets and its' utilisation therefore understand the asset performance.
- Identify an expected level of performance from this asset base, based on organisational objectives, customer expectations and performance indicators.
- Undertaking gap analysis – i.e. the difference between existing condition of the asset and expected condition of the Asset.
- Where appropriate include future demand on the critical infrastructure which can aid in developing long term and short term action plans.
- Provision of short term plans that are tied in with the asset performance and the developed gap analysis.
- Identify a Long term development plan that look at financial plans, risk management plans, intermediate plans i.e. medium term plans and develop medium term or intermediate financial plan and cash flow predictions.

Wenzler (2005) highlights that Asset Management is a process of identifying, designing, constructing, operating and maintaining physical assets. Faiz et al., (2009) highlight that for an organisation focusing on infrastructure assets, it is vital to focus on effective management of these assets which requires having the "*right information at the right time, in the right format providing to the right people*". Hence, many researchers and asset management experts have highlighted the importance of having a systematic approach, adequate and reliable information and a clearly well-defined organisational strategy as one of the key elements of effective asset management. This is the reason why many existing asset management decision support tools are focusing around information and data management. The following sub-sections discuss the tools and systems which are commonly used in industry and highlight the benefits and challenges faced therein.

2.14.1. Decision Support Tools

Decision-making processes require consideration of a broad range of problem areas and require suitable 'optioneering' approaches in order to develop effective solutions. A decision support tool is used to aid and improve this process. A typical decision support tool comprises of 3 components,

- An information database,
- a systematic course of action, which interrogates the existing knowledge from the stored data using a tool-based application which enables user interface (Faiz et al, 2009).
- Identification of optimal maintenance strategies, which minimise risk of failure along with whole life costs. (Faiz et al., 2009).

There are various ways of defining the cost of infrastructure assets which range from 'historical cost' i.e. what was paid in the first place, current replacement cost i.e. what will It cost to replace in today's time, equivalent present worth i.e. what is it worth today (similar to used car purchase) and 'net present value' what is the net present value of the benefit offered by the asset i.e. what one might be willing to pay to not lose it (Lemer, 1998).

Faiz et al., (2009) provides an insight into the world of decision-making tools. The author suggests that decision support tools can be either manual i.e. comprising of graphical tools, flow diagrams, etc. or a knowledge based system which is based on interrogating existing database using computerised application. The knowledge-based system can employ databases, which consist of a series of historic case studies with a range of possible questions and suitable answers in an integrated fashion. This is referred to as the 'Case Based Reasoning' method. When the user identifies and interrogates a problem, the system generates an output based on similar case from its archive and produces the case's solution as the output. (Faiz et al., 2009).

This provides an advantage of using experience form historic case studies. These systems can learn incrementally and adapt its system database to new cases and respective problem/solution combinations. However one of the limitations of such a system is that cannot provide a solution if it does not have a similar historic case study in its data base to deduce the results from and is therefore reliant on the available information within its data base. It also does not have the flexibility and ability to adapt to changing environments (Faiz et al., 2009). This is likely in cases where automated data management systems do not cater for user-defined inputs, which may be sensitive to individual cases or requirements. From this perspective it can be concluded that in asset management one-size does not fit all. Different asset management schemes may have a proportion (however small) of their own unique challenges and problems, which require special attention for effective decision making, which cannot be successfully provided for by such 'expert' systems (Faiz et al., 2009). As such Faiz et al., (2009) proposes developing an expert system combining fuzzy logic for effective decision making for maintenance and management of assets.

However, there is also a requirement for decision-making to be transparent and understandable. Hence for the purpose of this research, the decision support framework is based on manual decision support, system that is easily upgradeable and adopts a user friendly Excel based format. The details of the framework are described in detail in Chapter 4.

2.14.2. Data Management System

Beck et al., (2007) have shown that in UK over 4 million holes are dug every year for providing new utilities and connecting existing services without having adequate knowledge of existing services and utility information which results in digging the holes in the wrong location affecting third party land and causing disruption to road users. The authors suggest integration and sharing of knowledge on utilities can improve the co-ordination and quality of street works in UK and improve its efficiency. Similarly Lemar (1998) has highlighted that the main challenge to efficient asset management systems is an inaccurate and outdated construction records and plans for older infrastructure (i.e. > 50 years). Even if experienced asset managers have knowledge about the location and extent of the asset, information about the current asset condition is partially known limiting significantly the use of asset knowledge. The author highlights that in the recent years, new technologies are enabling better and efficient data capturing and recording systems by use of GIS, remote sensing, non-destructive testing mechanisms, pattern recognition and use of statistical modelling and analysis enabled efficient data collection.

2.14.3. Building information modelling (BIM)

BIM system have in recent times gained significance in the asset management industry as it offers the advantages on issues highlighted by Halfawy et al., (2006) and Lemer (1998). By providing a structured approach to creation, collation and exchange of information BIM offers advantage of providing a comprehensive data management model that sits within the strategic asset management framework and enables optimising maintenance costs. BIM can be used not only for a single asset but at a portfolio and a network level (Pocock et al., 2014).

2.14.4. Limitations of current decision support systems.

Halfawy et al., (2006) review the advantages and disadvantages of commercially available software systems for management of bridges, pavements, storm/sanitary water drainage water supply assets on the infrastructure in Canada. The authors suggest the common objectives of these tools are to enable capturing, recording and storing asset data efficiently, integrating and managing various aspects of whole life cycle for these assets and enable sharing of data between municipalities for strategic decision making. However, the current systems look only at operationally routine management activities but do not consider the long-term activities such as deterioration modelling, risk assessments and life cycle cost analysis. As such the authors suggest the need for current systems to incorporate performance modelling and maintenance prioritisation along with developing integrated sophisticated and comprehensive up to date data management system.

Prior to 2004-05 Network Rail did not have a uniform data recording and upkeep system (ORR, 2014). In part this was because, 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 (Amey 2009, http://www.amey.co.uk/media/press-releases/2009/april/single-supplier-amey-awarded-all-5-network-rail-cefa-contracts/). Unfortunately, Network Rail collected asset data regionally which subsequently led to an inconsistent database in terms of collecting and recording the information in standardised format. However, Network Rail has since then 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. Network Rail has an internal infrastructure database system "Geography and Infrastructure System" (GEOGIS) that identifies the track location, direction, use and number and contains the data of track and structures (ORR, 2014). The system uses a four digit code to identify the track line and location which includes first number representing the track direction, second number representing the track use and third and fourth number which represents the track number. Network Rail uses a civil asset register and electronic reporting system (CARRS) which collects and records structures asset information and operates at a national level and this also includes linear assets such as earthworks and drainage. Also, operational property asset system (OPAS) is the database for all operational property asset data used by Network Rail. (Asset information system and progress report on Asset Register, Network Rail, 2008)

Highways England has a geotechnical database system called as the Highways Agency's Geotechnical Data Management System (HAGDMS) which is an inventory of the various geotechnical assets on the Highways Agency network alone, it contains information on the condition of the geotechnical assets, and the associated severity of risks. The HA also has a database for structural assets called the Structures Management Information Systems (SMIS) and inventories for the drainage assets on the road network, called the Highways Agency Drainage Database Management System (HADDMS) and The Highways Agency Pavement Management Systems (HAPMS) (industrial experience and HD41/03). Until recently, there had been a lack of a standardisation, integration and uniform data management in a system that contains information about every asset at any given location on the entire road network. Bernhardt et al., (2003), highlights that within this system a geotechnical asset management system is required, and there should be the facility of 'cross referencing; different assets at the same location on the road network.

2.15. Asset Management Strategies

2.15.1. Asset Maintenance using Risk Management Strategies

There are a number of asset management strategies to maintain the condition of the assets. Prescott et al., (2013) summarises asset management strategies as 'corrective maintenance' which brings a failed system back to its operational condition and 'preventative maintenance' which is undertaken at scheduled intervals to reduce the risk of failure and consequent disruption. The authors highlight that asset maintenance activities are usually undertaken when there is an asset failure or as a part of a pre-determined schedule or if the condition of the asset is at a risk of failure which is called condition based maintenance. This might be considered to be too late, therefore it is not surprising that certain asset maintenance strategies consider not only the condition of the asset today but also the risk of failure (its likelihood) and the consequent impact on the network.

Raybould (2003) highlights that the commercial advantage of undertaking asset management is to enable planned maintenance before the ultimate limit state of the asset is reached i.e. the asset is no longer fit for use and enable planned maintenance which has proven to be more cost effective than unplanned works and repairs. Asset Management can enable planned works which therefore avoid disruption to traffic due to failures leading to road closures and most importantly avoid the risk of fatalities on road. Safety is always of paramount importance. Planned approach towards maintenance has shown significant savings up to over 80% on M23 Surrey (Patterson and Perry as seen in (Raybould, 2003). In general maintenance activities can occur according to a schedule, asset condition or risk of an asset failure. Much of the work to date tries to address this by finding a balance between both corrective and preventative maintenance (Prescott et al., 2013).

Traditional maintenance practices have typically been dedicated to corrective measures but in order to delay the ageing process of assets and reduce failure costs preventative maintenance are becoming ever more popular. In order to make the most use (and value) of proactive strategic or preventative maintenance, a risk based maintenance approach is considered. This is deemed to be of value whereby the strategy considers not only the asset condition but the risk of the failure and the consequence and impact on the performance of the network. The risk is considered in the form of likelihood and impact of the failure. The assets that have high likelihood of failure combined with high impact of failure on the system are considered higher risk and hence are given top priority in the maintenance regime. Such assets are therefore inspected and maintained at greater frequency (Prescott et al., 2013). However, Bernhardt et al., (2003) argue that sometimes, undertaking a risk based maintenance strategy will tend to place importance on the “worse first” approach. This approach is not always the best method as, more often than not even the smallest geotechnical failures affect the smooth functioning of the transport network - these are referred to as “nuisance failures”. These nuisance failures may be low risk but the volume of work they bring in is more than the “big failures”. Hence, adopting the worse first approach may be blinded in some ways to provide a judicious assessment of the maintenance requirement.

Relevant data on asset condition can be used in scheduling maintenance activities. Trends of a deteriorating condition of the asset can be obtained in real time and maintenance actions can be planned in a window of opportunity before the failure occurs. Therefore, in order to use condition based maintenance a lot of emphasis in research is placed on understanding the asset condition and its relationship in the useful remaining life (Lemer 2008 and Prescott et al., 2013).

2.15.2. Asset Management Strategy based on Group Maintenance

Prescot et al., (2013) discusses the concept of multiple component maintenance management in which asset components are maintained in a group. Group maintenance refers to the situation where if one of the components of the asset group fails, the whole group is maintained or replaced. The other type of multiple component maintenance management includes opportunistic maintenance in which preventative or corrective maintenance tasks are combined based on the accomplishment of certain economic or technical criteria. These methods provide significant cost savings. The authors suggest that while functional and economic dependency of one asset over the other within a complex network system is considered in order to avoid jeopardising the network operation, importance should also be given to the dependency of these assets to external conditions to provide better analysis.

2.15.3. Asset Management Strategy based on Deterioration Modelling

Asset deterioration modelling is used to predict changes in the asset condition over time and assess how this would affect the performance of the asset throughout its service life (Prescott et al., 2013, Faiz et al., 2009 and Halfawy, 2006). This comprises of determining (and recording) current asset condition based on information from data management systems and determining the impact of further asset deterioration on current and expected asset performance - thereby aiding with choosing the most effective maintenance strategy. Hence, within an asset deterioration modelling, a better understanding of how asset condition and its performance will be impacted in the absence of maintenance is undertaken (Prescott et al., 2013). Asset condition and performance are measured using specific key indicators, which are asset type specific. For example, for road pavements performance characteristics such as ride quality, surface distress and strength are significant indicators (Prescott et al., 2013). Whereas for geotechnical assets earthwork condition, slips, tension cracks, vegetation extent, soil characteristics are considered as key indicator components.

2.15.4. Asset Management Systems based on Integrated Asset Management

Lemer (1998) discusses an approach to developing an integrated asset management system based on five main principal stages which comprises of collection and analysis of data, performance modelling, scenario and management policy generation, decision analysis and management reporting. Unfortunately this approach does not include a feedback link, which is critical as it allows for continual improvement. The author argues that the integrated asset management system (IIMS) should be able to integrate information about asset data, condition, design and geographic location along with maintenance, inspection and monitoring records and can provide benefits which aid in planning operations. Hence, it is possible to reap the benefits of maintaining high level of service, reduction in the number of regular interventions and consequent reduction in the life cycle costs, environmental impact and disruption to road users and building residents. Pocock et al., (2014) reinforces the importance and benefits of adopting an integrated asset management approach and highlights the advantages in the use of building information modelling (BIM) system in effective data management and integrated asset management. BIM technology is the management of data throughout the life cycle of the asset. It enables the asset owners to develop and implement tools and collaborative working practices by sharing data and models to optimise costs and performance over the asset life cycle (Pocock et al., 2014).

Lemar (1998) gives examples illustrating the need for infrastructure assets to be able to be flexible, accommodative and adaptive to changing needs and transport patterns. This ties in with the need for this research work, which tests whether the proposed infrastructure solution (in this research, for geotechnical assets) will be fit for purpose and/or allow for change in use etc. therefore offering resilience to changing future needs. However, Lemar (1998) only states a research need and provides a generic framework for IIMS, unfortunately there is no methodology for developing an integrated system especially taking into account the aforementioned challenges.

Many scholars like Lemar (1998) have highlighted a clear message pertaining to the adoption and implementation of an integrated asset management system which facilitates providing a plan for managing the infrastructure system as whole and not individual assets thereby providing robust solutions that are economically and technically optimised. This includes taking cognisance of a whole life cycle period for the asset system, and utilises a more coherent, integrated data inventory system for the entire network rather than individual asset types. The Highways England is procuring and transferring its data for four key asset types (i.e. pavements, structures, geotechnics and drainage) to a single integrated repository (the HA Integrated Asset Management System, IAMS), which includes in-built reporting tools and links to a optimising decision support tools (industrial knowledge). 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.

2.16. Asset Management for Geotechnical Assets

The widely differing nature of the asset types found on any given infrastructure network is vast and complex. As such this research provides a focus on geotechnical assets integrated within infrastructure networks especially on road networks. Understanding what constitutes a geotechnical asset is fundamental to developing knowledge of the nature, interdependence and criticality of the asset to the network as a whole.

Bernhardt et al., (2003) defines a list of geotechnical assets in which their function is ranked from exclusively geotechnical through to minimally geotechnical, as shown in Table 2.1.

Table 2.1: Classification of geotechnical assets (Reproduced from Bernhardt et al., 2003)

Asset Type	Asset Function Category	Purpose
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

However, the manner in which these assets are managed and maintained differs significantly between organisations. In other words, organisational structuring may mean that asset groups, such as embankments, may be administered by the same team, which have responsibility to inspect and retain overall maintenance for say, bridges. This is especially true for smaller organisations.

2.16.1. Benefits of adopting Geotechnical Asset Management

All Infrastructure assets are founded directly or indirectly on geotechnical assets and hence this should not be ignored in the overall infrastructure asset management. Clayton (2000) highlights that construction industry, itself, has a high risk potential and no construction project is risk free, out of which ground related risks renders several ways of undermining the integrity of any construction project.

Findings by Tyrell et al., (1983), from a study of ten UK highway projects, shows that the cost overruns of those projects were just over 35% of which half were due to geotechnical problems (Clayton, 2000). In 1996, Turner and Schuster reported that the cost of repair for minor 'nuisance' sliding failures in US would exceed that of the repair cost for more major landslides. Unlike other construction materials that are man-made and hence easy to modify and control, dealing with natural ground conditions and groundwater is very complicated due to its varying properties in different regions and different depths (Clayton, 2000). Unfortunately, the predictability associated to construction materials does not apply to engineering ground conditions.

A geotechnical asset management approach will aid the designers in prioritising remediation of geotechnical assets and will enable in undertaking a whole life cycle analysis of these geotechnical assets which will determine the choice of treating recurrent geotechnical defects over conventional one-off treatments, the overall costs in choosing alternative treatment methods over conventional ones.

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 has become a popular terminology in current infrastructure industry, but managing geotechnical assets has not yet found its niche and is not developed fully.

2.16.2. Challenges in Geotechnical Asset Management

Bernhardt et al., (2003) throws light on several challenges faced in management of geotechnical assets which range from identifying and classifying infrastructure assets into geotechnical assets and determining the priority of maintaining them within the constrained budgets in today's economic climate. The authors highlight that in the case of geotechnical assets different remediation measures may have different shelf life and vary dramatically in their costs. Sometimes, use of alternative techniques may prove to be an economically and technically sound choice.

Bernhardt et al., (2003) argues that the existing asset management systems are more often than not ‘hazard’ management systems which give funding priority to those assets with the ‘higher risk’ potential, which although justifiable in terms of safety to the end user it is not necessarily the most cost effective method. Moving the maintenance cycle from a less ‘reactive’ to a more ‘proactive’ system would reap more benefits and lower risk, yet this very rarely occurs on the ground..

Geotechnical assets play a significant role in the continual operation of the overall road network. For example, there are several records of pavements which show early signs of failure much before their expected design life which requires yearly re-surfacing to improve its condition. This could be due to the lack of understanding of the underlying cause of failure, which could potentially be geotechnical in nature. Designing yearly re-surfacing treatment of the road pavement is insufficient if the underlying subsurface layers are weak and deteriorating. Likewise remediating a cracking carriageway signs of failure is ineffective if the supporting embankment has defects and is consequently slipping away, thereby disintegrating the support system for the carriageway. Hence, in order to effectively maintain and manage any asset on the road or rail infrastructure, it is of paramount importance to maintain and manage geotechnical assets effectively.

2.16.3. Geotechnical Asset Management on UK Highways Network by Highways England (formerly known as Highways Agency)

The key document for The Highways Agency’s Geotechnical Asset Management is HD41/03 standard, Maintenance of Highways Geotechnical Assets (The Highways Agency, 2003) which predominantly deals with stating the required competencies of geotechnical liaison engineers, asset inspection methodologies and frequencies and guidance on risk assessment for geotechnical assets by providing a risk assessment framework and the work flow and certification procedures for geotechnical works (Power et al., 2012). The other standard is HD22/08 ‘managing geotechnical risk’ (The Highways Agency, 2008) which includes details on the risk assessment for geotechnical assets based on location and condition of the asset now and its predicted condition in the next 5 years. In addition it provides details on the following: reporting and certification for geotechnical desk studies; investigation; and design and construction feedback thereby assuring required levels of quality and consistency across various managing organisations. Key components include appropriate standards and guidance, reliable and up-to-date data (including condition data), risk management, deterioration model, whole life costing tools, and a methodology to undertake proactive maintenance to achieve a set of required outcomes in terms of service delivery. (Power et al., 2012).

The data management system for Geotechnical asset management for Highways England is called 'The Highways Agency Geotechnical Data Management System' (HAGDMS). HAGDMS was developed and rolled out for use in 2002 (Power et al., 2012). It is a centralised system where geotechnical asset data is saved and can be accessed by anyone within Highways England or managing agencies that need to review and update geotechnical asset information. HAGDMS includes a layered mapping interface combined with a database of the following key geotechnical information:

- Geotechnical asset type and geometry (e.g. slope height and slope angle).
- Age, history and condition of the asset in terms of risk level, predicted risk level in the next five years and maintenance history.
- Information of Geology (i.e. Drift and Solid)
- Information on Coal Mining and other historical information (i.e. subsidence, land filling, artificial ground etc.).
- Environmental Information (e.g. Flood plains, likelihood of flooding etc.).
- Information about structures, bridges, highway furniture and link to the drainage database.
- Records of Historic exploratory holes, investigation reports, principal inspection records, desk studies, design reports and construction feedback reports.

2.16.3.1 Condition Assessment of Geotechnical Asset

The condition of geotechnical asset is determined based on visual inspections undertaken at regular intervals of time and includes details such vegetation extent, presence of slips, tension cracks, presence of hydrophilic vegetation, subsidence, rock falls, voids, evidence of animal burrowing, terracing, ravelling and observation of water on the slope such as ponding or marshy condition (HD 22/08 and HD 41/15).

The Highways England considers the current condition of the asset and the history of the asset to predict the possible potential for failure of the asset in future. Based on this a risk assessment is undertaken based on economic and safety risks. The risk assessment considers the cost of treating the asset now versus the cost of treating it in the future in line with the risk to the safety of travellers as a consequence of failure. The commercial aspects such as the value of the asset, significance of the road network, volume of traffic, diversionary route availability and the operational requirement of setting up traffic management which may cause disruption to users are considered to undertake a risk assessment which can be used to develop a funding case for either maintenance or remediation of the asset (Glendinning et al., 2009).

2.16.3.2 Risk Assessment technique adopted by Highways England

The key risk assessment of the asset is made based on visual inspection in the field with information fed into the HAGDMS system from with an office environment. Unfortunately, risk allocation has long been predicated by an engineers' judgement and experience and hence they need to be well trained in such an area in order categorise risks objectively rather than subjectively. The risk assessment for HA Geotechnical Asset management comprises of two key elements which are an observation class and the location index (HD 41/15):

- The observation class is categorised as Class 1, Class 2 and Class 3 which represent defects, areas considered to be at risk, areas of repairs, preventative or strengthening works respectively.
- The location index is assigned depending on the proximity of the defect of the asset to the carriageway or other highway furniture such as lighting column, CCTV mast etc. The location index ranges from A to D with A being in close proximity to the carriageway and D being far from the carriageway. (Power et al., 2012). Figure 2.4 shows the Location Index.

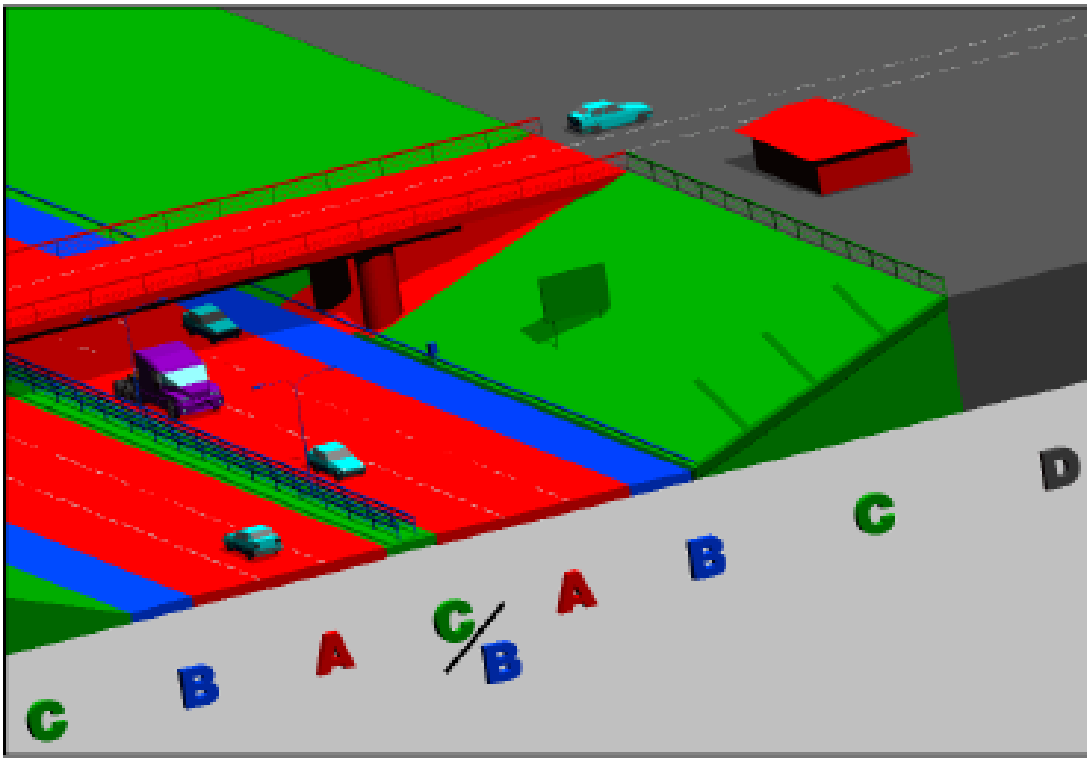


Figure 2.4: Pictorial representation of location index based on the location of the defect with respect to its proximity to the carriageway (The Highways England)

The subsequent risk category (based on these two elements) are assigned based on a baseline assessment and a secondary assessment (based on the predicted risk level in five years' time, or example a tension crack being a precursor to a slope failure in the future which is based on experience and expert knowledge.

The risk matrix from HD 41/15 showing how low, medium and high and severe risks are categorised based on the location index and Class is shown in Figure 2.5.

Risk Level NOW for observations of Class and Location Index NOW					
Location Index	Class				
	1A/1B/1C	1D	2A/2B	3A/3B	3C
A	S	H	M	N	N
B	S	M	M	N	N
C	H	M	L	N	N
D	M	L	N	N	N

Risk Level NOW for assessed Class and Location Index in FIVE YEARS time					
Assessed Location Index	Assessed Class				
	1A/1B/1C	1D	2A/2B	3A/3B	3C
A	H	M	N	N	N
B	H	L	N	N	N
C	M	L	N	N	N
D	L	N	N	N	N

Figure 2.5: Risk Matrix by Time Frame (Highways England, HD 41/15)

Power et al., (2012) provides an example of how a tension crack considered as minor defect (1 D), which is located away from the carriageway (Location Index C) may be have a risk level of 'Moderate Risk Level' now but in five years' time, the defect may result in a slip failure which may affect the hard shoulder and as a result the risk level increases to 'Severe'.

It is evident that geotechnical risk assessment relies on experienced judgement based on sound technical knowledge which in turn influences geotechnical works programme (Power et al., 2012).

Thus, the method of risk management is using a qualitative approach. This approach is similar to other qualitative approaches like using the matrix of severity vs likelihood such as the one suggested by Raybould (2003) shown in table 2.2. In this instance, the class which represents the condition of the asset viz; an existing defect, a risk or potential strengthening work identifies an opportunity to assess the likelihood of risk. Whereas the severity of risk is defined by the proximity of the asset to the road network. For example, if the asset already has a defect then there is likelihood for this defect to cause failure disrupting the traffic than the one with a potential risk or no defect just proactive maintenance requirements? Similarly, if the asset is in close proximity to the road network, its severity to affect the road users is proportionally larger than the asset farther away from the network. Hence, it can be said to be an adapted or modified version of the technique suggested by Raybould, 2003 and shown in Table 2.2 to suit the road network and devising practical forward works programme for maintaining and managing geotechnical assets on the road network.

However, in Geotechnical Asset Management, how do we measure the condition of the asset and how do we predict the performance and failure? We can assess the condition of the asset by visual inspection and by undertaking in depth investigation and tests on the soil samples. However, there are no tools or models, which predict the performance of geotechnical asset in real time. Hence, there is the element of engineering judgement where, through the eyes of experienced engineers, risk factors are allocated to the geotechnical asset and the maintenance strategies are devised based on the condition of the asset These are typically examined visually and a risk assessment is undertaken to assess what would be the likely condition of the asset in the next 5 years.

An alternative approach can include use of qualitative risk assessment technique suggested by The Highways Agency, (2010) described in section 2.3.5.1 and Figure 2.6 which can be deployed along with a framework containing asset condition specific questions. The questions could be developed to provide a better understanding of the risk in terms of likelihood and consequence of failure based on asset age, material type and site specific information such as significance of the road network, proximity to environmentally sensitive, volume of traffic, proximity to diversionary routes should be considered. Although there will be a certain degree of subjectivity associated in answering the questions, it will still be specific to the asset and more detailed giving a more comprehensive approach to assessing the likelihood and severity of geotechnical asset failure. Alternatively, this approach can be clubbed with the quantitative risk assessment approach by assigning scores to the responses in a logical fashion (influenced by Glenddining et al., 2009 and Raybould, 2003).

However due to the variability of ground conditions and lack of precise historical data available for geotechnical assets, risk assessment for geotechnical asset management will (to a degree) rely on experienced judgement from geotechnical engineers supported by sound technical knowledge.

2.16.3.3 Whole Life Costing

The Highways Agency (known as Highways England since April 2015) uses a whole life costing tool for all transportation assets including geotechnical assets called ‘project economic appraisal tool’ (PEAT). The tool is used to determine the whole life cycle cost of geotechnical asset solutions (renewal/remediation/improvement) which takes into consideration costs associated to geotechnical works, traffic management, maintenance costs and other costs such as design, operational activities, supervision etc. It provides the cost for different solutions proposed during the option feasibility stage along with economic indicator (EI). The EI is used as a driving factor across all assets providing a consistent approach for determining value for money assessments within the renewal maintenance programme (The Highways Agency, 2014).

2.16.3.4 Value Management

The value management (VM) process is a part of Highways England’s options appraisal stage where option identification, design and construction of improvement and renewal projects are assessed. This is based on the guidance from Network Delivery and Development Directorate (NDD) Value Management requirements. The output from the VM process forms the basis for asset improvement, renewal priorities and are determined nationally using a scoring process out of 100 based on which the projects are funded in each year and phase of the project. The scoring is divided between Value for Money, Environmental Sustainability and Economic Indicator that is obtained from the whole life costing process.

2.16.4. Other techniques for risk assessment for geotechnical assets

Risk associated with a hazard is the function of the probability and the consequence of that hazard occurring (Raybould 2003, FHWA 2003 and Pantelidis, 2007).

There are various ways of undertaking risk assessment for geotechnical assets which can be summarised as qualitative and quantitative (Raybould et al., 2003 and Pantelidis, 2007). Available risk assessment tools and techniques range in complexity and detail from qualitative risk matrices to complex Monte Carlo analysis requiring definition of ranges and distribution of all uncertain variables. Mian et al., (2011) suggests that the use of complex risk assessment methods and models are best suited when there is adequate and reliable data.

Although there is a good proportion of literature which discusses the geotechnical risk management strategies, the literature discussed in this section covering the context from Highways England (HD41/15), The Highways Agency (2010), FHWA (2003), Pantelidis (2007), Raybould, 2003 and Gleddining et al., 2009) provide a good representation of the available techniques in a concise manner with examples for better understanding.

2.16.5. Geotechnical Assets Risk Assessment Framework

Mian et al., (2011) provides a risk assessment framework which starts by identifying a clear scope, identifying the hazard that can lead to a loss of performance, estimating and evaluating the risk and finally undertaking a risk based decision making. Mian et al., (2011) suggest that asset risks should be defined using cross asset terminology using corporate risk scoring structure, particularly for geotechnical assets where the variability of ground conditions, low probability but high consequence of failure and the complex interdependencies between asset types are considered. Glendinning et al., (2009) have discussed the strategic and tactical risk assessment framework which can be used for geotechnical assets. Strategic risk assessment framework considers the risk based on the historical information, available from a database (example HAGDMS) along with the current condition of the asset evaluated from a system of regular inspections. Strategic risk assessment is undertaken considering the condition of the asset alongside the consequence of a potential failure allowing the resources to be targeted where they are most essentially required. Tactical Risk Assessment framework consist of undertaking detailed asset inspection followed by identifying a selection of mitigation measures, the costs and residual risks once the measures are implemented (Glenddining et al., 2009). This technique can be adopted to provide comprehensive risk assessment at any level for identifying the economic and safety related risks for highways network as discussed in section 2.5. The risk assessment frameworks once developed can be deployed at strategic level to enable planning capital and maintenance projects for geotechnical assets on the highways networks.

2.16.5.1 Qualitative Risk Assessment:

Highways England's HD 41/15 provides a process for risk ranking for geotechnical assets. A five point scale from negligible to severe is used for ranking the geotechnical risk and the geotechnical assets are categorised from low to severe. The assets with severe and high risks are passed forward in the works programme. The qualitative risk management process adopted by Highways England for geotechnical assets is explained in section 2.3.4.3 and figure 2.5. An example of qualitative risk assessment is when the consequence of failure is categorised as low medium and high and the probability of failure is categorised as low average and high. Hence the corresponding risks categories are given in table 2.2.

Table 2.2 Qualitative Risk Assessment Matrix (Raybould, 2003)

Consequence of Failure	Probability of failure		
	Low	***Average***	***High***
Low	Negligible	Low	Medium
Medium	Low	Medium	High
High	Medium	High	Unacceptable

The resulting risk category would then govern the extent of further works. Raybould (2003) suggests that an unacceptable risk category would require remediation works with highest priority, high risk category would require remedial works within next 5 years, medium would suggest remediation works may not be necessary, instead undertaking preventative works within subsequent five years and low risk would mean review value for money for undertaking preventative works and negligible risk would mean re-inspect in 5 years. The risk assessment matrix provided by The Highways Agency's report on developing a risk based framework for geotechnical asset management (The Highways Agency, 2010) comprises of a matrix of likelihood and consequence. The likelihood is categorised from unlikely to certain having a corresponding score between 1 and 5. Similarly the consequence is ranked from catastrophic to negligible having a corresponding score between 4 and 1. In the matrix the product of the scores are assigned in each cell providing a risk ranking. The matrix is shown in Figure 2.6.

Likelihood	Consequence					
			Catastrophic	Serious	Moderate	Negligible
			4	3	2	1
	Certain *	5	20	15	10	5
	Very Likely	4	16	12	8	4
	Probable	3	12	9	6	3
	Possible	2	8	6	4	2
	Unlikely	1	4	3	2	1

Figure 2.6: Qualitative Risk Assessment Matrix (The Highways Agency, 2010).

2.16.5.2 Quantitative Risk Assessment

Where qualitative risk-based analysis methods are not very widely adopted for geotechnical applications due to the difficulty in dealing with age and spatial extent variability related soil conditions (Bernhardt et al., 2003), Raybould (2003) suggest using quantitative risk assessment for such purposes. This comprises of a series of logical procedures based on the principles of an 'event tree' analysis, where the probability and consequence of each potential hazard is given a numerical score providing a tallied up to give an indication of '*likely 'risks'* to infrastructure assets (Raybould, 2003).

A report produced by the Federal Highway Administration (FHWA) (2003) on geotechnical asset management implementation concepts and strategies suggests that quantitative risk assessment is undertaken by determining the probability of failure using established practices such as numerical models and objective analysis such as slope stability models or using available historic data for example number of slope instability incidents and determining the consequence of failure which is based on a more subjective process which includes determining the tangible costs of repairs to a road pavement affected by the geotechnical defect or determining the road user delay or other impacts caused by disruption to service. Based on this an expected cost for given feature and the associated costs for the possible mitigation measures can be generated which form the basis of the decision tree based on which the quantitative risk assessment is undertaken.

Macmillan and Matheson (1997) describes a technique for rapid assessment of rock slopes and provides a Rock slope Hazard Index (ROSHI) The procedure of numerical rating results in four categories no action, review in 5 years, detailed inspection and urgent detailed inspection. ROSHI has been used extensively by Highways England for Asset Management over the last 18 years

A Soil slope risk value (SSRV) is a quantitative risk assessment procedure described by Manley and Harding in 2003 and it is used in the rail environment (Raybould, 2003). It is determined as a product of soil slope hazard index (SSHI) and Soil Slope Hazard Index (SSHI). SSHI uses a combination of scores from the earthworks factor, actual failure factors and potential failure factors resulting in the earthwork condition being characterised as poor, marginal or serviceable.

These systems have a pedigree within the asset management sector however there are risks and limitations associated with each as discussed below:

2.16.5.3 Limitations of current risk assessment systems

Risk assessment methods deployed for geotechnical assets should be able to consider the emphasis of geomorphology and geology of the slopes, factors such as climatic conditions which is a key triggering factor in number of landslides is not considered fully or even ignored (Pantelidis, 2011). The current risk assessment systems either consider a single aspect of ‘traveller’s safety’ or a number of elements and adds the scores which according to the author can lead to an underestimation of the role of a single factor which may have significant consequence on failure. However, with advancement in data capturing and recording techniques such as the use of remote sensing methods, and development of “risk based spatial systems analysis tools” a favourable transformation in risk assessment and asset management is occurring. Not least because of the attention now given to forecasting the long term behaviour of the geotechnical assets which enable efficient use of resources targeted at a network wide level (Glendinning et al., 2009).

2.16.6. Deterioration Modelling for Geotechnical assets

Bernhardt et al., (2003) suggest that typical deterioration models devised for pavement assets may not capture all the aspects affecting the performance of geotechnical assets, as these are influenced by random events such as extreme rainfall, abrupt changes to the use of the network etc. In addition they may not capture instances where an embankments condition, for example, can improve over time due to consolidation and compression of soft material gaining more strength with time (Power et al., 2013). Predicting the performance of any natural soil-based material and assessing its performance is not straightforward and certainly more complex than man-made materials such as concrete. Glendinning et al., (2009) are undertaking a research called as ‘Bionics (biological and engineering impacts of climate change on slopes) whose aim is to identify the impact of climate change on the long term behaviour of embankments by using newly developed highly sophisticated numerical models, system wide models and statistical analysis tools Bionics research is beginning to help determine the condition of geotechnical assets in the light of changing environmental conditions, such as rise in pore water pressure, material behaviour for certain types of clays, slope geometry etc. In combination this enables a better understanding of the characteristic behaviour of assets based on their material, topography and changing environmental conditions affecting the long term performance of the assets (Glendinning et al., 2009). Bionics research studies the changes in physical behaviour of slopes in the light of changing climatic conditions and its impacts. It does now study other anthropogenic factors such as change in demographics, social, economic, technology and shock events and the associated inter-relationship between these factors in designing geotechnical solutions which is included in this research

Bernhardt et al., (2003) highlights the advantages of adopting a reliability based model for determining the future condition of the asset as they enable comparison of different types of geotechnical conditions rationally based on life cycle costs of the geotechnical solutions. Such a method includes comparing high probability low cost conditions with low probability high cost conditions by providing a weighting system for costs proportioned according to probability of occurrence. Unfortunately this method still lacks the consideration for varying time scales i.e. what are the costs of repairing the asset now versus cost of repairing the same in a specified duration (1 year, 4 years or even the complete design life of the asset)

2.17. Resilient Asset Management

Section 1.4 established that there is a need for embedding resilience in the engineering solutions we provide today. This section furthers this discussion (2.17.1) by considering the literature to ask what must be done to ensure that solutions provided today are fit-for-purpose, acceptable and resilient to whatever the future might hold. Firstly the thesis establishes how resilience is conceived in each sector of the infrastructure industry (2.17.2). Secondly existing resilience frameworks are explored to find their capacity and scope (2.17.3) and lastly a broad understanding of the concept of futures in relation to asset management systems is obtained (2.17.4).

2.17.1. Need for a Resilient Asset Management System

In the past few years, a series of extreme weather conditions have forced asset owners to maintain the condition of assets but also to keep the network running at any given time. As such there is an increased need for multi-functionality and resilience incorporated on the system wide level. For example, in the light of the vulnerabilities exposed due to a changing climate where peak events are ever more present. This requires a diverse range of new technical solutions which may potentially pose higher uncertainty ultimately affecting the project programme and duration. As a consequence of which emergency works may increase in both frequency and severity. Requiring yet more frequent construction, maintenance and remediation works resulting in additional interventions and subsequent road closures/diversions affecting the overall smooth operation of the network (The Highways Agency, Climate Change Risk Assessment, 2011). A pertinent UK example of this can be seen with regard to the 2007 and 2014 floods which resulted in extreme damage to earthworks supporting transportation infrastructure (road and rail) which required investment of already inflated budgets to remediate and in essence keep the infrastructure up and running. In 2007 floods there was major disruption to the motorway network resulting in closures on M1, M4, M5, M18, M25, M40 and M54 and many local trunk roads. The repair costs for all roads were estimated to be £40-60 million. Flooding in 2007 cause 2% of the delays for the entire year. In 2009, floods in Cumbria affected many homes which were evacuated and roads closures and bridges being severely damaged (The Highways Agency, Climate Change and Risk Assessment, 2011).

This may likely get worse if one were to believe future climate prediction models such as UKCP09 where forecasts for an average UK summer temperature are expected to rise by 3-4 degrees and an average decrease by 11% to 27% by 2080 (The Highways Agency, Climate Change and Risk Assessment, 2011).. This is coupled with rising sea levels and more frequent extreme weather events (The Highways Agency, Climate Change and Risk Assessment, 2011).

The asset management strategies and policies prepared and adopted by various asset owners like Highways England (formerly known as The Highways Agency), Network Rail and Local Authorities are devised for short term period (2010-2014), covering the nature of funding cycles and is perhaps influenced by the political turn over, but there is no work done so far, for checking its robustness for medium to long term i.e. period later than 2014. Hence, there is a gap in the knowledge here, which can be filled by understanding how these strategies and frameworks are affected in the light of the conditions that the assets may be subjected to farther away in the future, which includes but should not be limited to Climate Change.

Various asset owners, like the local authorities e.g. Birmingham City Council and Sheffield City Council are looking at long term maintenance strategies and funding options which involve maintaining their infrastructure assets over a long period of 20 to 30 years. This requires partial funding to come from the private sector through what are called Private Finance Initiative (PFI) which looks at the ways of creating a public-private partnership (PPP). The new government proposals for improving the face of infrastructure emphasises the need for private investments which must look at long term maintenance strategies as opposed to the current 4 to 5 year period investment strategies being developed. This is all well and good, however there is still no consideration made for whether the solutions being provided today (and the related asset management systems being adopted) remain relevant and applicable after 20 years or more., Fortunately recent developments in the outlook of the government policy making and the strategies of asset owners makes it even more necessary to research into the robustness of the existing asset management approaches and systems to be resilient for the future.

It becomes all the more important to effectively and efficiently manage infrastructure assets as the failure of one asset may directly or indirectly lead to the failure of a set of surrounding assets, which may ultimately lead to the failure of an entire section on the network (Transport Sector, Climate Change risk assessment UK, 2012). Hence, determining if the given asset management systems and practices and the design solutions provided today for the remediation, maintenance and upkeep of transportation assets is resilient for the characteristic conditions that the future may hold is vital.

Timescales of managing and maintaining assets can have impacts on both economic and safety related risk on the transportation network. Economic risks include additional costs associated to modifying, demolishing, re-designing and reinforcing/constructing the assets. More so, there is the operational expenditure associated with recurring interventions on the road network for fixing one asset or other and or provision of diversionary routes. This also causes disruption to traffic and associated road user delay costs and penalties for road authorities. Hence, considering the network as a whole while designing long term solutions can improve the timescales of road maintenance and improve overall efficiency in delivering asset management. To address the risks associated with timescales, it is important to include contingency in planning (Oracle White Paper, 2009).

In the report drafted by The Highways Agency in 2011, the agency discusses resilience of the infrastructure network towards addressing and mitigating climate change. The document classifies Highways Assets based on its priority for taking adaption measures to mitigate climate change in which geotechnical assets are considered as one of the main priorities to be considered early on in the planning process along with culverts, bridges and lighting columns (The Highways Agency, Climate Change and Risk Assessment, 2011).

Due to the fact that infrastructure assets are directly or indirectly supported by geotechnical assets, effective management of geotechnical assets and in order to future proof the existing infrastructure asset management systems it is imperative to develop resilient geotechnical asset management system.

Resilience in the infrastructure industry implies that the network (road, rail, utilities, water telecommunications etc.) is up and running (providing continued performance) and continues to perform for its intended purpose even in harsh and unpredictable conditions that it may be exposed to at any given time. In UK, £30 billion a year is invested in maintaining and managing the infrastructure, which is set to increase to £50 billion by 2030 (HM Treasury, 2010). This justifies the need to embed resilience into planning and design for such an investment to reap benefits for the long term. This definition is considered aligned with the definition of resilience provided in the thesis i.e. “Resilience is defined as continued performance under changing conditions”.

The Cabinet Office provided a guide to improve the resilience of critical infrastructure in the UK in October 2011, which defined resilience as the “ability of assets, networks and systems to anticipate, absorb, adapt to and / or rapidly recover from a disruptive event” (Pitt, 2008). The report suggests the four strategic components which are ‘resistance’, ‘reliability, ‘redundancy’ and ‘response to recovery’ which when utilised effectively individually or in conjunction with each other, embed resilience into the system. Cabinet Office (2011) guidance document report suggests that while owners, operators, government regulators are primarily responsible for the resilience of critical infrastructure the industry also needs to work in collaboration to ensure that security and resilience are accounted for when investing in infrastructure.

Sir Michael Pitt (chairman of the Infrastructure Planning Commission which has the role of considering planning applications for national infrastructure projects under the Planning Act 2008), report on the 2007 defined resilience as “the ability of a system or organisation to withstand and recover from adversity"(Pitt, 2008). The Pitt report highlighted that the 2007 Floods in UK raised concerns on the lack of sharing information on the critical national infrastructure with the "right people at the right time". He suggested that there was a need to alter the thinking from the "need to know" to the "need to share" (Pitt, 2008).

The Cabinet Office provided a guide to improve the resilience of critical infrastructure in the UK in October 2011, which defined resilience as the "ability of assets, networks and systems to anticipate, absorb, adapt to and / or rapidly recover from a disruptive event". Thus, with regards to the transportation network, resilience implies that the network designed now will be fit for purpose, sustainable and flexible to the challenges of the future. A solution can provide best value for money by being technically sound and fit for purpose under both existing and changing future conditions and whilst it is impossible to predict the future precisely the art of knowing what uncertainties might exist or occur is of immense value. Thus, the definitions of resilience provided in the literature emphasise on solutions to be able to recover, resist and adapt to change in order to be considered as 'resilient'.

In line with the definitions provided in the literature, resilience for the purpose of this research is defined as "continued performance even under changing conditions". Performance entails that the asset in the light of changing conditions, is still in serviceable condition (either in part or full), is considered to be fit-for-purpose by offering flexibility and multi-functionality to cater for changing patterns in a sustainable and cost effective manner, allows change(s) in its use, offers ease of operation, maintenance, and if necessary easy to demolish (i.e. if outdated and/or obsolete).

The proposed resilience planning tool, assesses these very attributes on the basis of solutions' responses to the inter-relationship between critical factors and future conditions.

Figure 2.7 represents a resilient transportation network in line with the definition of 'resilience' proposed above.

A resilient transportation network should be able to offer flexibility and multi-functionality to meet changing demands and user patterns, continue to be fit for purpose under impacts of future conditions (such as changing environment and technology) and provide sustainable operation, maintenance and disposal in the light of changing conditions over its life cycle.

Therefore a solution which provides most (if not all) of these attributes is considered to provide resilience. Whilst this could be a relative comparison between various options, this definition and explanation covers the essence of determining a resilient solution which a range of stakeholders (i.e. industry, academia geotechnical engineers, strategic planners and asset managers) can relate to. Examples cited in section 5.2.5.1 provide an understanding of the above.

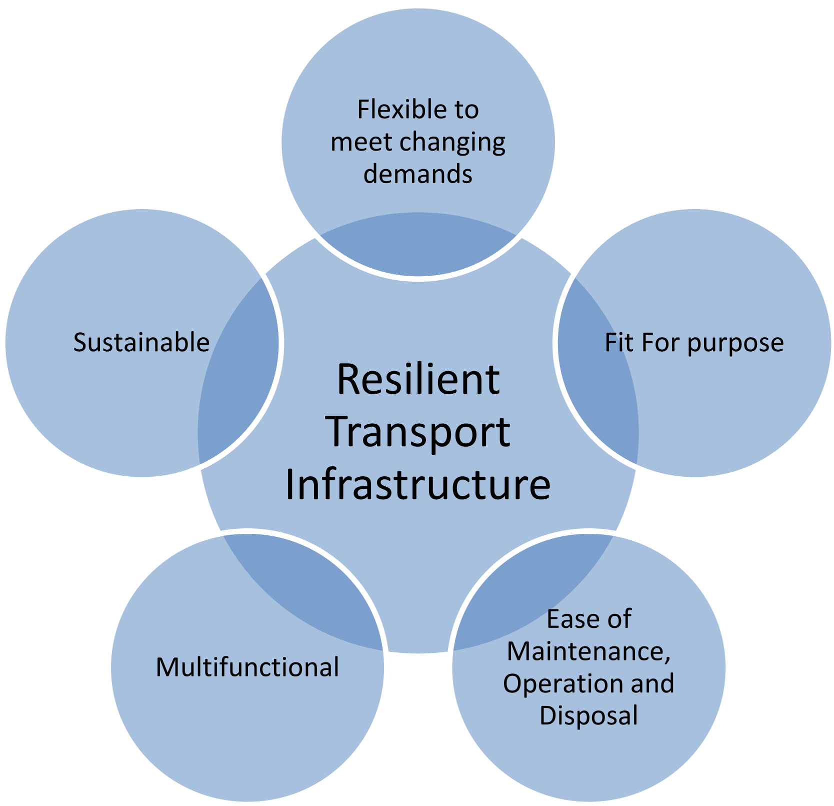


Figure 2.7: Resilient Transportation Infrastructure

2.17.2. Resilience Infrastructure Frameworks

2.17.2.1 The Highways Agency Climate Change Adaption Framework

The Highways Agency's Climate Change Adaptation Framework (2011) comprises of 7 stage process which starts with defining the objectives and decision making criteria, identifying climatic trends affecting the HA, identifying the vulnerabilities, undertaking risk appraisal, options analysis, developing and implementing adaption and action plans and defining and developing adaptation programme review. Treatment options for addressing the risks include future proofing of designs, retrofitting solutions, developing contingency plans, updating operating procedures, monitoring and undertaking advance research for developing innovative solutions. Once the possible solutions/treatments are identified they undergo a comparative assessment with a 'do minimum' alternative which is underlain by robust assessment technique provided by the framework.

The report drafted by the Highways Agency on Climate Change and Risk Assessment, (2011) highlights the risk associated to the vulnerabilities due to climate change. Asset vulnerability is defined by the uncertainty which is cited as "Embedded within the risk assessment is an uncertainty criterion which evaluates both the confidence of climate change predictions and the climate change impact on the asset/activity". The vulnerabilities are based on the criteria of uncertainty, rate of climate change, extent of disruption and severity of disruption. Vulnerabilities are then ranked using 'prioritisation indicators' based on the combination of the aforementioned criteria. The vulnerability assessment is undertaken using the uncertainty matrix shown below (figure 2.8) which comprises of the effects of climate change on the asset and climate change predictions compared using 'High, Medium and Low' scoring system. The document highlights the risks due to climate change vulnerabilities which includes reduced asset serviceable condition and safety, reduced network availability, increased costs to maintain a safe and serviceable network, increased safety risk to road users and workers, increased programme duration and quality standards due to changes in the construction activities which include more onerous design requirements, perhaps increase in the use of materials and design standards and components.

		Uncertainty level – effects of climate change on asset/activity		
		High	Medium	Low
Uncertainty level – climate change predictions	High	H	H	M
	Medium	M	H	L
	Low	M	L	L

Figure 2.8: Uncertainity Matrix (The Highways Agency, 2011)

2.17.2.2 Cabinet Office's Development of National Resilience Plan for Critical Infrastructure (Cabinet Office, 2010)

Cabinet Office (2010) developed a critical infrastructure resilience programme to improve the resilience of critical infrastructure in order to "prevent, protect and prepare for natural hazards" (Strategic Framework and Policy Statement, Cabinet Office, 2010). Critical infrastructure is defined by the government as "those infrastructure assets that are vital to the continued delivery and integrity of the essential services upon which the UK relies, the loss or compromise of which would lead to severe economic or social consequences or to loss of life". Some of the key issues addressed in the program include the threat from current and future natural hazards in the design of new assets and systems, increasing the robustness and resilience of existing services and assets by improving network connections and enhancing back up facilities. Actions may include protection measures such as construction of permanent or temporary flood defences. It uses a risk based approach to prioritise sector resilience planning which comprises of a matrix of criticality of infrastructure and assessment of likelihood which is a combination of vulnerability and threat. The criticality of infrastructure is categorised from 1 to 5 with 5 being most critical; the failure or loss of which would have a catastrophic impact on UK and 1 being low; the failure would have a minor impact (on a national scale). Risk among criticality of infrastructure ranging between category 4 and 5 corresponding with a likelihood of medium to high is given highest priority (Strategic Framework and Policy Statement, Cabinet Office, 2010).

2.17.2.3 Department for Transport's (DfT) Strategic Approach to Resilience Adaptation Planning

Department for Transport (2010) developed a set of actions to address climate change risks and embed the same across their decision making process. The plan includes generation of climate scenarios, identifying vulnerabilities (aligned with corporate objectives and business strategies), undertaking risk assessment, and generating risk management options, undertaking cost benefit analysis, and implementation of preferred option with subsequent monitoring. The report provides a list of key effects of climate change and its potential impact on transport network. Factors such as increased temperature, rainfall, rising sea levels and coastal erosion and flooding, increase in extreme weather storms and storm surges are considered and the potential implications include deformation of road and airport runway asphalt, rail track buckling, passenger discomfort, flood damage to rail and road infrastructure, rising water tables flooding underground networks, flooding of networks and affecting safety of network users, damage to utilities and asset failure due to long hot days followed by intense rainfall causing flash floods etc. A lot of these effects were considered important for geotechnical assets in the research in the light of environmental changes in the future.

2.17.3. Future Conditions

In Network Rail's strategic document 'Better railway for a Better Britain' (2013) the asset owner outlines its future plans. The document shows that one of the key drivers of future change for the railway is a continual increase in demand over time, such that by 2019, 170000 extra seats for commuters will be needed at peak times and will have to accommodate 30% more freight than today. The document suggests that one of the biggest issues is that although the Victorian engineers constructed the railway network 150 years ago, it has undergone 50 years of underinvestment and neglected maintenance (Network Rail, 2013). Although a lot has been done over the last decade to improve the condition of the railway, Network Rail continues to invest by allocating £4 billion per year for the period between 2014 and 2019 to replace and improve the railway that is fit for the future.

Moreover the world population is predicted to increase to 9 billion by 2050 (United Nations, 2004 referred from Hudson et al. 2012), which increases the demand of infrastructure.

The Pitt review stated that the driver for wider organisational resilience is the long-term commitment from the stakeholders to mitigate risks as a part of a continuous improvement cycle (Cabinet Office, 2010). Hence Governance (Policies) becomes a key driver in future proofing the infrastructure and making it resilient.

HM Treasury's National Infrastructure Plan, 2010 emphasises that Globalisation, Growing Demands, climate change, interdependencies and obsolescence are the future challenges that the infrastructure is faced with and the UK infrastructure needs to keep pace with these in order to give high returns on investments and keep it running and continue driving economic growth and social development. The document highlights the UK government's new approach towards infrastructure development, which aims to keep a coherent view of the long term needs for UK infrastructure by managing interdependency, building resilience and promoting engineering innovation.

Climate Change Risk Assessment undertaken by Defra in 2012 is based on the analysis provided by UKCP09, which summarised a range of predicted impacts in future that the transportation sector needs to prepare for and they include growing demands, change in social attitude, need for reduction in carbon emissions, closely interlinked network and the associated interdependencies with a focus on floods, landslides, damage due to heat, rail buckling and bridge failures due to extreme weather and fluctuating temperatures. The report did not consider impact of changes in society, new technologies, growth and development of areas, responses to climate risks in the form of government policies and private adaptation plans.

A report produced by The Department for Transport (DfT, 2013) titled 'Transport- an engine for growth' highlights the findings from their study comparing the quality of UK road network with continental Europe and the rest of the world. The report suggests that in recent times evidence shows that UK is falling behind other European countries in providing a robust and efficient transportation network in spite of being a compact well connected island. A reason for this is that countries in continental Europe trend to have a long term approach towards managing and maintaining their network and provide more freedom to their operators. The UK ranks 24th in the world for roads in terms of the quality of road infrastructure, behind many other developed countries. The report highlights figures which suggest by 2021 over 80% of the network will be resurfaced which shows that spending on the road network will have tripled from today's level and equally major investments are committed for rail and HS2 infrastructure, this reflects the age of the road infrastructure. The report highlights that in June 2013, the Chief Secretary of the treasury announced that £15.1 billion had been committed to be invested in UK strategic road network by 2021 in order to mitigate the effects of past under investment. This included the addition of an additional 221 lane miles of extra capacity to strategic and busy motorways. The report also highlights that additional schemes undertaking the managed motorway approach would be undertaken improving road utilisation and reducing congestion. The report provides an insight into the roads of tomorrow which will be technologically equipped to serve cars with better fuel economy, stability control and safety equipment. As a result of this the world can expect a network of *'connected'* vehicles and road users by 2040 and as a result, without any action undertaken today, growing demands and changing technological advancement would increase pressure on the road resulting in a constrained economy that limited rather than facilitates personal mobility. The report highlights that strategic road network already showed a significant increase in the number of road users (more than 1 billion extra miles) since 2010. Spending on Highways network is one of the few areas where DfT spends large proportion of money with limited flexibility as a result of this the strategic road network is under pressures resulting in short term approach and uncertainty of funding whereas funding for railway and local authorities are locked up in long term commitment although for railway also it is 5 year plans.

While addressing the risk and vulnerabilities due to climate change work undertaken by The Highways Agency and Department for Transport (DfT) the other factors such as social, economic, technology changes etc. are discussed briefly and their role and significance in the future of transportation industry is emphasised.

However, there is no methodology or framework to implement resilience based asset management planning provided.

Insights into how futures based research might be considered can be gained from a plethora of scenario based research which are discussed below:

2.17.3.1 Scenario Planning

Lindgren, 2003 describes ‘scenario planning’ as a powerful tool for envisaging and managing the variations on an industrial level and provides a strategic perspective which is vital in today’s difficult business environment and hence scenario thinking when integrated into scenario planning gives many benefits and can give answers to strategic questions in today’s world as it might be envisioned in a plausible future (not necessarily probable based on what we know now). As such it is a platform / forum where the current engineering solutions can be tested for resilience and robustness under a broad range of conditions.

2.17.3.2 Future Scenarios developed as a part of the research Urban Regeneration (Hunt et al., 2012)

The major research project entitled ‘Urban Futures’ simulates the future scenarios in the current urban context. In order to assess that the solutions proposed and used in the real world today are fit for purpose in the future and are resilient to the challenges posed, Hunt et al., (2012) developed a future scenarios tool to test and examine robustness of today’s sustainability solutions to urban re-development problems to possible future scenarios (in this case the year 2050) to ensure robustness, flexibility and resilience is provided in the most cost effective way possible. The study utilised current UK base line data for each scenario to provide a set of characteristics against which sustainability solutions can be assessed (Hunt et al., 2012 and Boyko et al., 2012). Reviewing the literature within an Urban Futures Monograph, Hunt et al., (2012) and Boyko et al., (2012) provide a brief description of the characteristics of four commonly occurring archetypal future scenario visions. They are:

*Market Force*s – This scenario is very similar to the current conditions, with similar demographics, economic, environmental, and technological trends. The market follows the self-correcting judgment and manages new problems and issues by itself. This therefore interprets the policies as being more market driven.

Policy Reform – This scenario characterises an environment with more government involvement to promote and encourage environmental sustainability and drive socially desirable outcomes through strong policy making and rising social and environmental consciousness which influences consumer behaviour.

New Sustainability Paradigm – This scenario characterises a modern socio-economic arrangement and a cultural change in the value system of the society. The ethos of 'One planet' prevails and planning policies are highly controlled focusing on sustainability and regional planning. This will result in an overall sustainable development in socio-economic and environmental fronts.

Fortress World – This scenario characterises division of the world in two groups – one which can have all the luxuries of a modern world and are thereby associated facilities like higher security, improved health and safety standards, improved lifestyle and dwelling conditions and hence they are responsible for higher emissions and are protected by biased policies. The other half of the world constitutes of the majority and they are denied access to luxurious dwellings and live under impoverished conditions thus increasing the inequality gap.

The urban futures research is based on the philosophy of 'futures research' for assessing the resilience and sustainability for urban regeneration solutions. The proposed research also adopts the 'futures research' to develop the plausible 'futures conditions' which affect the transportation network. However, the research does not use the same scenarios studied in Urban Futures i.e. market forces, fortress world, sustainable paradigm and policy reforms as it was not considered scalable in terms of geotechnical solutions on road transportation network. This was evident when the researcher adapted the 'Urban Futures' tool to compare the resilience of alternative geotechnical solutions. The result was that alternative geotechnical solutions showed no significant differences in each future scenario in terms of their resilience to enable constructive comparison. However, the urban futures research approach of asking 'what if' questions was considered to be relevant. Hence this approach was used to identify the impacts of the plausible future conditions on geotechnical solutions. This was undertaken using literature review and cross impact analysis techniques (discussed in chapter 3 of this thesis).

2.18. Summary of current research and industry uptake to the gap in research

Although there exists 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. Mian et al., (2011) have relied on geotechnical assets to explain the application of their risk-based framework; however, they do not fully elucidate the implications of their application for the maintenance of the assets. Moreover, their work presents a risk based framework, while the objective of this study is to present a long-term planning tool for geotechnical assets.

Second, almost all the models and the tools discussed above assist decision makers in identifying solutions given the budgetary constraints. This tool is slightly different in that it enables senior managers identify a resilient solution by appraising them in terms their responsiveness to changes in the future asset conditions. It offers a snapshot view of the diverse future conditions that may affect the performance of the geotechnical asset and allows for the selection of the most resilient solution. In that sense, this decision-support tool can be viewed as complementing some of the models and systems discussed above.

Third, unlike risk-based systems that rely on database information or tend to prioritise the risks relevant to a particular set of stakeholders, this proposed decision-support tool allows for the adoption of a more holistic perspective. It enables strategic decision makers to evaluate the socio-economic, technological, environmental and political conditions in the future and choose an asset management solution in light of these future conditions. Moreover, it relies on the use of expert opinion for estimating future conditions, which provides for better capturing of future variability than database records.

Fourth, the approach to conceptualizing resilience within the context of asset management offers further room for improvement. The existing resilience-based decision-support tools focus on asset performance under extreme shock events in urban environments or examine asset service level over a certain time under certain maintenance budgets. A comprehensive approach to estimating resilience, which takes into account economic, technological, social, political and environmental factors and the interactions between these factors, has not been undertaken. This study adopts a multi-dimensional futures-based outlook to estimating long-term resilience. It examines asset service level under various plausible future conditions, thus ensuring resilience from the perspectives of diverse yet important asset stakeholders.

In sum, the proposed tool fulfils the need for a long-term decision support instrument that enables the selection of a resilient solution for the management of geotechnical assets while adopting a comprehensive approach to the consideration of future conditions that can affect the lifetime of the asset.

3. Methodology of Research

3.1. Introduction

The subsequent sections explain the research methodology in detail. It is important to clarify at the outset that this work focuses on business research. The term ‘business research’ has been defined as “the application of the scientific method in searching for the truth about business phenomena. This process includes activities such as defining business opportunities and problems, generating and evaluating alternative courses of action, and monitoring employee and organizational performance.” (Zikmund et al., 2012). Steps such as “idea and theory development, problem definition, searching for and collecting information, analysing data, and communicating the findings and their implications” are also a part of the business research process. According to Collis and Hussey (2008), business research allows researchers 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.

This study began with the identification of a clear business problem - the lack of a long-term planning and resilience based decision-support tool for geotechnical assets. This continues to present a challenge for most asset management professionals because they are unable to predict or plan for future changes in the absence of such a tool. Currently for geotechnical assets, long term planning and decision making is based on engineering judgement supported by technical knowledge of ground conditions for condition assessment, risk management and developing maintenance strategies based on available budgets. Currently, transport resilience planning is undertaken at a network wide level (and not for an individual asset such as geotechnical assets) where the focus lies predominantly on factors which are affecting the operation and maintenance of transportation network such as extreme weather conditions and/or threats to security (Transport Resilience Review, 2014). Resilience studies include identification of a critical network by asset owners, developing risk based strategies and identifying key factors affecting their network. This involves extensive stakeholder liaison followed by developing contingency plans. It does not specifically develop planning frameworks which consider multiple future conditions (such as those included in this study) and their inter-relationships in a comprehensive manner as undertaken in this research. Apart from the need for such a tool in the field of asset management, the researcher's own academic and professional interests and the background of the organisation sponsoring this work contributed to the selection of this research topic. The sponsoring organisation is a multidisciplinary consultancy that provides asset management solutions for the road and railway network in UK. Further, the researcher's use of established qualitative research techniques for developing and refining the planning tool firmly entrench the study within the broader domain of business research.

3.2. Boundaries of Research

The broad outline and boundaries of the research are shown in the Figure 3.1. The red broken line represents the boundary conditions of the study. Thus, out of the many highways assets, geotechnical assets such as cuttings, embankments slopes, retaining structures and foundations are the key focus of this study. In addition determining the critical factors that pose challenges to their performance are determined and tested in the light of plausible future conditions influencing the transportation network in the long term i.e. 35 years (see section 4.3.2).

Table 3.1 highlights the methodology adopted in the research aligned with objectives of the research and also presents the corresponding outputs.

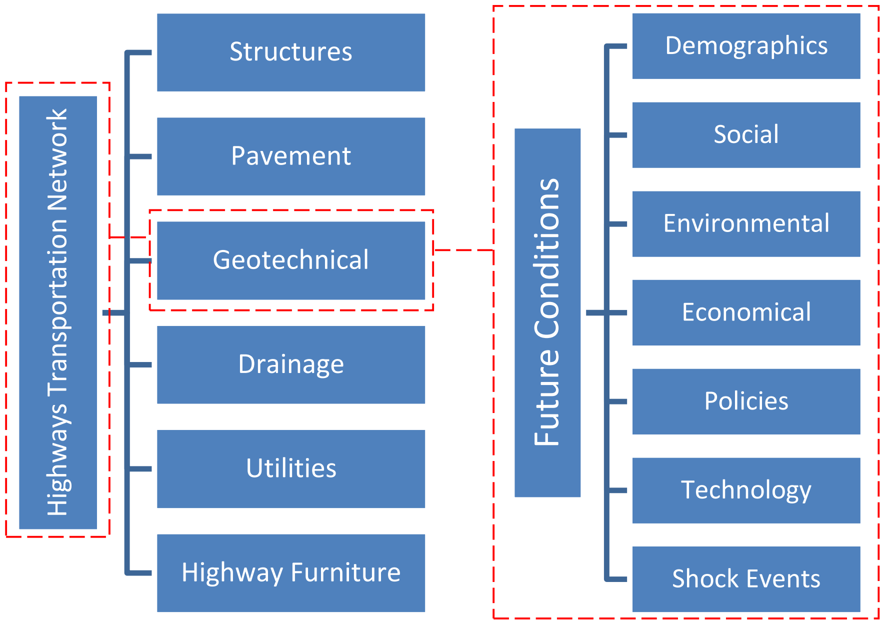


Figure 3.1 Proposed Research Boundary

Table 3.1: 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** Online keyword searches were conducted on reliable and verified sources such as online scholarly databases (The Highways Agency Geotechnical Data Management, ASCE library, Google Scholar, Science Direct), peer-reviewed articles and material from high-quality conference proceedings. Keywords used for the searches included the following: • “infrastructural asset management theories” • “asset management” + “transport sector” • planning” + “ asset management” + transport” • “roads” + “asset management” + “geotechnical assets” • “planning tools” + “geotechnical assets” + “UK” • “decision support” + “geotechnical assets” + “tools” **Backward and forward journal searches** References, authors and keywords obtained from the thematic review were used to further uncover more information. Papers that had cited the articles obtained from the thematic review were also studied.	14 critical factors integral to the performance, serviceability and stability of geotechnical assets on the road network in the UK (Phase A). 7 future conditions likely to impact the highways geotechnical assets were derived from the literature study

Table 3.1: Research Methodology and method of study			
STAGE.	**Objectives of the Research**	**Research Method**	**Output**
2	**Objective 3:** To study the ground-structure interaction and determine factors affecting the performance of the geotechnical assets including groundwater, seepage, soil properties, geology and hydrogeology	**Concept mapping** Mapping used to highlight through a diagram the relationship between the critical ground-structure factors pertaining to geotechnical assets and the performance and failure of the assets. The purpose of the map was to help the user develop and visualize the different types of failure hypotheses for a geotechnical asset based on the critical factors involved.	Rose diagram indicating the interrelationships between triggered and triggering critical factors for each type of geotechnical asset failure (Model 1)
	Objective 4: To classify and evaluate the plausible future conditions relevant to the road transport network and the associated geotechnical assets.	Concept mapping was again used to visualize the interconnections between future conditions and the critical factors of geotechnical assets	Rose diagram to visualize the future conditions and critical factors (Model 2)
3	**Objective 5:** To develop a resilience based geotechnical asset management framework for use in the planning stage of an asset management lifecycle and to develop a tool which supports these assessment.	**Cross-impact analysis** A two-dimensional cross-impact matrix was constructed with the future conditions on the rows and the critical factors on the columns. Experts were asked to assess resilience of an asset solution against every interaction of a critical factor and a future condition (on the matrix). Negative scores indicated a poor fit between the asset solution and the interaction factors, 0 indicated neutral fit or a non-applicable solution and positive scores indicated a good fit between the solution and the interaction—that is, the solution works without any change in design.	Developed a five step framework for resilience assessment of geotechnical assets. This includes an excel-based decision-support tool with 7 future conditions and 14 critical factors. The tool included a 6-point rating scale, ranging from –3 to +3, weightages for future conditions, and pre-fixed scores for critical factors. Once values were inputted, the tool yielded a resilience score.
4	**Objective 6:** To test the framework through case studies and validate the tool.	**Workshop** A structured workshop was conducted to explain the purpose and working of the tool and to test its robustness with two real case studies. The workshop participants consisted of 6 attendees from the asset management industry which included geotechnical experts, consultants, engineers and the end-clients.	Robust and fully validated decision-support tool for the assessing the long-term resilience of geotechnical asset solutions

In order to make the proposed framework holistic and comprehensive, it considers the whole life cycle of a geotechnical asset i.e. project development, maintenance and operation and finally demolition or re-use as shown in figure 3.2. The framework is a planning toolkit that can be re-visited at all stages of the life cycle of geotechnical project. Project development includes its inception, its design and construction, followed by its operation and maintenance and finally its end of design life stage which includes either demolition or reuse depending ultimately on its condition and the type of project being considered.

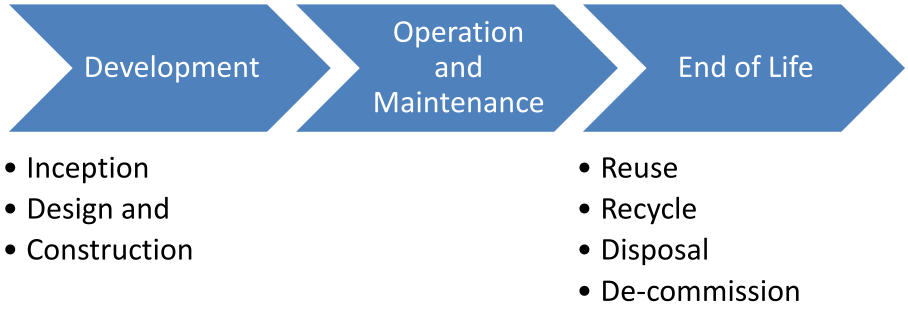


Figure 3.2 Whole Life Cycle of a Geotechnical Project

This research aims to answer the question ***'is the proposed or existing geotechnical asset management solution resilient under changing future conditions?' A resilient asset management solution supports long term planning of the transportation network by keeping the network up and running even in changing conditions while continuing to maintain, operate and upgrade it 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 in Chapter 1 of this thesis.

3.3. Research Approach – 'Futures Research'

Literature on conducting business research is replete with references to qualitative or quantitative approaches. It has been argued that choice of qualitative or quantitative approach is guided by the research paradigm or the perspective from which the research problem is viewed (Collis and Hussey, 2008; Amaratunga et al., 2002). The research paradigm can also be understood as a school of thought on how best to conduct research. Collis and Hussey (2008) discuss postivism and interpretivism as two dominant approaches to empirical research investigation. Positivism rests on the premise that social reality is independent and objective i.e. there is only one reality and everyone has the same sense of reality. Interpretivism, on the other hand, considers that social reality is subjective and everyone has their own sense of reality (multiple). Thus, it follows that intrepretivist studies use methods that allow for the use of words and observations of people and concepts as they occur in a natural setting (qualitative), whereas positivistic studies rely on methods that attach numbers to the observations (quantitative).

However, de-linking paradigms from research methods and techniques, Sandelowski (1995, 2000) argues that qualitative or quantitative methods used in business research are not necessarily influenced by the researcher's perspective. The author argues that two researchers studying the same topic but from differing paradigms may use the same research technique, for example, interviews, but treat the results of the research differently, which may be suggestive of their paradigmatic leanings. Similarly, Eriksson and Kovalaine (2008) state that qualitative and quantitative approaches are difficult to define per se; therefore, they are often compared in an attempt to clarify the differences. Some of the well-known quantitative approaches used in business research are experimentation, structured observation and social survey (Eriksson and Kovalaine, 2008) and some of the qualitative approaches are case study research, ethnographic research, grounded theory research, focus group research, action research, futures research, critical research and feminist research (Eriksson and Kovalaine, 2008; Remenyi, and Money, 2004) A strong recommendation that emerges from these works is the adoption of an approach that is based on the actual situation being researched. The proposed research is based on futures research and hence it adopts a qualitative approach.

As mentioned earlier, the purpose of this work is to address an existing business need through the development of a long-term planning and decision-support tool that enables the selection of a resilient solution for the management of geotechnical assets. To identify the most appropriate or resilient solution from the options available, the researcher calls for a careful consideration of the plausible future conditions that may affect the asset (e.g., social, environmental, and financial). Studies such as this, which have a future-driven outlook, belong to the category of futures research. Not to be confused with forecasting, which involves mathematical simulations and regression analysis of past data for future projections, futures research relies more on anticipated outcomes to visualize the future. For practitioners of such research, a key concern is the usability of the research results (Mannermaa, 1986). They are deeply invested in identifying and augmenting aspects of reality that are desirable in the long-run and mitigating and eliminating those that are detrimental. The pursuit of such research is strongly linked with having an impact on an organization, the government, the environment, or society at large. According to Amara (1991, p. 646), futures research helps shape perceptions and future choices by:

- 'laying out paths of possibilities (the art of the "possible");
- examining in detail particular paths and the likelihood of their occurring (the science of the "probable");
- expressing preferences for, and implementing, particular paths (the politics of the "preferable")'.

3.4. Research Methods

Fundamentally, futures research deals with identifying possibilities and alternatives and determining their desirability. Investigations into future events that seem plausible are exploratory, whereas those into events that are desirable are normative. Broadly speaking, the purpose of planning activities usually involves bridging the gap between the exploratory and normative future events (Gordon, 1992). Because of its emphasis on planning and decision-making, futures research has been applied in many disciplines such as education, management, economics and policymaking. In fact, most of the theories employed in futures research are derived from traditional disciplines such as sociology and psychology; therefore, the use of inter-disciplinary methods and perspectives is common and warranted (Mannermaa, 1986; Schwarz, Svedin & Wittrock, 1982). Moreover, given that futures studies consider long timespans, such as 50–100 years, it is difficult to rely on any single scientific method to effectively capture all the dynamics that may influence future development.

Many scholars have discussed methods and techniques that are appropriate for futures research (Amara, 1991; Börjeson et al., 2006; Godet, 2000; Gordon, 1992; Gordon, Glenn, & Jakil, 2005; Mannermaa, 1991; Popper, 2008). It is clear from these studies that there are no methods exclusive to this type of research; therefore, and also because of the inter-disciplinary nature of the approach, experts have discussed a number of varied techniques—both quantitative and qualitative. Regression analysis, probabilistic models such cross-impact or trend impact, and time-series analysis are examples of quantitative techniques used by experts to predict the future as objectively as possible on the basis of past events or data. For example, future studies in the field of economics often employ such techniques. On the other hand, qualitative methods such as Delphi, decision trees, scenarios and in-depth interviews are based on the view that the future cannot be wholly predicted— one can only estimate the alternatives and plan accordingly. Such techniques are used in management studies and operations research among others.

While both quantitative and qualitative futures research studies have been undertaken within the field of asset management, this researcher has used an exploratory angle and qualitative techniques for the development of a planning and decision-support tool for the following reasons:

- The decision-support tool is intended to help managers select the most resilient management solution for highway geotechnical assets by estimating the plausible future conditions. It is difficult, if not near impossible, to objectively predict these conditions on the basis of past data. Thus, a more exploratory research direction was called for, involving the use of more descriptive measures, as offered by qualitative techniques.
- Risk assessment models in asset management estimate the probability of certain events; however, the researcher’s objective in this work was to comprehensively map plausible future conditions that can affect the behaviour of geotechnical assets in the UK. Given the complexity of the inter-relationship between the futures and impacts on asset performance, adopting a consultative approach was vital to keep the assessment project specific and focussed. Such consultative approach is afforded by qualitative techniques.
- Lastly, a decision-support tool meant for the experts should be validated by them. This exercise, again, involved discussions with industry experts, which is a qualitative technique.

For achieving the objectives outlined in this thesis, the researched uses three main qualitative techniques: literature reviews, cross-impact analysis and expert consultation which are the commonly used tools of future research (Keenan, 2007, Cronin et al., 2008).

3.5. Research Techniques for the Development of the Tool

3.5.1. Thematic Literature Review

A thorough and systematic investigation of the existing knowledge is essential for undertaking any kind of research effort. Exploring the existing body of the work within a particular domain helps researchers identify the dominant focus areas, recognize gaps in knowledge and gain insights into how the gaps can be bridged (Cronin et al., 2008). For this work, the researcher conducted a thematic literature review, collecting, analysing and synthesizing works relevant to infrastructural asset management. As literature reviews these days are mostly conducted online, keyword searches are a popular technique to find works (Ely & Scott, 2007). To ensure only high-quality work was collected, analysed and synthesized, the researcher used reliable and verified sources such as online scholarly databases, peer-reviewed articles and material from high-quality conference proceedings (Levy & Ellis, 2006). The database maintained by the Highways Agency Geotechnical Data Management, the ASCE library, Google Scholar, Science Direct, and reputed journals within the fields of transport and asset management were combed for information using keywords such as the following:

- “infrastructural asset management theories”
- “asset management” + “transport sector”
- “planning” + “ asset management” + “transport”
- “roads” + “asset management” + “geotechnical assets”
- “planning tools” + “geotechnical assets” + “UK”
- “decision support” + “geotechnical assets” + “tools”

Starting with the extant body of knowledge on infrastructural asset management, the researcher progressively narrowed the scope of the keywords to focus on the asset management planning tools, systems and approaches used by transport authorities for the management of geotechnical assets linked to highways. Abstracts and summaries of research articles were perused to determine the relevance of the papers to the research topic. To streamline the search process, the researcher used the following exclusion criteria: only studying the asset management appropriate for physical transportation infrastructure and not for financial assets.

In addition to keyword searches, backward and forward searches were used to enrich the exploration into planning approaches used for geotechnical assets. This includes references, authors and keywords contained in the articles obtained from keyword search results were used to further uncover more information. Similarly, other papers that had cited the article obtained as part of keyword search results were also studied.

Conducting a thorough literature review helped the researcher justify the need for a long-term planning and decision-support tool specifically targeted towards the resilience assessment of geotechnical assets. The review highlighted the absence of a long-term planning framework that enabled decision makers to identify the resilience of geotechnical asset management solutions. Given that the longevity of an asset solution is of critical importance, planners need to estimate future changes that are likely to affect asset performance and select a solution that is appropriate and long-lasting. In terms of the development of the decision-support tool, the literature review helped the researcher accomplish several important goals: (1) it helped the researcher identify a set of **14 critical factors** that are integral to the performance, serviceability and stability of geotechnical assets on the road network in the UK (Phase A), (2) a list of **7 future conditions** likely to impact the highway geotechnical assets were derived from the literature study (Phase B) and (3) the reviewed knowledge acted as the foundation for the development of a resilience assessment framework, which was the starting point for the excel based decision-support tool (Phase C).

3.5.2. Concept Mapping

The researcher identified 14 critical factors indicative of the performance of geotechnical assets that were classified into triggering and triggered factors on basis of whether they were viewed as internal or external to the asset. External factors referred to elements that surrounded the geotechnical asset in the environment and singularly or in conjunction with the others affected the integrity of the geotechnical asset. The internal factors referred to soil properties or phenomena within the soil system itself, which when triggered ultimately led to asset failure. Thus, external factors acted as the triggering points affecting one or more of the internal factors (triggered points), affecting the performance and ultimately leading to partial or complete physical failure of the geotechnical asset. To depict the relation between the geotechnical assets, the triggering and triggered factors which influences the geotechnical asset performance, the researcher has used concept mapping technique.

Concept mapping is an established technique used to highlight the relational links between concepts (Davies, 2011; Jackson & Trochim, 2002; Cañas et al., 2003). It is used to diagrammatically communicate the structural relationships that two or more concepts share. While concept maps allow for easy assimilation of ideas, the creation of such mapping requires expertise and knowledge. In this study, the researcher's intention was to visually represent the likelihood of asset failure by highlighting the interrelationships between the triggering critical factors (internal) and the triggered critical factors (external) for each type of geotechnical asset. The use of a typical spider web diagram yielded an unduly complex map, with multiple triggered factors radiating from each triggering factor. To solve this, the researcher opted for a rose diagram with three concentric circles, one each for triggering factors, triggered factors and asset type. Rose diagrams or circular histograms are often used in geology studies (Nemec, 1988; Autodesk, 2015). In this work, the three layers of the rose diagram can be viewed as three dials of a vault, which can be turned to help the user visualize the different types of failure hypotheses for a geotechnical asset and the critical factors involved. Moving from the outer circle (e.g. climate change) through the middle circle (e.g. pore water pressure changes) and finally to the central circle (e.g. asset failure) allows a user to estimate the critical factors associated with a particular type of geotechnical asset and its performance or failure. Termed as Model 1, this rose diagram was subjected to an alpha test in the form of an expert review. Feedback was solicited from asset management experts on the following criteria: coverage, significance of the factors considered, classification of the factors into triggering and triggered, and overall presentation. Minor modifications were made in line with the feedback received (see Figure 4.1).

The next step in the process was the incorporation of the future conditions into the resilience assessment framework. While critical factors are the indicators of asset performance or failure, future conditions are the elements that influence these factors, contributing to the failure. The purpose of the decision-support tool is to drive the selection of an asset solution that is resilient to the future conditions that may affect the geotechnical asset. A set of 7 future conditions likely to affect geotechnical assets on highways network over a time frame of 35 years (i.e. until 2050) were derived from literature. Not all future conditions are likely to affect every geotechnical asset; therefore, the interrelationships between future conditions and the critical factors of geotechnical assets were established, again with the help of concept mapping. For instance, a change in demography (future condition) can be linked to a change in loading conditions (critical factors); however, it is unlikely to be induce a change in the seepage characteristics (critical factors) of a geotechnical asset. Thus, the correspondence between the future conditions and critical factors was visually represented in the form of another rose diagram (Model 2). It important to highlight that while this could have been presented as a logical extension of Model 1 and combined with the previous diagram; adding this layer of complexity i.e. linking the 7 future conditions to each of the triggered and triggering factors problematized the visualization of the relationships between the two. Therefore, the researcher decided to represent the two conceptual interrelationships separately, via two rose diagrams. As with Model 1, expert feedback was solicited on the various aspects of Model 2, and minor modifications were incorporated.

3.5.3. Cross Impact Analysis: Development of the Decision-Support Tool

To identify and select the most resilient solution for the management of a geotechnical asset, it is necessary to anticipate the future behaviour of an asset in response to the likely changes in the future conditions. That is, it is important to carefully study the future conditions and critical factors in conjunction and explore the implications of their interactions on resilience management. Cross-impact analysis is popular futures research method used by experts to analyse how a variable within a particular set impacts all the other related variables (Richards & Pherson, 2011). In a cross-impact analysis, experts predict the probability of a future event, taking into account how the other related future events and their interactions are likely to enhance or reduce the probability occurrence (Richards & Pherson, 2011; Gordon, 1994; Gordon & Hayward, 1968). The cross-impact matrix provides a good platform for directing such a discussion (Richards & Pherson, 2011; For-Learn, 2005) and recording how a variable is affected by the interaction of the other variables in the set.

In this work, the researcher adopted a qualitative approach to cross-impact analysis (Asan et al., 2007; Asan et al., 2004 and Helmer, 1981). A two-dimensional matrix was constructed with the future conditions in the rows and the critical factors in the columns. To predict the resilience of a geotechnical asset management solution, expert views were sought on the interrelationships between 7 future condition and 14 critical factors for that particular solution. In their work on fuzzy cross-impact analyses, Asan et al., (2004) discuss the use of different scales for recording expert evaluation such as a linguistics scale or a fuzzy-rating scale. In this work, the researcher used a 6-point rating scale, ranging from –3 to +3, to evaluate the fitness of a solution against every relevant interaction of a critical factor and a future condition. Negative scores indicated a poor fit between the solution and the factors, 0 indicated neutral fit or a non-applicable solution and positive scores indicated a good fit between the solution and the factors—that is, the solution works without any change in design. It is important to note that though the matrix in this work featured different variables on the two axes, unlike conventional cross-impact matrices, the score assigned in each cell required the experts to consider the interrelationships between the future conditions and critical factors and assess the impact of these multiple interrelationships on the resilience of the solution. The evaluation of interrelationships as opposed to isolated factors ensures that this method it true to the principles of cross-impact analysis.

This cross-impact matrix was presented to experts on an Excel-based spreadsheet. The spreadsheet also contained pre-fixed factors scores (out of 100) attached to each of the critical factors and a column for weightages to be assigned to the future conditions by the experts. The Excel-based tool enabled the computation of the resilience score of a solution once the values were inputted by the experts. In a nutshell, the tool facilitated assessing resilience of a proposed geotechnical solution under every relevant combination of critical factors on the one hand and future conditions on the other. It yielded a numerical output, on the basis of which asset managers could compare geotechnical management solutions for a project and select the most resilient one.

3.5.4. Multiple Criteria Decision Making Process

Multiple criteria decision making process refers to a process where decisions have to be taken between multiple objectives/alternatives/ criteria which are more often than less conflicting in nature (Hwang et al., 2012 and Saaty et al., 2006). As an example: Developing a transport system which encourages social development along with being adaptable to change due to changing demographics and technology affecting the way in which people function in their day to day life. Multi-criteria decision making process involves searching or designing the most befitting criteria. (Hwang et al., 2012, and Keenay et al., 1993). Solutions to these challenges can be found either by designing a solution which meets all these criteria or to select the one which is best fit among previously selected criteria. (Hwang et al., 2012, Bui et al., 1987 and Keenay et al., 1993). Multiple criteria decision making can be undertaking using processes such as analytical hierarchy process (AHP) or group ranking techniques which are discussed below.

3.5.4.1 Challenges in multi-criteria decision making process

Undertaking group decision making when there are multiple criteria to be assessed, can pose certain challenges such as ‘differing objectives’ for each decision maker which others in the group may or may not share. Another challenge could be “conflict among criteria” where the choice of selecting a criteria may clash with another criteria or they may share equal importance. For example: selecting ‘social’ benefits to build a road network versus ‘economic’ implications associated with maintenance and operation costs for the road network can both be considered equally important factors. In the proposed research, these challenges were addressed by allowing the decision maker to assign weightages to a set of predetermined 7 future conditions in line with their objectives along with the option to assign equal weightages to the future conditions.

The research has used multiple criteria decision making method arranged in a group setting to assign weightages to the future conditions. The research presented here, does not aim to get a target weighing for a future condition. The choice of selecting multiple criteria decision making in a group setting is to enable a face to face stakeholder communication and judicious weightings to future conditions for individual project in order to enable resilience assessment. This allows decision makers to concentrate on analysis of choices which are ‘reasonable’ for the project rather than how the choices are made from individual preferences. It also allows the group to consider the factors comprehensively for the overall good of the project. Another technique which can be used in the multiple criteria decision making process is the analytical hierarchy process (AHP). This is a three part decision making process which includes identifying and organising decision criteria, limits and considerations in to a hierarchy of importance, undertaking pairwise comparison for each option in the same level of hierarchy and finally synthesising the solution algorithm of results obtained from pair wise comparison across all the hierarchy levels (Saaty et al., 2006, Saaty et al., 1998 and Hotman, 2005). However for the purpose of the research, group ranking techniques were considered to be more appropriate and these are described in detail in section 3.5.5.

3.5.4.2 Group Ranking

Group ranking used within the multiple decision making process can be based on a variety of techniques such as social choice theory such as voting, expert judgement/group participation analysis which discusses the variety of pros and cons for a project or the game theory approach that considers 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 the light of all future conditions to arrive at the weightages. The 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.

3.5.4.3 Majority method

This technique applies the 'majority wins' rule. Mathematically, this means one alternative should have more than 50% of total votes to have a total majority. But when there are three or more choices this method does not always guarantee a winner. As even if a candidate had higher votes than the other two options, the total may not be a majority of the total votes and hence may not provide a clear winner (Cox 1997 and Wright et al., 1989).

3.5.4.4 Plurality Method

This technique only considers the first place voters' i.e. whichever alternative receives maximum votes in rank 1. Although this is an easy to use method, it does not consider voters' other preferences so if there are three preferences, only the first preference is accounted not the second or third preference (Cox, 1997, Wright et al., 1989 and Brams et al., 1978).

3.5.4.5 Borda Count Method

This method assigns points to each alternative based on how it performed in each ballot. Points are assigned so that the first place gets as many points as the number of alternatives. Each place below receives one less point. The total points are determined by multiplying the total number of votes received for each alternative with the points assigned based on its place in the ballot. Winning alternative would get more points for being ranked higher in the ballot. So for each alternative the total score is sum of product of number of votes and rank. Winner is the alternative with highest score. It takes into account all the information from the preference ballots and also gives a ranking to the alternatives (Hwang et al., 2012,Lansdowne et al.,1996 and Newenhizen,1992)

3.5.4.6 Pairwise comparison technique

In pairwise comparison technique, elements (designs, objectives or attributes) are ranked on a pair by pair basis. All possible options are therefore matched each other in a head to head comparison until all the permutations have been covered. In this series of one to one match, each winning option is awarded 1 point. Where there is a tie between a competing pair, both the options are given a 0.5 score. The points awarded to each option is added to determine a final score. The option with the most score wins (Bradley et al., 1952, Jamieson et al., 2011, Koczkodai 1993, David 1963, Straffin 1980). This technique also takes in to account the voters' other preferences and not just the options with the highest vote similar to Borda count method.

Sari (2001) highlighted that one of the drawbacks of this method is that in some cases, it results in rank reversals when the lowest ranking alternative is dropped from the assessment. Contradictorily Dym et al., (2002) argue that in practical applications pair wise comparison shows consistent results even if low ranking alternatives are dropped from the assessment. The authors have demonstrated with examples, that effective decision making in engineering design is possible using pair wise comparison notwithstanding concerns related to the technique. As it is not the inherent pair-wise comparison technique which results in erroneous results due to rank reversals which essentially occurs when (low ranking) alternatives are dropped from further consideration. The concern raised by Sari (2002) about rank reversals on dropping low ranking alternatives does not potentially affect the proposed research, because at no point any of the future condition (in spite of securing a low rank i.e. weightage) is intended to be eliminated from resilience assessment process. The resilience assessment process is proposed to be undertaken across the range of all the 7 future conditions provided in the framework, to determine the solution which is resilient across most if not all future conditions and identify areas where they perform better or worse than its counterparts in a given future condition. Similar to Dym et al., (2002) Clive et al., (2002) have compared various rank ordering techniques and concluded that for ranking design alternatives pair wise comparison procedure has advantages over other alternative options.

3.5.4.7 Instant Runoff Technique (IRV):

This technique is also called 'plurality with elimination' and attempts to address the issue of insincere voting. In this method, voting is done and a preference schedule is generated, the alternative with the least preference is eliminated from the exercise and its votes are redistributed to next choice. This process continues until a majority is achieved. (Cox 1997, Wright et al., 1989 and Brams et al., 1978).

But it does not account for a tie. If there are two alternatives which have the same preference, but they are not a majority they both will be eliminated from the process. It can violate the "Condorcet criterion" (Fishburn et al., 1977, Saari et al., 1999 and Gehrlein et al., 1980). There are other methods such as apportionment method also called as 'Webster method' (Ballinski et al., 1978 and Ballinski et al., 1980) which is not discussed as this was not considered very relevant to the proposed study.

Based on the review of all the above methods, pairwise comparison technique is considered to be apt for the following reasons:

- It covers all alternatives and considers voters' other options/preferences and not just the first ranked alternatives. This is necessary for the resilience assessment of solutions across all future conditions and not just a single preferred future condition.
- It meets the 'Condorcet fairness criteria' i.e. if one future condition is preferred over all the other future conditions then that future condition will win overall competition. Therefore, obtaining the highest weightage and in turn having the maximum influence on the final resilience score.
- And most importantly it allows a way to address a tie between future conditions by splitting the score which none of the above methods allows.

- With regards to the limitations, the process can be tedious and results are more likely to give a tie which can be considered acceptable as for the proposed tool the advantages stated above far outweigh the limitations.

3.5.5. Tool Validation Workshop

As explained earlier, the involvement of experts is central to futures research methods (Amara, 1989) and more so to asset management. Ruitenburg et al., (2014) explain that expert insights and knowledge are invaluable for the estimation of asset failure, especially when the asset is still intact. Their experience in dealing with similar situations enables them to offer information that can be used to anticipate the future and plan for it accordingly. An expert is any person “whose opinions may be useful to futures thinking” (Roubelat, 2000). To validate the decision-support tool developed in this study, the researcher conducted a cross-impact analysis involving with six experts from the field of asset management. The expert panel consisted of geotechnical experts, geo-environmental expert, engineering geologist and asset management experts including the end-client, as a multidisciplinary panel is known to mitigate the risk of biased views (For-Learn, 2005; 33. Asan et al., 2004).

In a workshop-based setting, the decision-support tool and its purpose were explained to the gathered experts. Typically, cross-impact analysis is combined with the Delphi method, where experts are consulted anonymously. However, a structured workshop is now preferred over Delphi as it is less time-consuming and allows for open and collaborative interactions between experts holding disparate viewpoints (Amara, 1991 and Lauttamäki, 2014). A workshop is also known to be a good starting point for involving those who have not been exposed futures research (Dator, 2002).

To test the tool, the experts were provided information on two actual geotechnical case studies on the UK highways network and asked to assess the resilience of the proposed solutions for both the studies with the help of the tool. The case studies consisted of one remediation project and one improvement project (new build) with two different geotechnical solutions considered for each project. In all, the four types of asset solutions covered as part of tool validation included Gabion Retaining Wall, Sheet Pile

Retaining Wall, Installation of Counterfort Drains and Re-grading of embankment using Engineered Fill. These solutions accounted for the commonly considered geotechnical solutions for earthworks covering a wide range of applications from strengthening works to drainage measures within the UK. The sample size of two case studies, although small, is not inadequate for qualitative research studies, which relies on fewer samples than quantitative studies (Mason, 2010). In fact, by combining philosophical claims from epistemology, pragmatism and critical realism, Easton (2010) argues that even a single case study is sufficient if it provides relevant basis for study. Further, while some researchers have offered advice on the sample sizes considered sufficient for ethnography (Morse, 1994) and grounded theory research (Creswell, 1998), such guidelines are missing in the field of futures research, possibly because this branch of research is relatively recent and continues to grow (Amara, 1991). Mason (2010) explains that the concept of saturation—where the addition of more samples does not add new value—and the objective of the research can also help in determining sampling adequacy. Here, the objective of the researcher was to develop a long-term planning and decision-support tool that enabled the identification of the most resilient solution for the management of geotechnical assets. The validation exercise with two case-studies and involving an external panel of experts allowed the researcher to demonstrate the usability of the tool as well as its robustness. Thus, from the perspective of fulfilling the objective of the research, the sample can be regarded as adequate. Further, as a geotechnical designer with work experience in the field of infrastructural asset management, the researcher was knowledgably competent to identify the common types of geotechnical projects undertaken in the industry and therefore chose an improvement and a remediation project. Second, the two case studies used in the validation exercise were obtained from the Highways Agency Data Management system and included real-world confidential data, used with the explicit permission and consent of the asset management client to whom the data belonged. Third, for the testing of the tool, critical feedback and judgements were solicited from experts who were not only the potential users of the tool but also key stakeholders in the projects under consideration. These three reasons attest to the quality and the authenticity of the samples used in this PhD thesis. They show that the researcher has taken the necessary precautions to safeguard against the lack of generalizability and a bias towards verification: two common criticisms levied against the use of the case studies in research (Flyvbjerg, 2006).

The workshop exercise confirmed the usability of the planning and decision-support tool and marked the completion of the resilience assessment framework. As recommended in literature on futures workshops (Dator 2002 and Lauttamäki, 2014), open-ended feedback on the tool was solicited from the experts at the end of the workshop.

3.6. Fundamental Research Elements

Having discussed the overall methodology of the research and the research techniques in the above sections, the following section discusses the fundamental elements of the research. For adopting a structured development approach the researcher adopted the 'Agile' concept to address the multiple components of the research and follow an iterative approach in the development of the framework.

Based on the stages of research methodology described in Table 3.1, Figure 3.3 has been derived which defines the fundamental core elements of this research. The proposed research output, in the form of a 'Resilient Geotechnical Asset Management Framework', will provide a comparative assessment of proposed solutions based on the understanding of the three fundamental elements, in order to decide the most resilient solution, i.e. that which is flexible and workable under most (if not all) of the future conditions.

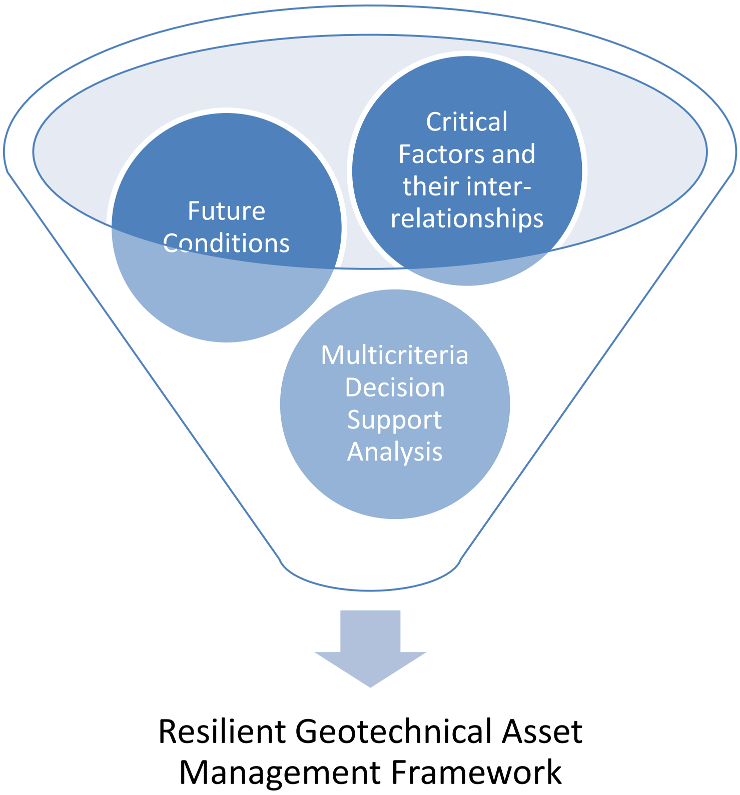


Figure 3.3: Fundamental Research Elements

3.7. Use of Agile Technique in managing and delivering research objectives.

Due to the multiple components of the research and the complex nature of the development of the framework, an iterative methodology has been adopted, so as to incorporate feedback from academic and industry professionals during the development process. This necessary feedback loop helped check the relevance of the overall framework and its underlying components as the research progressed - rather than having one final protracted validation loop at the end of the research. Based on these considerations, the research has adopted the concept of 'Agile' responsive framework that breaks complex processes into simple elemental stages (and deliverables). The reason for adopting 'Agile' approach in this research is because, it enables undertaking an iterative methodology allowing engineering and technological developments to be considered in a flexible and interactive manner. Being iterative in nature it gives feedback early on and hence enable a change of direction at a time that is most necessary (Wernham, 2012). Moreover the presentation of the methodology in this form gives a logical flow of research development for others to follow. As such it helps individuals from the industry and academia to provide their input on complex projects so that the final output is adequately validated (and robust). The iterative (and incremental) approach adopted within this agile methodology makes any changes much less disruptive than a conventional style of research development. The key advantages of using the agile methodology (Koch, 2011) are:

- Research objectives are met.
- Early involvement and regular liaison with stakeholders throughout the process resulting in continual improvement and fit for purpose output. This includes feedback from geotechnical engineers and geotechnical asset managers during interim stages of testing during the development of the framework
- Ensuring that the resilience assessment framework has been developed taking continual feedback from the stakeholders by adopting an iterative approach and the tool has been validated with two real case studies.
- It is realistic in terms of time and research milestones by continually refining the process and not just at the end where the output may not be as per the originally set plan for one or many reasons. The research outputs were monitored annually based on the research program and milestones identified at the beginning of the research.

Analogy presented here is that the proposed research is like a ‘Project’ with a definitive start and end with interim junctures (such as annual academic reviews) that are accomplished by finalising research objectives. Final output is validated by the group of geotechnical experts in order to meet the research objectives and demonstrate a practical use allowing for longevity in its future application.

Project management provides the technique with which the implementation of any aspect of asset management can be undertaken effectively. Hence project management can be undertaken for projects identified within the domain of asset management. The domain of asset management is broader than project management as it considers creating strategies, implementation plans, delivery and the supporting operating model for efficiently managing physical assets. It is not time bound with a definite start and end and is an ongoing process of implementing good asset management practice. Whereas, project management is a temporary group of related tasks and activities with a finite time scale and budget. Asset Management looks at the entire life cycle of an asset from inception, planning, design, operations, maintenance and disposal. Because transportation assets have a long service life, asset management has a long-term focus. Project has a definitive start and end with a clear set of outputs which links with the goals of the organisation but has a short-term focus. Each of the above stages within the lifecycle of an asset can include smaller projects.

Figure 3.4 represents the 'Agile' methodology used for developing and managing the research on a strategic level. A more detailed representation which includes a breakdown of the 'Design Phases' of the research and all corresponding iterations are shown in Figure 3.5.

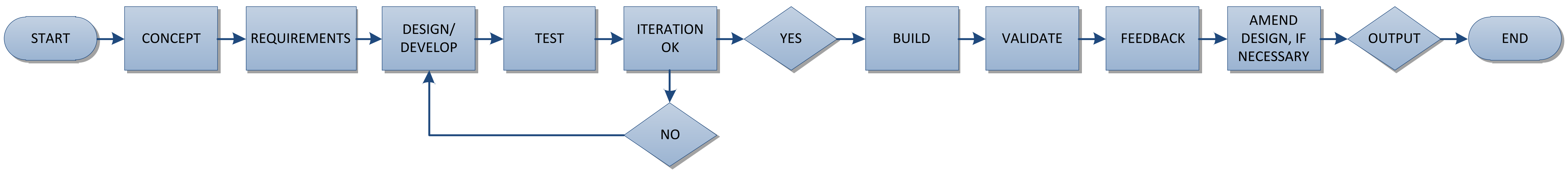


Figure 3.4: Methodology of Research represented using Agile Project Management Concept

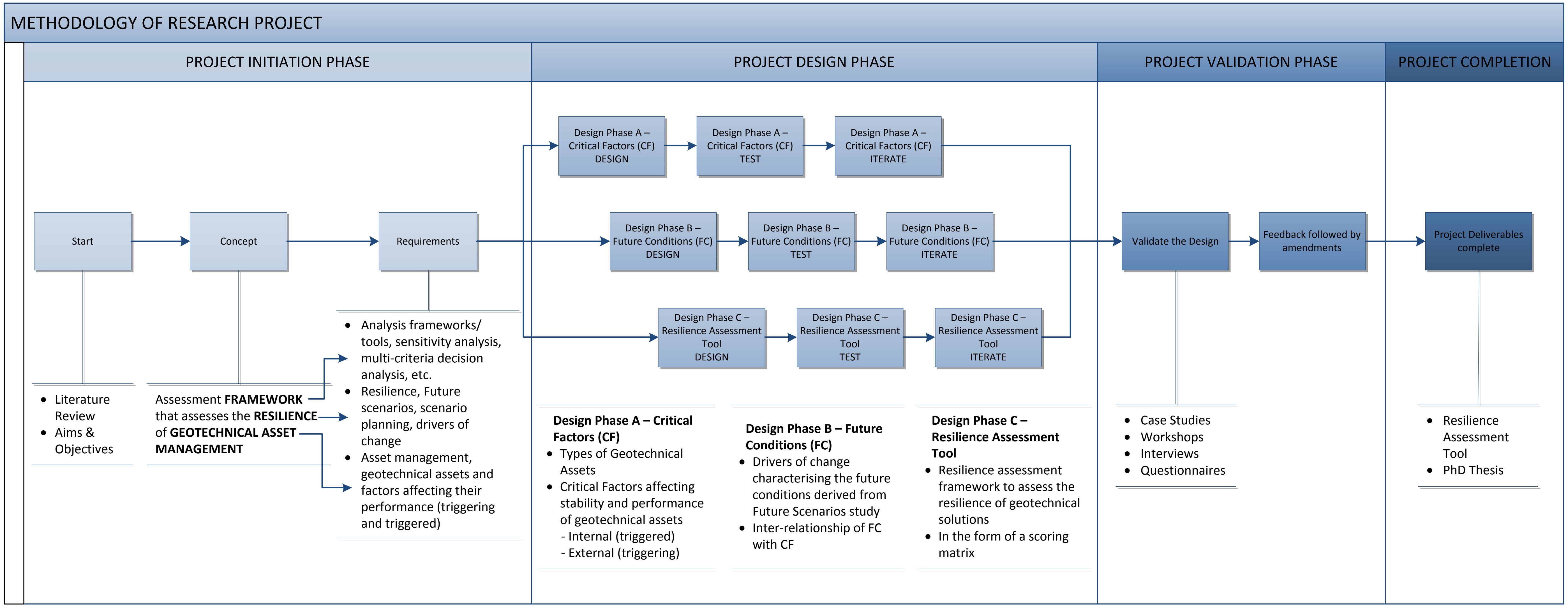


Figure 3.5: Detailed Research Methodology

Based on Figure 3.4 and 3.5, the research is divided in the following stages:

3.7.1. START

This marks the beginning of the process. Key steps were to:

- Develop the aims and objectives of the study
- Develop a Literature Review based on existing practices for asset management and understand what future implies to transportation industry.
- Define knowledge gap and address the issues related to the same.

3.7.2. CONCEPT

As the aim of the research is to develop a Resilient Geotechnical Asset Management Framework which tests the resilience of existing geotechnical solutions to the conditions exposed by the future. The objectives were therefore defined by the requirements discussed below.

3.7.3. REQUIREMENTS

The requirements are those objectives which when met will enable the research aim to be accomplished. Thus the requirements considered necessary for the aforementioned framework are shown in Table 3.2:

Table 3.2: Requirements for the Resilience Assessment Framework

Requirement no.	Description
Requirement 1.	To meet objective 1 and 2 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 the long-term planning needs and resilience assessment in asset management within the road transportation infrastructure (with focus on geotechnical) industry.

Table 3.2: Requirements for the Resilience Assessment Framework	
Requirement no.	**Description**
Requirement 2.	To meet objective 3: To study the ground-structure interaction and determine factors affecting the performance of the geotechnical assets including groundwater, seepage, soil properties, geology and hydrogeology.
Requirement 3.	To meet the objective 4: To classify and evaluate the plausible future conditions relevant to the road transport network and the associated geotechnical assets.
Requirement 4.	Identify and analyse a co-relation between the future conditions and critical factors.
Requirement 5.	To meet Objective 5 and Objective 6 To develop a resilience-based geotechnical asset management framework for use in the planning stage of an asset management lifecycle and to develop a tool to support these assessments. To test the framework through case studies and validate the tool.

3.7.4. DESIGN

Once the requirements were established it was the design phase, where each and every requirement was worked through in order to develop the concept. Design stage(s) included a series of test, iteration and feedback until a satisfactory design had been achieved. The design process was the longest as it continued to evolve with time (and with each iteration) and was subject to much improvement as outlined below.

The design process and the testing and iteration process form the chunk of the research undertaken. The design phases are sub-divided in to 3 subcategories A, B and C.

Design Phase A includes fulfilling the requirements 1 and 2 i.e. to determine the critical factors that influence the performance of geotechnical assets and develop a model that highlights its inter-relationship.

Design Phase 'A' Output: Model 1 – Rose Diagram (see Figure 4.3 in Section 4.2.2) showing the critical factors affecting the performance of geotechnical assets and inter-relationships between them. The methodology used for developing Model 1 is concept mapping which is explained in section 3.5.2.

Design Phase B includes fulfilling the requirements 3 and 4, which looks at the plausible futures and the conditions that may influence the performance of geotechnical assets. In order to develop resilient solutions, it is important to envisage what exactly the solution needs to be resilient to. Hence design stage B focuses on future conditions and establishes a relationship between the critical factors (derived in Design Phase A) and future conditions.

Design Phase 'B' Output: Model 2 – Diagram showing interrelationships between future conditions and critical factors affecting geotechnical assets (as shown in Figure 4.5 in Section 4.2.4). The methodology used for developing Model 2 is concept mapping which is explained in section 3.5.2.

Design Phase C includes a final stage of developing a matrix, which enables assessing and quantifying the resilience of proposed solution in the light of both, critical factors and future conditions. Hence provide a platform for determining resilient geotechnical solutions.

The 'Design' stages are discussed in detail in the Chapter 4 along with the development of the Resilience Assessment Framework. The methodology used for developing the framework is cross impact analysis which is explained in section 3.5.3.

3.7.5. TEST

At the end of each design phase, the research output once developed was initially tested referred as ‘alpha tests’ both in industry and with university supervisors. It is considered essential, to undertake this alpha test while producing the framework, in order to ensure that even in its design phase it is robust, applicable and understandable by fraternity from both industry and academia.

Geotechnical engineers, hydro-geologists and geologists were consulted to obtain their feedback on the outputs in the form of informal discussion. Geotechnical advisor to Highway Agency was also consulted to understand the implications of such a tool and its use in the overall strategic decision making for highways asset management. Their questions, ideas and suggestions were incorporated into producing the draft tool which was later validated in the next iteration. The methodology on the testing and validation is provided in 3.5.6. The copy of the questionnaire and the recorded feedback is provided in Appendix A.

3.7.6. ITERATION

Within each design phase, there were multiple iterations, which came about from the authors’ refined working knowledge of and feedback from application of the framework and its components during alpha testing. It was considered essential to record these iterations in order to present the development steps of the research and to determine what worked (or not) and why. This iteration stage allowed for adequate interim validation and a 360 degree review developing a more robust methodological technique that became more streamlined as non-relevant aspects were ruled out.

3.7.7. BUILD

This stage includes the actual building of the framework (i.e. flowcharts, diagrams, excel spreadsheets etc.) into a more finished ‘polished’ product. As such this stage also included drafting a manual, which will take the user(s) through the process of using the proposed framework as a decision support tool in the final validation stage.

3.7.8. VALIDATE

Validation stage is considered necessary to ensure that the proposed designed framework was workable as an overall concept and practicable for application in industry as a decision support tool. This was undertaken with the help of case studies, industrial workshops, feedback and a range of stakeholder interviews, which included geotechnical engineers, hydro-geologists and geologists and geotechnical advisor. In addition, The Highways Agency (known as Highways England since April 2015) was consulted to obtain their feedback (akin to beta testing) on the built version of the framework. The copies of the questionnaire with the feedback are provided in Appendix B. It was also considered important to present the tool to the participants with an accompanying manual of instructions of the working of the tool with examples. The copy of the manual is attached in the Appendix B.

3.7.9. FEEDBACK

Feedback from the validation stage was recorded and incorporated within the framework.

3.7.10. DELIVER/OUTPUT

Delivery/output incorporates finishing the proposed resilient geotechnical asset management framework and associated manual (for use by industry and academics at the University of Birmingham).

Further work and development can be undertaken e.g., making it a web based tool or for future work and/or adapt this for other types of infrastructure assets. These are beyond the current outputs.

The primary output of the research will be a PhD dissertation for part fulfilment of the PhD.

3.8. Summary

In summary, this chapter looked at the overarching research philosophy i.e. the 'Futures Research' along with the research methodology adopted in developing the resilience assessment framework which include literature review, concept mapping and cross impact analysis. The chapter presented the boundaries of the research and its' fundamental elements.

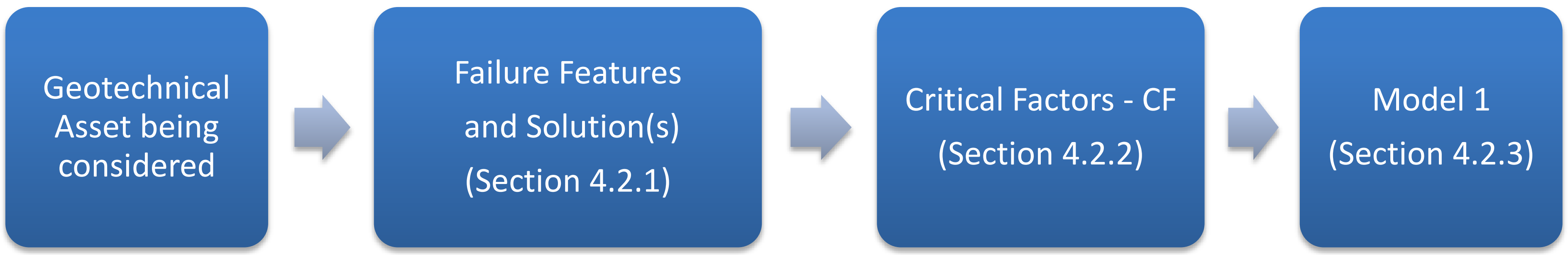
The chapter discusses the step-by-step method of developing the tool using the concept of 'Agile' technique including the associated iterations. The chapter highlights the pros and cons of various research techniques and provides a justification for selecting suitable research techniques such as use of multiple criteria decision analysis using group ranking techniques like 'pair wise comparison' for assigning weightages to the future conditions. It also throws light on the methodology of undertaking validation of the tool such as involvement of experts in a workshop based setting and using the appropriate sample type and sample size in validation of the proposed research.

In the next chapter the detailed design and development of the resilience assessment framework is discussed in further detail.

DESIGN PHASE METHODOLOGY

DESIGN PHASE A - ITERATIONS	DESIGN PHASE B - ITERATIONS	DESIGN PHASE C - ITERATIONS
Design Phase A – Critical Factors (CF) • Types of Geotechnical Assets • Critical Factors affecting stability and performance of geotechnical assets - Internal (triggered) - External (triggering)	**Design Phase B – Future Conditions (FC)** • Drivers of change characterising the future conditions derived from Future Scenarios study • Inter-relationship of FC with CF	**Design Phase C – Resilience Assessment Tool** • Resilience assessment framework to assess the resilience of geotechnical solutions • In the form of a scoring matrix
ITERATION 1 • Table of External and Internal Critical Factors (CF) – interrelation ship represented using arrow heads => complex, unclear and difficult to follow **ITERATION 2** • Spider web diagram – internal factors radiating out from corresponding external factor => inter-relationship difficult to represent, multiple diagrams and complex **ITERATION 3** • Rose diagram – 3 concentric circles with external, internal and geotechincal assets failure features with inter-relationship represented by failure lines => too many permutations and combinations making it complex and difficult to read **ITERATION 4 (successful)** • Rose diagram – Same as iteration 3 with inter-relationship represented by nomenclatures (E1, E2,.....En; I1, I2... In). Establish failure hypothesis using failure paths (En + In -> Fn) and use of RAG colours to establish hierarchy of failure paths => Simple to follow, allows development of failure hypotheses and establish hierarchy. Data feeds into the framework.	**ITERATION 1** • Extension of Design Phase A Rose diagram – additional tier showing Future Conditions (FC) => Interrelationship between CF and FC difficult to represent in one single diagram **ITERATION 2 (successful)** • Rose Diagram 2 – 2 concentric circles showing inter-relationship between FC and CF. Colour coding for each FC => Easy to follow, logical extension of thought and creates data input for framework (i.e. defining default settings for the framework).	Matrix of FC and CF – establishing inter-relationships between FC and CF as default settings from Design Phase 2 Rose Diagram 2 using the same colour codes => Easy to understand and clear to represent **ASSESSMENT FOR SOLUTIONS ITERATIONS** **ITERATION 1** • Use of Traffic Light colours – Use of RAG => Simple and easy but doeas not allow prioritisation/hierarchy of FC as per stakeholders requirements. **ITERATION 2** • Use of scoring between -3 to +3 with priority ranking to FC – gives an absolute resilience score (sum product of FC rank and solutions score for each CF) => unable to provide equal priority to different FC if required. **ITERATION 3 (successful but Draft)** • Use of scoring between -3 to +3 with weightage to FC and scoring to CF – gives a resilience score out of 100 => project specific score but can be compared across like-for-like projects. Allows FCs to have equal weightage if required.

Figure 4.1: Detailed Design Phase Methodology



.Figure 4.2: Methodology for developing Model 1

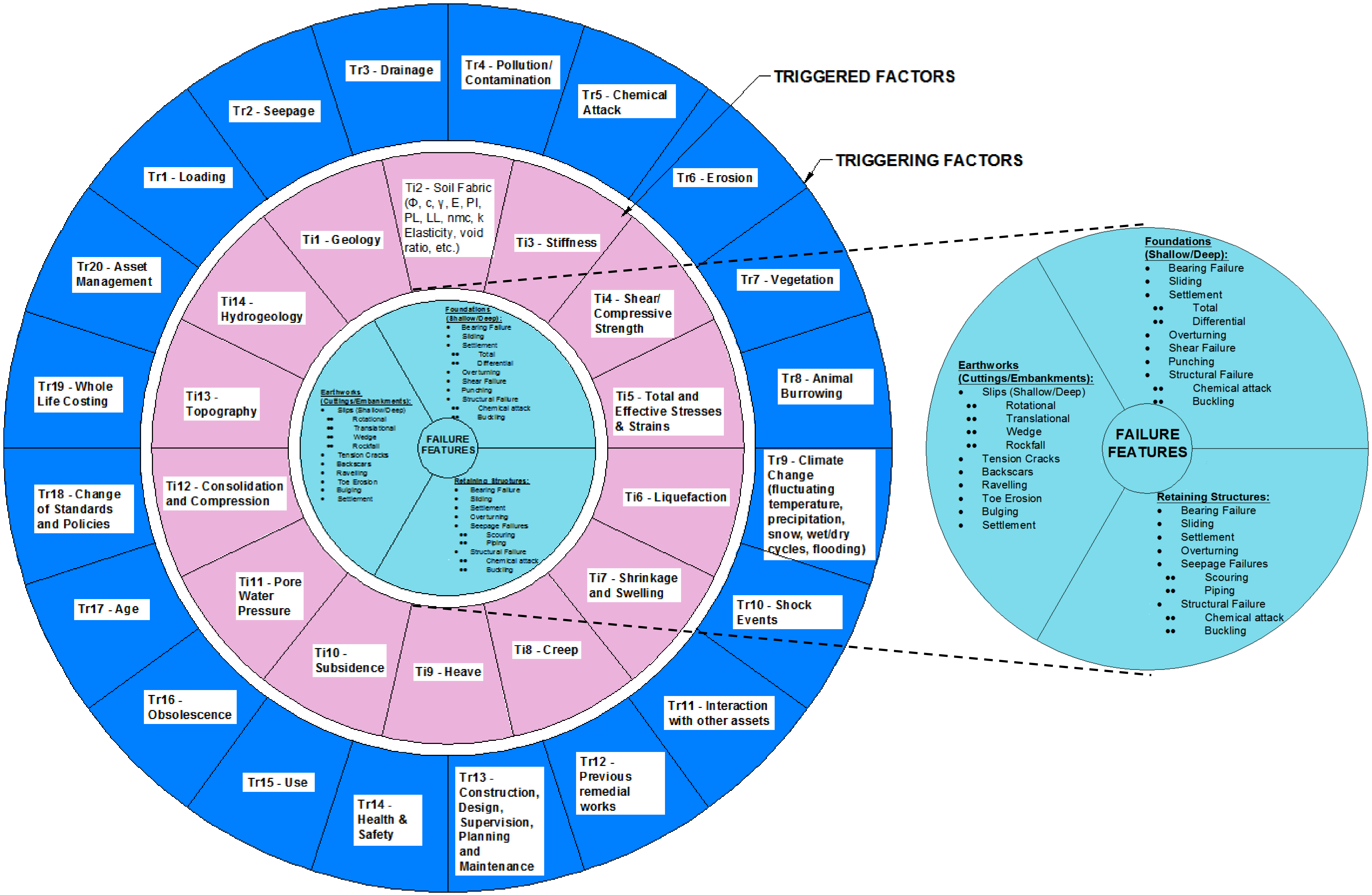


Figure 4.3: Model 1 – Rose Diagram showing the inter-relationship critical factors affecting the performance of geotechnical assets on the transportation network.

4. Detailed Design and Development of Resilience Assessment Framework

4.1. Introduction

This chapter discusses the design and build stages of the Resilience Assessment Framework. As such it provides a detailed description of Design Phases A, B and C (Section 4.2 to 4.4 respectively), and highlights the various iterations undertaken therein. Figure 18 shows the detailed design phase methodology and the various iterations that were undertaken to achieve the final version.

4.2. Design Phase A

This phase of the methodology defines the geotechnical assets being considered and determines the failure features, potential remediation solutions as shown in table 4.1 (Section 4.2.1) and influencing critical factors affecting them (Section 4.2.2). The output of this stage is in the form of Table 4.2 which identifies the critical factors affecting the performance of geotechnical assets. Section 4.2.2 provides the literature supporting Table 4.2.

Based on the inter-relationship between these critical factors (identified in Table 4.2) they have further been classified into triggering and triggered factors depending on how they influence the performance of geotechnical assets. This is discussed using examples in Section 4.2.3 and shown in Figure 4.4. Using this inter-relationship between the critical factors, Model 1 is developed which aids in deriving a failure hypothesis for geotechnical assets by determining the most critical failure path. The methodology underpinning this is shown in Figure 4.2. Model 1 (Figure 4.3) a rose diagram comprising of three concentric circles (one inner blue ring for geotechnical asset and typical failure features and two outer rings for triggering and triggered factors). This and its derivation and is explained in further detail in Section 4.2.4.

4.2.1. Failure Features - and Remediation Solutions

Table 4.1 lists the typical failure features and common remediation solutions for typical geotechnical assets considered within this study (industrial experience and Glendinning et al., 2009).

Table 4.1: Typical Geotechnical Assets Failure features and Remediation Solutions

Geotechnical Asset	Failure Features	Common Remediation Solution
Earthworks Cutting/ Embankment	Slips • Shallow/Deep • Rotational • Translational • Rockfall • Wedge Failure Tension Cracks Backscars Ravelling Toe Erosion Bulging Settlement	• Granular replacement • Lime and Cement Stabilised Fill • Reinforced Soil • Re-grading or Toe Berms • Soil Anchors and Soil Nailing • Rock Anchors and Rock Bolts • Catch Fences • Electro-osmosis • Improving the Drainage using Counterfort or herring bone type drains • Top soiling and Vegetation • Hand scaling of loose fragments of weathered rock slope and shortcreting on the face of the slope
Foundation (Shallow and Deep)	Bearing Failure Sliding Overturning Settlement • Total • Differential Shear Failure Punching Failure Structural Failure • Chemical Attack • Buckling	• Ground Improvement • Repair and Retrofitting Foundation • Injection Grouting to improve the bearing capacity of soil supporting the foundations.
Retaining Structures	Bearing Failure Sliding Overturning Seepage Failure • Scouring • Piping Settlement Structural Failure • Chemical Attack • Buckling	• Grouting the voids • Remove and Replace the weak supporting Material. • Soil improvement • Ground Anchors and Angled Piles and tied walls • Concrete Retaining Wall or Gabion Walls. • Bored or Mini Pile Retaining walls • Sheet Pile walls • Structural Repairs to the Retaining Wall structure.

4.2.2. Critical Factors

The second part of this design phase is to identify critical factors which affect the performance, serviceability, stability and safety of the use of geotechnical assets on highways. These are determined according to reference with the literature and the author’s industrial experience. They are described in detail below.

4.2.2.1 Geology and Ground Conditions

Dijkstra and Dixon (2010) and Perry et al., (1995), suggest that excessive deformation of slopes are largely interdependent on a multiple elements which can be grouped into material properties, site specific conditions including geology and topography, hydrogeology and vegetation cover and environment surrounding the geotechnical asset which include climate change, changes in use of the network etc. Pantelidis (2009) highlights that though risk assessment strategies have developed over the last decades; there is a lack of emphasis on geology, geomorphology and climate change which triggers slope failures to a considerable extent. For example the rise in precipitation results in increase in ground water level and excessive pore water pressure which influences the stress condition in the slope and affects its stability.

Leroueil (2001) categorises slope failures into pre-failure, onset of failure, post failure and reactivation of failure. The author suggests that though geology plays a vital role in slope stability, understanding of soil structure interaction and mechanical responses to loading and changes in geometry, boundary conditions, strength parameters and pore water pressure with time is equally essential. Thus slope stability is best understood by a joint effort of geologists, geomorphologist and hydro geologists. Ridley et al. (2004) states that a key aspect in determining the condition of the asset is the pore water pressure.

4.2.2.2 Asset Interaction

Asset interaction is the interface between different assets on the transportation network and how they behave together. For example, interaction of drains (drainage assets) within the slopes (geotechnical assets). If the drains case to function smoothly due to blockage or any other cause, it may result in leakage of water in the slope and this may affect the serviceability of the slope due to change in stresses on account of an increase in the pore water pressure. Bernhardt et al., (2003) highlights that geotechnical assets are often considered supporting assets that interact with primary assets such as pavements, bridges etc. on a transportation network. Transportation agencies therefore do not have direct goals of maintaining the geotechnical assets, these often arise out of maintaining the performance objectives of other ‘primary assets’. Hence, geotechnical asset management should offer integrated approach and include interaction with other assets as a progressive step in development of such systems.

4.2.2.3 Topography

Anderson and Kneale (1982) suggest that the slope topography plays a vital role in understanding soil moisture interaction and how the slope angle and height can influence the movement of water and catchment properties of the area surrounding the asset.

4.2.2.4 Effects of Climate Change and Precipitation and Fluctuating Temperatures

Clarke et al., (2010) also throw light on a very significant issue concerning the fact that the highways geotechnical infrastructure is designed for a minimum of 120 years; the construction industry however should account for climate change and associated uncertainties and its implications on the design. The author suggests if this element is not taken into consideration then this might result in increased maintenance costs, contractual liabilities and a lack of robustly operating infrastructure along with dampened reputation of transportation network owners and managers. This argument is supported by Wilks (2010) who suggests that the UK transportation network is definitely going to be affected by changing climate and one way of mitigating the associated risks is to forecast the behaviour of slopes under the influence of changing climatic conditions, which will then enable development of maintenance and management strategies. Clarke et al., (2006) highlight the rising concern related to the long term stability of the slopes which are subjected to fluctuating temperatures and varying weather conditions resulting in increased and fluctuating pore water pressures in the slope which affects the stress condition. The authors refers to a study conducted by Perry et al. (2003) on UK motorway earthworks which estimates that if no preventive action is taken, then conservatively three times more slopes are likely to fail in the future than those failed till date, owing to changes in the climatic conditions. Loveridge (2010) highlights that extreme events on account of climate change can lead to catastrophic failures due to excessive movements as a result of increase in pore water pressure and/or decrease in strength of the soil. Kilsby (2009) highlights that hotter drier summers with wetter winters associated with intense rainfalls will have a significant impact on the integrity of embankments and cutting slopes. Clarke and Smethurst (2012) suggest that future warmer and drier summers along with wetter winters will result in large “soil moisture cycles” which will impact the serviceability and stability of a number of slopes on the transportation network.

4.2.2.5 Vegetation Cover and Animal Burrowing

Norris and Greenwood (2006) and Ridley (2004) highlight that while vegetation and use of bioengineered slopes provides aesthetical landscaping advantages along with reduces soil erosion and shallow landslides, the detrimental effects of vegetation resulting in extraction of moisture from the ground and causing shrinkage and swelling of cohesive soils and resulting in instability of earthworks. Burrowing by rabbits and badgers in earthworks, results in excessive voiding of the slopes which can undermine the serviceability of the structure (industrial knowledge). It also, provides access for water ingress affecting the stresses in slope material and resulting in instability of earthworks.

4.2.2.6 Age and History of the asset:

The history of the asset includes the age of the asset, type of construction, mechanism of construction and the material used (Glendinning et al., 2009, Anderson et al., 2012, Loveridge et al., 2012 and Ridley, 2004). Most of the infrastructure assets are over 50 years old on highways network and on railway network over 100 years old. Geotechnical assets such as embankment were built using locally sourced material not always of sound quality and performance characteristics. Inadequate quality control on construction and lack of adequate maintenance often results in serviceability issues related to current geotechnical assets. In railway many of the earthworks were built much before concepts of soil mechanics were developed and with time, the change in the condition of the material used to construct these earthworks and their deformation has affected the long term performance of geotechnical assets (Ridley, 2004). Presence of historic coal mines explored during industrial era, in the vicinity result in presence of shafts (which may or may not have been sealed) which can result in subsidence or even failure of the asset. Hence knowing the asset history is of paramount importance in order to develop a hypothesis of its performance behaviour.

4.2.2.7 Construction, Design, Planning and Maintenance

Gue and Tan (2004) investigated 55 cases of geotechnical assets built on soft ground of which 50% failed largely due to inadequacy of design and 15% due to poor construction, workmanship and lack of adequate supervision. The authors highlight that the key factors are proper planning, design and construction along with vigilant supervision and the lack of appreciation of the ground and soil properties and inadequate checks on design models accounting for various permutation and combinations of failures play a significant role in triggering geotechnical failures. Wilks (2010) argues that while maintenance, inspection, evaluation and assessment processes emergency and such other reactive works are necessary, allocation of resources for proactive planned and preventative measures is equally important. Marr (2001), advocates the advantages of instrumentation and monitoring geotechnical assets that warns of forthcoming failure and minimises damage to adjacent structures. Marr (2001) highlighted that adequate and timely monitoring not only helps in keeping a control over construction and operation activities but also provides information on selecting appropriate remedial methods. Beena (2011) emphasised that the use of adequate and accurate database of geotechnical assets, adequate monitoring and instrumentation and knowledge of the drainage and seepage forces are essential in the upkeep of geotechnical assets. In addition to this, sound design standards, methods and specifications have a significant effect on the safety and serviceability of geotechnical assets.

4.2.2.8 Use of the asset

Holland (1998) highlights the problems related to the canal earth structures which he suggests are related to the fact that these were predominantly built in late 18th and early 19th century, long before the principles of soil mechanics were well developed. Their problems are relating to its function of retaining water, its history and geological setting, usage and interactions with other structures. The author suggests that many canals were originally built at ground level and were affected by adjacent development or subsidence due to adjacent mining operation and as a result they were progressively raised to counter the effects of subsidence. Variability of fill materials and mining waste underneath gave rise to potential leaks releasing acidic water, poor vegetation and collapsing bank protection. This results in saturation of embankments, loss of strength, consolidation and failure. The author therefore highlights problems associated to material variation in construction, construction age, homogeneity, and lack of adequate compaction during construction due to method of construction, height of the structure, extent of vegetation, location and interaction with other structures in the vicinity.

4.2.2.9 Whole Life costing of Geotechnical Solutions

Whole Life Costing of projects and solutions is one of the important factors, which will affect and influence the choice of geotechnical solution. Whole life costing of assets and the maintenance/upgrade/remedial solution has become an important element of feasibility studies highlighting the significance of costs.

Table 5 shows the aforementioned critical factors which are likely to affect the performance of geotechnical assets and rendering them unserviceable. For simplification and ease of understanding, the factors are broadly categorised into the Geology, Asset interaction, Topography, Environmental, Hydrogeology and History abbreviated to "GATE2H" factors. The subcategories identified in Table 4.2 provides the basis for Figure 4.3 (Model 1).

Table 4.2: Critical Factors affecting Geotechnical Assets on Transportation Network

Classification	Description	Subcategories
Geology and Ground Conditions (See 4.2.2.1)	This comprises of the ground conditions of the asset the geology of the area, soil properties, presence of faults and weak planes etc.	**Geology** • Solid Drift Deposits • Landfill Materials • Artificial ground • Geological Features • Ground Conditions **Soil Type** • Soil Fabric Properties like Angle of internal friction, cohesion, Young's Modulus, Strength (Compressive and Shear) and Stresses (Effective and Total), Poison's Ratio etc. • Soil Properties like Shrinkage Swelling, Liquefaction etc.
Asset Interaction (See 4.2.2.2)	This comprises of the interaction with other assets such as drainage, pavement, utilities present in the vicinity.	• Pavement • Drainage • Structure • Adjacent Landowners • Foundations • Soil Mechanics

Table 4.2: Critical Factors affecting Geotechnical Assets on Transportation Network		
Classification	**Description**	**Subcategories**
Topography (See 4.2.2.3)	This includes the features such as slope angle, gradient etc.	• Slope Angle • Slope height • Length of the Asset • Contours • Vegetation • Offset from verge, hard shoulder, highways/ railway boundary.
Environmental (See 4.2.2.4 and 4.2.2.5)	This includes factors like climate change resulting in extreme weathers, frequently fluctuating temperature, rising ground water levels, increased precipitation, flooding etc. vegetation, animal burrowing etc.	• Climate Change factors like excessive precipitation, increased temperature levels, fluctuating weather. • Rising groundwater levels • Vegetation • Animal Burrowing
Hydrogeology (see 4.2.2.1)	This includes ground water levels, presence of aquifers and water courses adjacent to the asset.	• Ground Water levels • Pore water pressure • Presence of Aquifers and • Watercourses adjacent to the site • Seasonal Moisture Changes
History (See 4.2.2.6, 4.2.2.7, 4.2.2.8 and 4.2.2.9)	This includes the history of the asset like the age, construction, design and supervision details, historic evidence of mining, old as built records suggesting nature and type of development in the vicinity of the asset through time. Records of historic activities that may have resulted in contamination of the site. Sensitivity of the site location.	**Early Planning, Design and Construction Stage** • Inadequate knowledge of the geotechnical design parameters of the site • Lack of robust design • Incompetent and inadequate supervision on site during construction • Poor quality materials, labour and construction negligence. • Changes since construction **Maintenance and Operation Stage** • Lack of adequate maintenance • Lack of funds • Inadequate risk mitigation and risk measurement and hazard identification • Out of date Risk assessment • Lack of inventory • Lack of sound, adequate, accurate data base • Whole Life Costing, Risk Management and Asset Management Strategies • Silo Organisation structure for maintenance of different asset base on the network. **Changing Patterns of use** • Loading • Multi-functionality • Over Use • Age • Obsolescence • Change in Standard provision • Historic records of mining • Development of the site. • Contamination History • Sensitive Area- Site of Special Scientific interest. Special Cultural Importance and Heritage Site

4.2.3. Inter-relationship between critical factors

While deriving these critical factors, the researcher could inter-relate and categorise the factors in two broad classifications ‘External’ and ‘Internal’. The external factors incorporate those elements which surround the geotechnical asset in the external physical environment and singularly or in conjunction with the others, affect the integrity of the geotechnical asset. The internal factors incorporate those elements which represent soil properties or phenomenon within the soil system itself and which when triggered ultimately mobilises the physical failure. The external factors are the triggering points that affect one or more of the internal factors (triggered points) affecting the performance, serviceability and ultimately leading to the partial or complete physical failure of the geotechnical asset. Hence these factors can also be classified as ‘Triggering’ factors and ‘Triggered’ factors respectively (Figure 4.4). The term ‘failure’ represents the physical failure of the assets making it unusable and unserviceable on the transportation network.

Figure 4.4: List of Triggering and Triggered factors affecting the performance of geotechnical assets

To better understand the inter-relationship between these factors and the performance of geotechnical assets a few typical examples are described below.

Example One

Asset: Earthwork – Embankment

Failure Features - Erosion at the toe due to running watercourse undermining the stability of the slope

Features of Failure: Shallow Slips showing backscar and tension cracks on the crest of the slope

Factors: Erosion at the toe, Seepage and topography to some extent.

Remediation: Provision of Sheet Pile Wall at the toe of embankment

Example Two:

Asset: Cutting

Type of Failure: Shallow slips

Failure Features: Slip material bulging at the toe approaching the hard shoulder increasing risk of accidents on carriageway. Additional features include backscar, leaning trees and leaning lighting columns.

Factors: Hard shoulder at the toe used as an active traffic lane on the peak hours of the day, as a result increase in loading, drainage from adjacent farmlands at the crest of the slope seeping into the slope due to lack of efficient drainage or failed drainage, increased slope angle and height of slope.

Remediation: Re-grade and refill with stronger engineered fill to replace the failed material, improve and install new slope drains.

Example Three

Asset: Embankment

Type of Failure: No Failure, however installation of new safety barrier to revised standards requiring additional setback from carriageway. Due to inadequate verge at the crest of the slope the installation of safety barrier requires verge widening. Or installation of an additional lane and/or increased verge.

Failure Features: None.

Factors: increased verge widening requires additional room at the toe and interaction with other assets like lighting columns and existing drainage in the slope.

Remediation: Increased verge using engineered fills at appropriate slope gradients, removal and installation of lighting columns, traffic signs if necessary and alteration of existing drainage.

4.2.4. Model 1

Model 1 is a well-structured rose diagram (consisting of three concentric circles). A snapshot of the Model 1 is shown in Figure 4.4. The triggering factors (Tr1 - Tr 20) and triggered factors (Ti1- Ti14) shown in Figure 4.4 are represented in a clockwise manner in the outermost circle and intermediate circle respectively of the Model 1. Finally the innermost circle is divided into three sections that represent the following assets and typical failure features which is derived from Table 4.1:

- Embankments and Cuttings;
- Retaining Structures
- Foundations

The aim of this diagram is to facilitate in generating the failure hypothesis of a geotechnical asset, based on the interrelation between the aforementioned critical factors. This is undertaken by demonstrating the correlation between the triggering (external) and triggered (internal) factors to highlight the most likely failure path. For example: the model leads the user to go from the outer circle (e.g. climate change) through the middle circle (e.g. pore water pressure changes) and to the central circle (e.g. asset failure). A hypothesis is laid out establishing the critical factors that led to the asset failure.

Although there is considerable literature related to this process much of this is currently being done based on experience and sound technical knowledge and historic geotechnical records.

4.2.5. Critical Factors embodied in Resilient Assessment Framework

In order to keep the matrix succinct the 20 triggering factors are consolidated into 14 critical factors to be incorporated in the assessment framework. This is shown in table 4.3. The triggering factors ‘Pollution / Contamination’ (Tr4) and ‘Chemical Attack’ (Tr5) are grouped together as critical factor ‘Effect of Pollution and Contamination’ (CF 4), as the response of a geotechnical solution to both these factors will be of a similar nature. Similarly a geotechnical solution can offer biodiversity by allowing for vegetation growth and animal burrowing. Hence the triggering factors ‘Vegetation’ (Tr7) and ‘Animal Burrowing’ (Tr8) are grouped into the critical factor ‘Maintaining Bio-diversity’ (CF 6). Historical remedial works carried out either on the geotechnical asset or the surrounding assets can be in the form physical changes for e.g. addition of drains in the slope or construction of a retaining wall. The response of the proposed solution to these remedial works will not be dissimilar to any other assets in the vicinity and hence ‘Interaction with other assets’ (Tr11) and ‘Previous remedial works’ (Tr12) are grouped together to be critical factor ‘Flexibility of interaction with other assets’ (CF 8). Similarly, the other groupings have been undertaken following a similar reasoning and approach as seen in Table 4.3 below.

Table 4.3: Critical Factors embodied within the Resilience Assessment Framework			
Triggering Factors		**Critical Factors considered in Resilience Assessment Framework**	
Tr 1	Loading	CF 1	Flexibility to allow loading variation
Tr 2	Seepage	CF 2	Seepage Characteristics
Tr 3	Drainage	CF 3	Effect on Drainage
Tr 4	Pollution/Contamination	CF 4	Effect of Pollution/ Contamination

Table 4.3: Critical Factors embodied within the Resilience Assessment Framework

Triggering Factors		Critical Factors considered in Resilience Assessment Framework	
Tr 5	Chemical Attack		
Tr 6	Erosion	CF 5	Impact of Erosion
Tr 7	Vegetation	CF 6	Maintaining Bio-diversity
Tr 8	Animal Burrowing		
Tr 9	Climate Change	CF 7	Response to Extreme Climatic Conditions
Tr 10	Shock Events		
Tr 11	Interaction with other Assets	CF 8	Flexibility for Interaction with other Assets
Tr 12	Previous Remedial Works		
Tr 13	Construction, Design, Supervision, Planning and Maintenance	CF 9	Ease of Maintenance and Operation
Tr 14	Health and Safety	CF 10	Health and Safety Consideration
Tr 15	Use	CF 11	Flexibility of Use/Multi-functionality
Tr 16	Obsolescence	CF 12	Obsolescence/ Ease of Disposal
TR 17	Age		
Tr 18	Change of Standards and policies	CF 13	Change in Standards and Policies
Tr 19	Whole Life Costing	CF 14	Whole Life Costing
Tr 20	Asset Management	Not Considered	

4.3. Design Phase B

Design Phase B is focussed on future conditions and establishing its relationship with the critical factors affecting the geotechnical assets, as derived in Design Phase A.

This phase comprised of reviewing existing literature on future scenarios in order to establish future conditions that might influence/impact upon geotechnical assets within UK transportation networks. These were analysed using cross-impact analysis and concept mapping techniques as described in Chapter 3 earlier. This included looking at the recent work of the Urban Futures project (Boyko et al., 2012), literature relating to the key drivers of change by Hunt et al. (2012) and resilience of local infrastructure by Rogers et al., (2011). In addition it looked at works published by UK governments'

'Foresight' Programme, HM treasury Cabinet Office (Office, 2011) and Association of Directors for environment, economy, planning and transport (ADEPT, 2008-2009), strategic documents from Department of Transport (DfT, 2010 and DfT, 2013), The Highways Agency (2011) and Network Rail (2012) on the future of road and rail network.

4.3.1. Derived Future Conditions

Rogers et al., (2011) highlights that the physical infrastructure is faced with challenges which includes increasing and ever-changing demands, deterioration through ageing assets and adverse ground conditions, effects of climate change, effects of population increase, funding constraints and severe natural hazards. Hence in order to make infrastructure resilient it needs to account for these changing conditions by developing a better approach of planning, designing, building, maintaining, adapting and valuing physical infrastructure (Rogers et al., 2011).

Derived Future Conditions: Based on these conditions, Rogers et al., (2011) suggest resilience factors for infrastructure which include ecological, economic, community/social and government systems.

The urban futures methodology suggests asking the question "will today's sustainability solutions deliver their intended benefits, whatever the future brings". The study had a similar objective of focussing on the likely long term performance of today's sustainability solutions throughout their intended life span irrespective of changing future conditions. The scenarios for the study are set in year 2050 (as it aligned with UK's carbon emissions reduction targets set for year 2050 along with a 40 year regeneration cycle typically used for planning investment and development proposals). The future conditions considered in this study include social, technology, economy and policies which are commonly used in scenario analysis (Boyko et al., 2012).

Derived Future Conditions: The indicator themes within these futures considered are demographics, economy, transportation, governance, planning/land use, society, air quality, urban form and energy water and housing.

The Highways Agency (2011) highlights the broader uncertainties that face the transportation network in addition to uncertainties relating to climate change by developing scenarios for addressing these uncertainties and determining its impact on the network (The Highways Agency, 2011). PESTLE (political, economic, social, legal, technological and environmental) method of analysis is used for enabling scenario planning which allows giving a bird's eye view of the environment the infrastructure is operating. The report supported by Department for Transport (DfT) suggests increasing the resilience planning to account for adapting to financial uncertainties which can cater for long term needs such as longer than 60 years. In addition, greater uncertainty exists over future transport and road user demand (including greater GDP growth, changes in the fuel prices and vehicle efficiency) over the long term. The report highlights that there is limited information on the impact of weather on road user behaviour and its impact on the use of the network. Other factors include public awareness and interdependences between assets and infrastructure types.

> *Derived Future Conditions: the report includes factors such as climate change, financial uncertainties, future transport, road user demand, changes in fuel price and vehicle efficiency.*

Network Rail's report 'Our Railways Future' (2012) highlights that scenario planning provides "plausible" and "challenging narratives" about the future which provide a representation of the "possible future pathways". The report considers the future of rail in year 2025. The report includes future uncertainties such as government transport policy, energy availability, climate change policy, new technology and innovation, patterns of work, urbanisation patterns, and customer service expectation.

> *Derived Future Conditions:* the report includes *future uncertainties such as government transport policy, energy availability, climate change policy, new technology and innovation, patterns of work, urbanisation patterns, and customer service expectation.*

Glasgow and the Clyde Valley Strategic Development Planning Authority (GCVSDPA Futures Group, 2009) published a report conducing STEEP analysis for demonstrating how 'futures thinking' can identify and shape the strategic thinking for local development in the region. The purpose of STEEP (Sociological, Technological, Economic, Environmental and Political change drivers) analysis is to review the conceptual environment to characterise the operating drivers of change and consider what (if any) effect they might have on future design, maintenance and operation of infrastructure. The report includes the factors relating to changing driver such as Sociological (includes population, wealth, happiness, wellbeing and size and mix of population), Technological (includes connectivity, technological advances, low carbon technologies, smart use of technology and energy), Economic (responsiveness to economic agility, globalisation, localisation, resources and economic competitiveness), Environmental (sustainability, climate change, resource mix, and land management demand) and political (level of public demand and accountability, political change and state/private sector balance). A similar publication by Arup (2006) also uses the STEEP methodology to address the key drivers of change of energy and access to energy, demographics, urbanisation, climate change for the future. The indicators used for these drivers of change are Social (Education, Aging, Community and social structure), Technology (globalisation, new economic energy, resource depletion), Economic (Shortage of energy, pensions, wealth distribution, geographic location of resources and energy), Environmental (Transport supply chain, aging infrastructure, sustainable infrastructure and global warming) and political (definition of UK role/ vision and political agendas over energy and other resources).

> *Derived Future Conditions:* the report suggests Sociological, Technological, Economic, Environmental and *Political (STEEP) factors covering various indicators*

The Institution of Civil Engineers State of the Nation Report (2009) addresses the UK infrastructure's vulnerability to changing future threats which include system failure, climate change and terrorism and suggest long term policies should address these conditions and build reserve capacities to protect from threats.

> *Derived Future Conditions:* the report highlights *system failure, climate change and terrorism*

A publication by Arup by Goulding et al., (2014) highlights the forces that drive the change for the future of highways which include ‘megatrends’ of increased urbanisation, technology and connectivity, growing and ageing population and changing behaviour, changing weather patterns, smart and integrated mobility (technology), energy and resources.

Derived Future Conditions: the megatrends of the future highlighted are changing demographics (including urbanisation) and behaviour, technological advances, changing weather and energy and resources.

4.3.2. Future Conditions

Based on the aforementioned literature and background study, the following set of future conditions (and associated indicators) that are applicable to a timescale of 35 years (i.e. 2050) were derived. These are necessary in order to consider the applicability of geotechnical solutions in a much changed future, perhaps significantly different from what we know now. In the first column of Table 4.4 a list of Future Conditions (FC) considered within this research is provided. The second column lists the indicators that characterise these corresponding Future Conditions. Finally, the last column describes the likely impacts of these Future Conditions on geotechnical assets. [Hence this achieves objective 3 of the research as mentioned in Chapter 1.]

Table 4.4: Future Conditions and their Effects on Geotechnical Assets

Future Conditions – FC	Indicators	Impact on geotechnical assets
Demographics	Population	Increased demand and use of transportation assets. Hence increased pressure and deterioration of geotechnical assets. Growing demands requiring development of new roads, strategic network connections between major cities, change of use of existing infrastructure requiring verge widening, use of hard shoulders as live lanes, use of underground space etc.
	Density	
	Urbanisation	
	Globalisation	
Environmental	Climate Change	Increased environmental uncertainties and fluctuations may lead to detrimental effects on the stability of geotechnical assets
	Pollution/Contamination	
	Biodiversity	
	Waste generation	
	Conservation of heritage and sensitive site	
	Recycling	
	soil condition	
Social	Standard of living	

Table 4.4: Future Conditions and their Effects on Geotechnical Assets		
Future Conditions – FC	**Indicators**	**Impact on geotechnical assets**
	User pattern/Behaviour Health Safety Welfare Accessibility and reliability	Safe and convenient transportation networks require regular maintenance of transportation assets, systematic and organized framework for management and improved level of service
Economics	Value for money/Return on Investment (UK and International) Whole Life cycle cost (Asset value or Replacement Value including Inflation) Socio-economic benefit ratio	More budgets and economic freedom will mean more maintenance funds available for regular on-going monitoring and upkeep thereby reducing the whole life cycle cost. budgets affecting the types of remedial solutions proposed for geotechnical problems
Governance	Long-term and short-term policies Political stability	Policy affecting funding influencing all of the above characteristics
Technology/ Innovation	Multi-functionality Technology	higher innovation and technological advancements may require upgrading the existing geotechnical asset condition
Shock Events		
Man-made threats	Terrorism/Revolution Negligence E.g. Oil Leaks	Will affect the stability, serviceability and integrity of the geotechnical assets
Natural threats	Flooding glacial melt Tsunamis/flooding Snow extreme weather conditions hurricanes and earthquakes	

Based on this information, the framework enables decision makers to think along the lines of the aforementioned factors and provides a methodological approach for consideration of future conditions for undertaking resilience assessment. The detailed description of the Future Conditions and their impact on the infrastructure is discussed below with the use of examples throughout.

Demographics

Change in demographics could be attributed to: a change in population, density of an area, urbanisation patterns and an overall impact of globalisation that has an effect on the trade and migration patterns (Goulding et al., 2012, Rogers et al. 2011 and Hunt et al., 2012). Changes in demography have a direct influence on the infrastructure network and in particular the use of transportation networks (Network Rail, 2013 and DfT, 2013). Transportation assets are likely to be affected by usage, need and level of service expected.

Example 1: Imagine a strategic network of road(s) connecting a city with foreseen increasing density. Hence, the road will be required to meet increased demands of traffic which puts additional pressure on the network. This in turn triggers a change in use of assets, resulting in an increased demand for multi-functionality and also increases the need for efficient interaction between different assets on the network.

Example 2: A decreased use of the network occurs due to emigration, poor economic conditions and / or susceptibility to environmental hazards such as floods etc. Hence, the solutions devised today may be over engineered for the needs of the future.

Environment

Environmental change accounts for increased effects of climate change such as increased precipitation, extreme weather conditions such as drier summers and wetter winters (Kilsby, 2009 and The Highways Agency Climate Change and Risk Assessment, 2011). It also accounts for the need of adopting sustainable practices, use of renewable energy and prudent use of resources. Protecting the biodiversity and maintaining the balance of the ecosystem is also an integral part of this future condition. The infrastructure network is vulnerable to such events both in the present and the effects are likely to continue in the future. The solutions provided today should be able to meet the needs of increased environmental impacts in the future. For example: Use of recycled materials, reduced waste generation, and conservation of special interest sites require special attention.

Example 1: An increased sensitivity towards the environment is a growing trend. Encouragement to employ techniques with reduced carbon emissions such as use of LED lights on transportation network are examples where environmental consideration are in the forefront (http://birminghamnewsroom.com/city-is-shining-thanks-to-10000-eco-friendly-leds/). Hence, environmental sustainability assessment of Asset/Solution may be considered in the future. The construction, maintenance and disposal i.e. whole life cycle of the asset and solution may be encouraged in order to ensure reduced carbon footprint and better environmental credentials.

Example 2: Imagine an area of special scientific interest (SSSI), where transportation asset management solutions will require special attention. Here, special attention needs to be given in areas which are prone environmental impacts such as extreme flooding or an area of special interest where conservation of heritage sites, biodiversity are of immense importance.

Example 3: With increased precipitation patterns, storm water drainage will require additional capacity to cater for increased load which in turn influences the transportation drainage and hence geotechnical assets such as slopes which support these drains. Consideration to the history of the area in terms of vulnerability and susceptibility to environmental events should be given.

Social

Change in Social attitudes towards the use of infrastructure and especially transportation network is the essence of this future condition (Climate Change Risk Assessment, UKCP09 and Goulding et al. 2014). The social interests could be influenced by factors such as the employability, education, health safety and welfare, biodiversity and reduced pollution in a specific region (Arup, 2006). There is higher connectivity of the network and ease of accessibility from one part to the other (Arup, 2006). The use of the transportation network is governed by the geographic areas it connects, thereby making connectivity, accessibility and reliability of the transportation network key to society. There is an increased need for safety and security with improved levels of service to meet customer expectations (Network Rail, 2012). The transportation network has to cater for these expectations and hence there should be room for increased need of multi-functionality.

Example 1: Change in social attitude towards use of cycling and/or other public transport would reduce the traffic congestion on the network which may result in change in the use of the network, hence the solutions may need to cater for changing demands and offer flexibility of use. Change in use could also mean certain solutions could be over-engineered. A key question, such as ‘Does the project/ transportation network have higher community and social stakes and interest?’ needs to be answered while considering this underlying future condition.

Example 2: Need for multi-functionality may increase due to development in an area, requiring consideration for built in spare capacity and room for installation of additional utilities and telecommunications cabling. Hence the solutions should be able to cater for flexibility to allow these changes to occur (perhaps a multi utility conduit that avoids digging up the roads, see Hunt et al. 2014). In this case the user will have to think along these lines in addition to ensuring that there is minimum disruption to traffic during the maintenance and operation services of the network.

Economics

Changing nature of funding dynamics is the key in this future condition (The Highways Agency, 2011). Economic elements such as the funding strategy, budgets (capital expenditure / operational expenditure) and its influence on the socio-economic credentials are considered. Elements such as responsiveness to economic change (agility) is considered important(GCVSDPA Futures Group, 2009) and is a sentiment that is envisaged to be carried forward especially on projects where the return on investment is long term such as PFIs or DBFOs on transportation network.

Example 1: Change in funding policies may affect the budgets for future maintenance requiring more robust solutions with less operational expenditure. Future discussions related to new policies suggesting privatisation of transportation network while keeping in mind the declining income streams needs to be accounted for. Consideration for future budgets on maintaining and operating transportation networks is crucial in this scenario. In this case the user should consider whether solutions provided today are fit for purpose and require less (or more) maintenance and operational costs.

Example 2: While the UK infrastructure is rapidly ageing and there is an increased need to provide an improved level of service with restricted budgets there are examples of economic agility required where government policies are emphasising on improving the socio-economic conditions of specific regions. Thereby, allocating additional funds for undertaking improvements works in such areas. For example, the contracts operated by Highways England , where a separate pool of resources is used to fund PPP (Pinch Point Programme) which aims to improve specific junctions on strategic motorway networks. This demonstrates the change in economic spending over the years. In this case the user should consider whether new trends such as the effect of global economy will influence local funding decisions (reference http://www.highways.gov.uk/our-road-network/managing-our-roads/improving-our-network/pinch-point-programme/ accessed, November 2014).

Governance

Political stability and security significantly govern policy making (GCVSDPA Futures Group, 2009). Various strategic policies and government legislations influence the funding decision for infrastructure asset management. Most of these strategies are short term to medium term almost dictated by the political turnover. However, resilience assessment aims to enable long-term decision making and hence drive long term strategic thinking. With regards to the Infrastructure network and transportation industry, The Pitt Review (HM Treasury Cabinet Office, 2010, Network Rail, 2011) and various other government strategic documents have outlined the need to embed resilience in to a decision making process (i.e. governance) for achieving a better and brighter Britain.

Example 1: With increasing demand for higher level of services and poor funding resources, policies are pushing towards obtaining results that provide 'more for less'. This drives the need for multi-functionality in the solution

Example 2: For example, speed limits on road networks, loading standards of special vehicles, set back distances in the verge behind safety barriers, design changes to suit adoption of Eurocodes 2007, landfill taxation to minimise pollution and contamination, etc. are some examples cited to show how government policies and regulations define various standards and practices of maintaining and managing transportation assets. The use and obsolescence of transportation network is also influenced by policy making. Health, safety and welfare is always at the forefront of any political decisions and influences changes in standards and policies time and again. This drives the need for catering to these factors in the proposed solutions.

Example 3: As government policies and regulations have improved health and safety, risk management and sustainability standards over the past few decades, there is likelihood that future regulations will advocate the use of long term strategic thinking and adoption of resilience within transportation sector.

Technology/Innovation

The key question the user needs to ask within this future condition is that, 'is the project/infrastructure network in concern, located in an area of higher scope and implementation of new technology?' Future infrastructure has higher dependency on IT development and smart technologies such as use of wireless techniques and advanced materials. Technology is changing which has a strong influence on the user behaviour connectivity of the transportation network and informed users (DfT, 2013 and Goulding et al., 2014).

On England's motorway network, managed by Highways England, range of new technologies are being used to vary speed limits in response to driving conditions. The introduction of the 'Smart motorways programme' formerly known as 'Managed Motorway Programme' now uses the hard shoulder as a live lane on strategic motorway corridors, either permanently or during peak hours. This requires building additional emergency lay-bys and also caters for additional traffic using the hard shoulders. As a result of this, asset owners like Highways England have the opportunity to optimise the use of the network. These smart motor-ways are managed by our regional control centres where CCTV is in operation so that Highways England's traffic officers can be deployed to incidents if they occur and help to keep traffic moving (The Highways Agency 2012, http://www.highways.gov.uk/our-road-network/managing-our-roads/improving-our-network/smart-motorways/). The implication of the increased loading at the toe of the cutting slope and the associated vibration and erosion activity causes changes in the stresses within the soil which can cause deterioration of the slope. An example of such an occurrence is described in Case Study 2 in Chapter 5 of this thesis.

Example 1: With a significant boost in Information Technology, there comes the need to embed flexibility to accommodate innovation such as the provision for technological infrastructure (fibre optics, cables utilities, driverless cars sensors, etc.). In this case consideration must be given by the user to allow for contingency on the transportation network. Solutions may also need to be flexible to promote multi-functionality.

Example 2: With increasing and fast paced technology there are chances of increasing interdependency between various infrastructure networks. This may result in change of use or obsolescence of certain parts of the network.

Example 3: With changing technology and innovation, there might be less mobility due to online education, online shopping and home working, which means less overall usage of transportation network. As such there might be need for multi-functionality of the solution and flexibility to allow for technological bolt-ons. This might include allowing sensors to be implanted on transportation networks for the digital network for example driverless cars.

Shock Events

Infrastructure network must be able to cope with system shocks (Rogers et al., 2011). This accounts for both man-made (terrorism) and natural threats (Rogers et al., 2011). This emphasises the need to think about the 4 Rs of resilience – recovery, redundancy, response and robustness (Cabinet Office, 2011). The key question that needs to be answered in this future condition is ‘does the project/ infrastructure network have a history of vulnerability or exposure to extreme (i.e. weather) events? Does the project have increased risk of security such as an area of strategic importance such as nuclear power plants, military and defence infrastructure, etc.’ With growing vulnerabilities of transportation network there is a direct impact on the lives of people by causing disruption to daily activities and has a knock on effect on the economy (Hudson et al., 2012).

Example 1: Man Made concerns such as security threats and natural phenomena’s such as increased precipitation or flash flooding and other extreme weather events. In an event of such a shock, the solutions should be able to offer flexibility and multi-functionality i.e., be able to do more than its intended purpose such that it limits unnecessary damage. Alternatively, depending on the situation and the project requirements, the solution should be able to work independently and offer redundancy in an event of such an extremity. The solution, ideally, should not cause a domino impact on the surrounding assets (Rogers et al., 2011) paralysing the entire network and hence increasing the risk and economic impacts.

4.3.3. Inter-relationship between Future Conditions and Critical Factors

The next logical step within this Design Phase 'B' is to develop interrelationships between the Future Conditions (FC) and Critical Factors (CF). This interrelationship is represented in Model 2 (Figure 4.5). This information is then layered in the form of a matrix where solutions can be tested and scored.

The detailed description and reasoning for the relevance of Critical Factors (CF) to each Future Condition (FC) is shown in Tables 4.5 to 4.11. The interrelationships between CF and FC are used as to develop the matrix used for Resilience Assessment Framework (RAF) of geotechnical solutions which is discussed in the next section. The inter-relationships between FCs and CFs have been developed using concept mapping and cross impact analysis techniques (see sections 3.5.2 and 3.5.3). This is visually represented in the form of a rose diagram – Model 2 (Figure 4.5). The inter-relationship between each FC and the associated CF are described along with its reasoning in Tables 4.5 to 4.11 in this section (see sections 4.3.3.1 to 4.3.3.7).

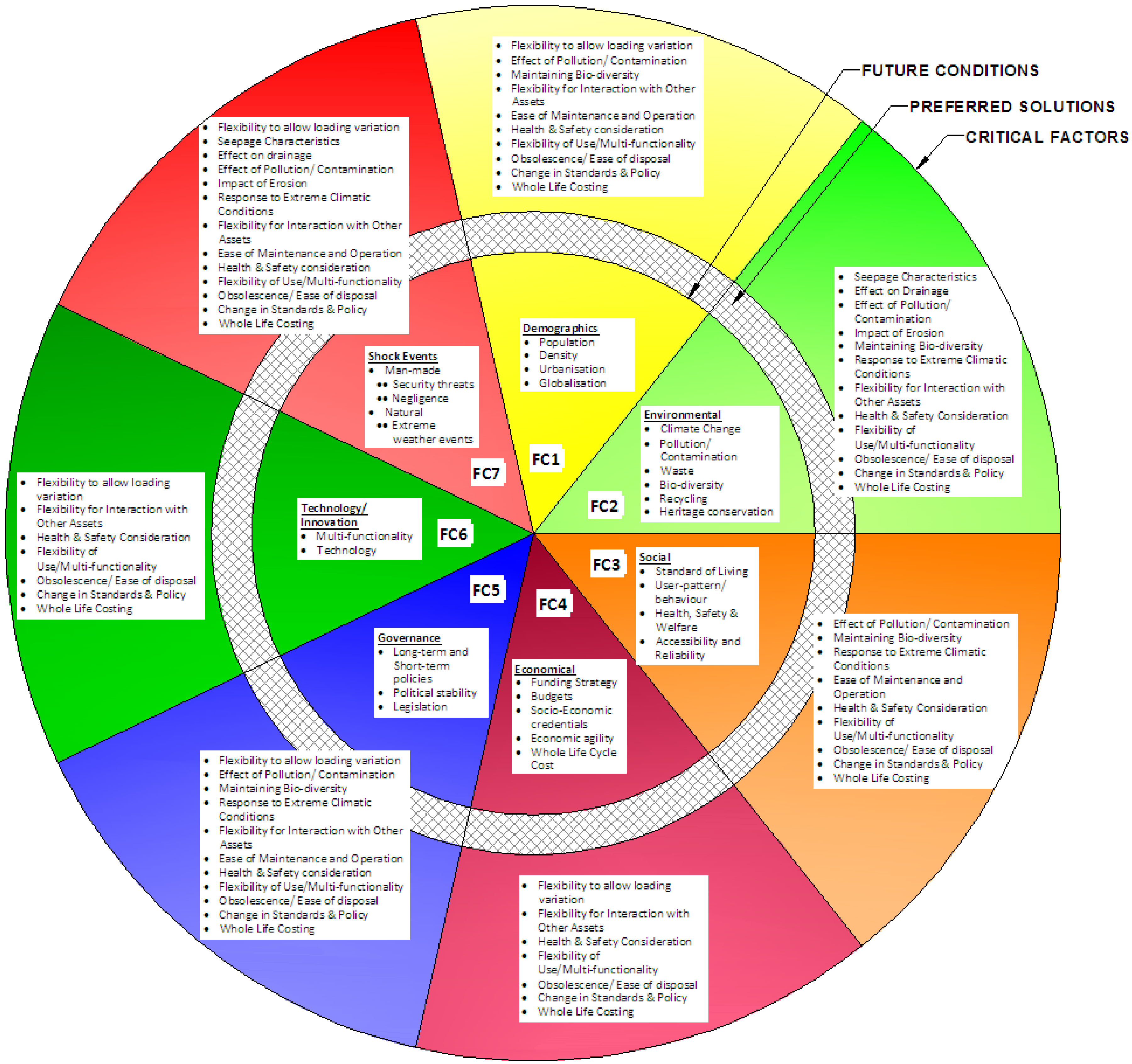


Figure 4.5: Model 2 – Rose Diagram showing the inter-relationship between Future Conditions and Critical Factors affecting the performance of geotechnical assets on the transportation network

4.3.3.1 FC1 – Demographics

Critical Factors likely to be affected due to change in demographics and its reasoning is provided in table 4.5.

Table 4.5: Inter-relationship between Critical Factors and FC1 – Demographics

No	Critical Factors	Reasoning
CF1	Flexibility to allow loading variation	If the demographics in two cities connected by the road increases or decreases, it will affect the usage of the network and influence traffic conditions and hence loading.
CF4	Effect of Pollution/Contamination	Higher traffic volume due to increased urbanisation may increase the chance of contamination through fuel spillage, waste generation, etc. Also, if the demographics in the cities surrounding the road network increases or its use changes, it may influence contamination patterns.
CF6	Maintaining Bio-diversity	Increased demographics in the area may put more pressure on the local bio-diversity, flora and fauna and also through deforestation.
CF8	Flexibility for interaction with other assets	Increased/decreased demographics may have a direct or indirect effect on the use/extent of the network which may mean changes in the usage, resulting in increased interface between asset types. Also, this may be due to change of use as well.
CF9	Ease of operation and Maintenance	When the demographics increase the network downtime (traffic management, closures, diversions, etc.) have to be kept to minimum to avoid inconvenience and has time and cost implications and even safety. Hence, the solution should provide ease of operation and maintenance.
CF12	Obsolescence and Ease of Disposal	If the demographics decrease, this may result in negligible use of the asset. Then the asset/proposed solution should be such that it is easy to dispose. Although, preferably it should not be of the nature that It may become obsolete.
CF13	Change in Standards and Policies	Increase in demographics/increase in use may result in introduction of policies (funding) leading to additional improvement works. Hence requiring flexibility to allow changes and expansion.
CF14	Whole life costing	This includes the overall optimum costs throughout the life cycle of the asset right from material, transport, construction, maintenance and disposal of the solution. Hence this CF is relevant in all FCs for the solution to be cost effective irrespective of the changing future.

4.3.3.2 FC2 – Environment

Critical Factors likely to be affected due to change in Environmental conditions and its reasoning is provided in table 4.6.

Table 4.6: Inter-relationship between Critical Factors and FC2 – Environment

No	Critical Factors	Reasoning
CF2 CF3 CF7	Seepage Characteristics Effect on Drainage Response to Extreme Climatic Conditions	With extreme events such as flash flooding and excessive snowfall, geotechnical assets such as slopes have to deal with an increase in ground water level and as a result require increased drainage capacity and effective seepage to keep them dry and release excess pore water pressures. Wetter winters, drier summers and increased precipitation along with extreme weather events and fluctuating temperatures, are likely factors to affect the serviceability of the geotechnical asset. The solution provided should be able to respond effectively to such events.
CF4	Effect of Pollution/Contamination	With increased environmental consciousness/ sensitivity/ importance, response to deal with the effects of pollution/ contamination is likely to be more stringent. Hence the solution provided should be environmentally friendly in this context during its whole life. Considering the impact of pollution and contamination along with seepage and drainage characteristics, the effects are likely to be more problematic. For example: within an embankment slope (made with fill material comprising of waste and contaminants) on a road network, a slope drainage failure and resultant seepage into the soil will therefore allow waste and contaminants to flow away with the leaking water percolating into the slope and washing away soil and thereby contaminating surrounding areas.
CF5	Impact on Erosion	With increased precipitation, and other extreme climate events, geotechnical assets may have to deal with high flood levels in watercourses resulting in internal and external erosion of the assets and cause dysfunction of the asset. E.g. toe erosion, silting of drains, rock/slope weathering, etc.
CF6	Maintaining Bio-diversity	With increasing environmental consciousness and importance in the future maintaining of bio-diversity and/or improving biodiversity may become significantly important driver. Hence the solutions which are likely to maintain or improve the scope of biodiversity are likely to be more preferred.
CF8	Flexibility of interaction with other assets	If environmental conditions require the assets on the network to be upgraded or changed then the solution provided should be flexible to be able to respond to it. For example, upgrading drainage system to account for increased precipitation, the asset solution should be flexible to accommodate or allow flexibly for interaction with other assets.
CF11	Flexibility of Use/Multi-functionality	If Environmental conditions or considerations require the assets on the network to be used for a purpose not initially planned or intended, it still gives the flexibility to either provide that function or allow changes to be made easily for the same. E.g. free draining material used as engineered fill

Table 4.6: Inter-relationship between Critical Factors and FC2 – Environment		
No	**Critical Factors**	**Reasoning**
		in replace and refill option, not only is a slope remediation solution but also acts as a drainage medium and improves the slope drainage there provides additional use and multi-functionality.
CF12	Obsolescence and Disposal	During increased environmental considerations or conditions, some materials or remediating technique may not be easy to dispose or easily made obsolete (this is in context of solution provided).
CF13	Change in Standards and Policies	Rising environmental concerns the policies are put in place to minimise contamination/pollution, increase safety by building flood barriers in areas susceptible to high risk of flooding. Hence the solution provided should be able to adapt to such similar considerations in the future.
CF14	Whole life costing	This includes the overall optimum costs throughout the life cycle of the asset right from material, transport, construction, maintenance and disposal of the solution. Hence this CF is relevant in all FCs for the solution to be cost effective irrespective of the changing future.

4.3.3.3 FC3 – Social

Critical Factors likely to be affected due to change in Social factors and its reasoning is provided in table 4.7.

Table 4.7: Inter-relationship between Critical Factors and FC3 – Social		
No	**Critical Factors**	**Reasoning**
CF1	Flexibility to allow loading variation	Due to change in social preferences (standard of living, service, safety and use of network) certain parts of the network may be subjected to additional loading due to increased traffic of heavy haulage for changes of trading conditions in the area, increased pavement thickness, to provide better level of service, etc. Hence the solution should be flexible to allow for these changes.
CF4	Effect of Pollution and Contamination	Change in Social behaviour and/or considerations have an effect on the pollution and contamination (increased fuel usage, waste generation, etc. trends for households). Solution should not increase the effect of pollution/contamination and also by becoming a pathway.
CF6	Maintaining Bio-diversity	Changes in social requirements may lead to measures such as more vegetated slope, improved bio-diversity preference, etc. Solution should allow for minimal or no changes to accommodate the same.
CF7	Response to Extreme Climatic Conditions	Society expects an increased level of service, requiring a network that is accessible and operational also during extreme climatic events. Hence, the solution should be able to respond accordingly in the future.
CF9	Ease of Maintenance and Operation	Social preferences/changes in the future may require for more constraints on the operation and maintenance (O&M) regimes and methods. The solution should be able to

Table 4.7: Inter-relationship between Critical Factors and FC3 – Social		
No	**Critical Factors**	**Reasoning**
		accommodate the same and also be easy to O&M in most circumstances.
CF10	Health and Safety Consideration	Solution should be such that O&M, functioning, etc. should be safe to network, workforce and road-users.
CF11	Flexibility of use and multi-functionality	Solution should be able to offer flexibility/ multi-functionality for changing social requirements/ considerations. E.g. increased use of public walkways and cycleway in the future may require changes to the network and the solution should be able to accommodate the same.
CF12	Obsolescence and Ease of Disposal	Changes in social behaviour may lead to obsolescence of certain parts of a network leading to de-commissioning or disposing of the solution. This should be a consideration while providing the solution.
CF13	Change in Standards and Policies	To suit the changing social requirements, the policies may be driven in the future. Solution should be able to allow for that change. E.g. change in standards for increased safety of road users can be accommodated easily by the solution.
CF14	Whole life costing	This includes the overall optimum costs throughout the life cycle of the asset right from material, transport, construction, maintenance and disposal of the solution. Hence this CF is relevant in all FCs for the solution to be cost effective irrespective of the changing future.

4.3.3.4 FC4 – Economics

Critical Factors likely to be affected due to change in Economic factors and its reasoning is provided in table 4.8

Table 4.8: Inter-relationship between Critical Factors and FC4 – Economics		
No	**Critical Factors**	**Reasoning**
CF1	Flexibility to allow loading conditions	If economic policies improve and as a result, trade and development flourishes there may be a boost in the use of the infrastructure. This may result in variation in traffic and loading conditions similar to demographics.
CF8	Flexibility of interaction with other assets	If economic conditions dictate the use of infrastructure, there might be advancement and development in the use of network, and as a result there may be more increased interface between network assets (old and new) and this may provide additional reasons for increased interactions between different assets.
CF9	The ease of maintenance and operation	Is not considered as a triggering factor in terms of cost is included in the whole life cost factor, this is purely the EASE of O&M which is unlikely to get affected by changing economic conditions.
CF10	Health and Safety Considerations	To have a safe and reliable network is of paramount importance and hence although there is no direct connection in the change in economic condition, at any point no compromise to the H&S of the network can be acceptable. But safety takes precedence over cost and hence solutions should consider this.

Table 4.8: Inter-relationship between Critical Factors and FC4 – Economics		
No	**Critical Factors**	**Reasoning**
CF11	Flexibility of Use and Multi-functionality	Under the economic agility consideration, a solution which offers higher flexibility of use and scope of multi-functionality, the solution therefore provides more value for money in the future.
CF12	Obsolescence and Ease of Disposal	Under changing economic conditions, where maintenance regimes, use of the network, operational costs, etc. are dictated purely by the available funding and budgets, certain assets and network may become obsolete depending on its value and its use and hence these sections are decommissioned if they are no longer in use. The solution should be easy of dispose of or decommissioned.
CF13	Changes in Standards and policies	A good example is asset owners' funding and spending reviews which promotes 'Do Minimum' as a preferred option, which means the solution should be able to provide longevity in its useful service life.
CF14	Whole life costing	This includes the overall optimum costs throughout the life cycle of the asset right from material, transport, construction, maintenance and disposal of the solution. Hence this CF is relevant in all FCs for the solution to be cost effective irrespective of the changing future.

4.3.3.5 FC5 – Governance

Critical Factors likely to be affected due to change in governance and policies and its reasoning is provided in table 4.9.

Table 4.9: Inter-relationship between Critical Factors and FC5 – Governance		
No	**Critical Factors**	**Reasoning**
CF1	Flexibility to allow loading variation	Change in policies and regulations may have an impact on the loading conditions and considerations on the network and hence the solutions responsiveness to this change is assessed.
CF4	Effect of Pollution and Contamination	Policies and Standards and regulations concerning pollution and waste disposal is a good example and how the solution meets this and adapts to this is assessed.
CF8	Flexibility of Interaction with other assets	By allowing for increased interaction with other assets with minimal disruption provides highest return on investment and improves the economic viability of the asset solution and in turn meet probable changes in governance conditions.
CF9	Ease of maintenance and operation	By Improving the maintenance and operational convenience and alleviating costs, the overall economic viability of the project increases in due course and in turn meet probable changes in governance conditions.
CF10	Health and Safety Considerations	The solution continues to provide health and safety to the road users and the operatives in the light of changes in policies and regulations requiring increased H&S consideration.

Table 4.9: Inter-relationship between Critical Factors and FC5 – Governance		
No	**Critical Factors**	**Reasoning**
CF11	Flexibility of use and multi-functionality	If the policy or regulation or standard is changed, how the proposed solution responds to the same, i.e. is it adaptable, does it require marginal change or is it completely obsolete and requires disposal.
CF12	Obsolescence and Ease of Disposal	Does the solution offer the ease of disposal if policies are reformed either due to economic drivers or environmental concerns or social factors. Will the solution offer the ease of disposal without any significant implications and damage in terms of cost, time, social welfare and environment?
CF13	Change in Standards and Policies	This ties in with governance because governance influences changes in standards and policies. Although these may be implemented by asset owners (such as Highways England or local authorities).
CF14	Whole life costing	This includes the overall optimum costs throughout the life cycle of the asset right from material, transport, construction, maintenance and disposal of the solution. Hence this CF is relevant in all FCs for the solution to be cost effective irrespective of the changing future.

4.3.3.6 FC6 – Technology and Innovation

Critical Factors likely to be affected due to change in technology & innovation and its reasoning is provided in table 4.10.

Table 4.10: Inter-relationship between Critical Factors and FC6 – Technology and Innovation		
No	**Critical Factors**	**Reasoning**
CF1	Flexibility to allow loading variation	Installation of Gantries, Sign Posts, Heavier Utilities or reduction in the same may have variation in loading on the network.
CF8	Flexibility of interaction with other assets	Innovation may mean use of digital installations on the network which may direct traffic, hybrid cars, self-driven cars etc., which may mean installation of modern equipment on the network and this may lead to higher interface between asset types and increased interaction amongst them which needs to be addressed by the solution.
CF10	Health and Safety Consideration	Innovation and Technology may improve the road users' safety and operative's safety; the solution should allow inclusion of any innovative systems.
CF11	Flexibility of Use and Multi-functionality	Innovative and Technological advancements should be allowed and accommodated by existing solution such as sensors in the road network for self-driven vehicles.
CF12	Obsolescence and Ease of Disposal	With improvement in technology and innovation, there is a very high likelihood that existing solutions, technology and material may become redundant and as a result this may require disposal and the existing solution should preferably be adaptable to the same.

CF13	Change in Standards and Policies	For improved innovation and technology which, for example, promotes environmental and social credentials, are very likely to become regulations, hence the solution should allow accommodating the same.
CF14	Whole life costing	This includes the overall optimum costs throughout the life cycle of the asset right from material, transport, construction, maintenance and disposal of the solution. Hence this CF is relevant in all FCs for the solution to be cost effective irrespective of the changing future.

4.3.3.7 FC7 - Shock Events

Critical Factors likely to be affected due to shock events (man-made or natural) and its reasoning is provided in table 4.11.

Table 4.11: Inter-relationship between Critical Factors and FC7 – Shock Events

No	Critical Factors	Reasoning
CF1	Flexibility to allow loading variation	If a landslide or accident occurs on one section of the network, resulting in diversion routes this may increase the loading on other connecting section of the network. Depending on the location of the site and its strategic importance, loading variation can be significant consideration.
CF2 CF3	Seepage Characteristics and Effect on Drainage	Seepage and Drainage of the slope from flooding events and extreme rainfall. The solutions should be able to adapt to this.
CF4	Effect of Pollution and Contamination	Pollution and Contamination from Nuclear Power Plant leakage or Oil Gas Leaks are clear examples against which strategic parts of the network should be made resilient to.
CF5	Impact of Erosion	Erosion of River Banks due to excessive flooding. The solution should be able to cope with the detrimental effects of erosion without compromising its serviceability.
CF7	Response to extreme climatic conditions	The essence is how responsive is the solution to extreme climate conditions under natural shock events.
CF8	Flexibility of interaction with other assets	Redundancy in the network is also sign of a resilient system, how the solution does and interacts with other assets in the event of shock. Does it impair its own performance and also paralyses the network or at least offers redundancy but allows the rest of the network to function?
CF9	Ease of Maintenance and operation	During a shock event, if one section of the network ceases to function, the operation of arterial routes to supply food and water to victims is crucial and hence ease of operation is very important and the solution should allow for this.
CF10	Health and Safety Consideration	In the event of shock events, the health and safety of road users, community and general public is of most importance. This is why the section of the network, asset stability on the network is crucial. Responsiveness of the solution in the light of these conditions is critical.

Table 4.11: Inter-relationship between Critical Factors and FC7 – Shock Events		
No	**Critical Factors**	**Reasoning**
CF11	Flexibility of Use and multi-functionality	Multi-functionality where embankments act as Flood Banks during flood event is an example of multi-functionality.
CF12	Obsolescence and Ease of Disposal	Redundancy and Recovery are key factors required during shock events. How does the solution respond to the same should be assessed. If the solution is not performing, and post the shock event how easy it is to dispose or decommission, is equally important E.g. Power plants etc.
CF13	Change of Standards and policies	Examples such as Flood Plans, Resilience Statements, government initiatives and policies concerning resilience in flood and extreme weather may affect the use of network and these changes may have an effect on certain asset types, how the solution responds to this is to be assessed
CF14	Whole life costing	This includes the overall optimum costs throughout the life cycle of the asset right from material, transport, construction, maintenance and disposal of the solution. Hence this CF is relevant in all FCs for the solution to be cost effective irrespective of the changing future.

4.4. Design Phase C

The Design Phase 'C' consists of building the Resilience Assessment Framework (in the form of a matrix) for assessing the resilience of geotechnical solutions. The principles and methodology used in the development of this framework is discussed in detail within the section 3.5

Figure 4.6 provides a visual skeleton of the components of the RAF matrix. The resilience of the solution is tested based on its performance under the influence of critical factors specific to each future condition. The detailed working of the framework is explained along with a case study in detail in the Chapter 5.

Figure 4.6: Diagrammatic Representation of Proposed Framework Elements

This section describes the 'Resilience Assessment Framework - RAF' in detail.

4.4.1. Geotechnical Assets

The framework has been developed for application on geotechnical earthwork solutions, but can be adopted for other geotechnical assets. The geotechnical assets considered for the scope of this research are:

- Foundations
- Slopes/Earthworks (Embankments and Cuttings)
- Retaining structures

4.4.1.1 Typical Failure Modes/Symptoms

The failure modes considered for the aforementioned geotechnical assets includes cognisance of their performance, serviceability, safety and stability.

4.4.2. Development steps for the Tool

The main steps for the development of this tool are three fold

- To determine the critical factors which lead to (or trigger) the deterioration and/or failure of geotechnical assets.
- To establish an interrelation between these critical factors and future conditions (Demographics, Social, Economic, Environment, Political, Technology and Shock Events such as manmade and natural hazards)
- To facilitate testing the resilience of the proposed geotechnical solution(s) in the light of plausible changing future conditions.

4.4.3. The What, How, When and Who

4.4.3.1 The 'What'

Solutions provided today have a minimum design life of 60 years (The Highways Agency, HA43/91), but the conditions they may be subjected to, are changing also, altering their role and intended purpose. This has required 'resilience' to be built into Geotechnical infrastructure asset management in the best way possible. It is proposed that the methodology presented here provides a holistic framework in order for this to occur. This forms a key thread in the contribution to knowledge of this piece of research work. The purpose of the framework is to enable effective decision-making by selecting the most resilient solution (i.e. technically sound and fit for purpose) regardless of what the future may hold. Resilience Assessment does not replace any of the existing assessment processes, but rather is a form of acid test on the proposed solution which tests its applicability and flexibility under changing conditions such as environment, economy, social, political and technological.

4.4.3.2 The 'How'

The assessment framework utilises a scoring matrix that provides a resilience score for each proposed design solution. The methodology is sufficiently flexible that a bespoke resilient assessment framework can be adopted for any asset specific to any project. The process for application is described fully in Chapter 5 (Section 5.2).

4.4.3.3 The 'When'

The proposed framework can be adopted at the 'options analysis' stage for asset management systems (strategic) or engineering design (operational) where different options are evaluated and a feasibility analysis is undertaken to select the most technically sound, cost effective and sustainable solution

4.4.3.4 The 'Who'

Anyone can use the framework from the stakeholders to the client, project manager and the designer. The benefits are seen across the project.

4.4.4. A Five-Stage Methodology

The Resilience Assessment Framework (RAF) uses five stages of analysis (Figure 4.7) within an overarching nested methodology that goes considerably beyond the bounds of existing frameworks (Stage 1 in Figure 4.7). This requires 4 additional stages of investigation, synthesis, and application (with adequate iterative validation of key research outputs) that are appropriate for managing and maintaining Geotechnical assets into the long-term future. The framework is built in the form of an Excel spreadsheet. Each of the steps seen in the Figure 4.7 are located on different hyperlinked tabs.

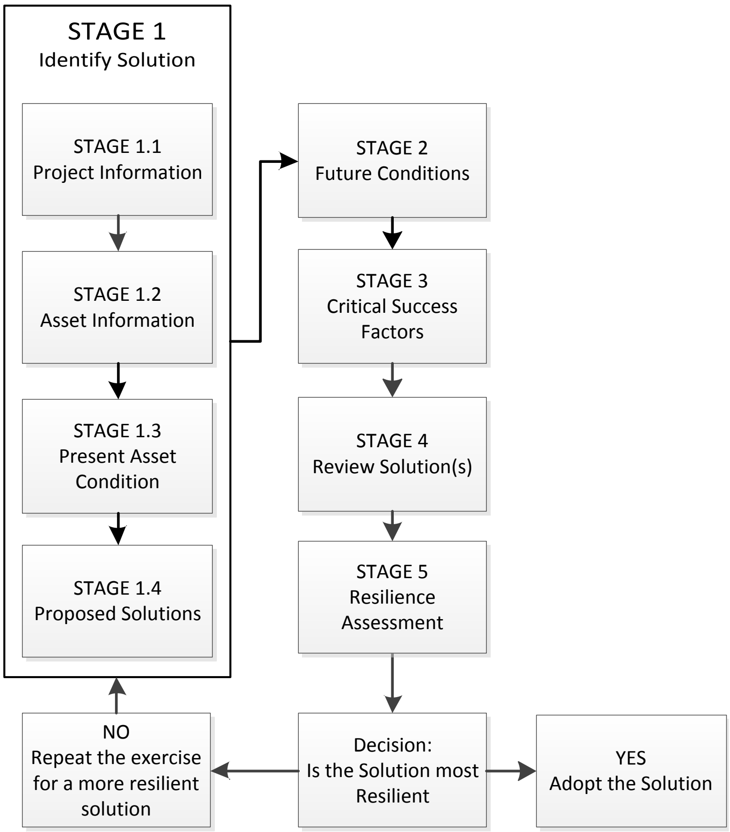


Figure 4.7: Resilience Assessment Methodology

The work presented in this section highlights the overall philosophy of a Resilience Assessment Framework (RAF) developed specifically for assessment of geotechnical asset management solutions. However, these principles can be adapted to suit any geotechnical asset base and can be adapted to extend its use to other transportation assets. This requires a wide range of user involvement including SMEs, Client organisations, Asset Management Organisations and Engineers to define the specific aspects of the framework.

In the framework matrix, the cells which represent the inter-relation of the factors and the drivers are un-shaded to indicate the cell for input. It is in these cells, that the resilience scores assigned for the preferred geotechnical solution are input. The users assessing a geotechnical asset solution are required to provide a resilience score on a 6-point Likert-type scale, ranging from –3 to +3, where –3 indicates considerable re-engineering needed with high time and cost implications, and +3 indicates that the existing solution works without any change in design. A scoring key is provided to aid the user in assigning resilience scores. The scoring scale is a logarithmic scale. A range of -3 to +3 was selected indicating that a positive or negative score implies that the solution does or does not work in its original form. The magnitude of scoring was limited to (+/-) 3 because having a higher magnitude would increase the degree of user subjectivity and the overall arithmetic sum without adding any further value to the outcome. The scoring system is provided as a comparator for design options to demonstrate the strength or weakness of a solution versus its counterparts for the given conditions on a project. The objective is not to achieve a certain target score. The intention is to compare solutions for a given project and not to compare project with another project. Negative scores indicated a poor fit between the asset solution and the factors, 0 indicated neutral fit or a non-applicable solution and positive scores indicated a good fit between the solution and the factors—that is, the solution works without any change in design. There is also the opportunity to provide a weightage to the future conditions. This can be done by extensive stakeholder and Client involvement. The Critical Factors are assigned specific scores based on their relevance with Future Conditions. The Critical Factor (CF) relevant in maximum Future Conditions (FC), has maximum score and the order of scores for other CF in decreasing order of relevance in FCs get scored in relation to the maximum scores. So the higher the relevance the greater the score which decreases in the order of relevance to FC. The final 'Resilience Score' is obtained by applying an algorithm which gives a score out of a total of 100. This algorithm is derived and explained in detail in Chapter 5.

A snapshot of the framework is shown in Figure 4.8.

Project	0
Project Ref.	0

Proposed Geotechnical Solution 1	
Proposed Geotechnical Solution	0
Geotechnical Solution Ref. no.	0
Document Ref.	0
Document Revision	0
Date First Prepared	0
Date Updated	0

Future Conditions (FC)			**Critical Success Factors (CSF) - Future Consideration**															**Resilience Score**		
Description	**FC Ref**	**FC Weitage (%)**	***Factor***	**CF1 - Flexibility to allow loading variation**	**CF2 - Seepage Characteristics**	**CF3 - Effect on Drainage**	**CF4 - Effect of Pollution/ Contamination**	**CF5 - Impact of Erosion**	**CF6 - Maintaining Bio-diversity**	**CF7 - Response to Extreme Climatic Conditions**	**CF8 - Flexibility for Interaction with Other Assets**	**CF9 - Ease of Maintenance and Operation**	**CF10 - Health & Safety consideration**	**CF11 - Flexibility of Use/Multi-functionality**	**CF12 - Obsolescence/ Ease of disposal**	**CF13 - Change in Standards & Policy**	**CF14 - Whole Life Costing**	**FC Score**	**Resilience FC Score**	**Total Resilience Score**
			Factor Score (Fixed to a total of 100)	**8**	**3**	**3**	**8**	**3**	**6**	**8**	**10**	**10**	**6**	**10**	**10**	**11**	**5**			
Demographics	FC1	10%		0			0		0		0	0	0	0	0	0		**0.0**	**0.0**	
Environment	FC2	20%			0	0	0	0	0	0	0					0		**0.0**	**0.0**	
Social	FC3	30%		0			0		0	0		0	0	0	0	0		**0.0**	**0.0**	
Economics	FC4	10%									0	0		0	0	0	0	**0.0**	**0.0**	**0.0**
Governance	FC5	10%		0			0		0	0	0	0	0	0	0	0	0	**0.0**	**0.0**	
Technology/ Innovation	FC6	10%		0						0	0	0		0	0	0	0	**0.0**	**0.0**	
Shock Events	FC7	10%		0	0	0	0	0		0	0	0	0	0	0	0		**0.0**	**0.0**	

Figure 4.8: Resilience Assessment Framework

4.5. Use of pairwise comparison for assigning weightages for Future Conditions

As discussed in section 3.5.4 and 3.5.5 there are several techniques for group ranking or voting in a multiple criteria decision making process. Pairwise comparison discussed in section 3.5.5.4 is the chosen technique to derive the weightages for future conditions. The rankings are assigned by stakeholders in a group participation method. The detailed methodology of undertaking a pair wise comparison process is explained in this section with an example.

Pairwise comparison technique offers a unique problem solving method as it enables comparison of alternatives in a one to one match (similar to a two candidate election). For each pair of alternatives, the ‘more popular’ of the two is selected by the voter and is awarded a point. If there is a tie, both the alternatives are awarded a 0.5 score (pair wise therefore provides an opportunity for voters to address tie situation which is very useful in the proposed framework. For instance, a stakeholder comparing solutions for a proposed geotechnical scheme intended for improving social welfare but is required to be delivered in restricted budget the stakeholders may encounter a tie between future conditions ‘social’ and ‘economic’ conditions as maintaining budgets is as important for the project as delivering social welfare. Therefore on such an instance, the stakeholder an assign a 0.5 score to both these future conditions using the pairwise technique. The above example is relevant to the proposed study and highlights one of the important reasons for selecting pair wise comparison in the proposed research.

4.6. Methodology of undertaking pairwise comparison

The methodology comprises of setting up a pair wise comparison chart for each stakeholder i.e. voter and then comparing the final results to determine the final scores. This technique is used to obtain the weightages for the future conditions in the two case studies discussed in chapter 5 of the research and is explained below using an example.

There are five steps to set up a pair wise comparison chart.

Step 1: Identify the alternatives to be ranked. For this research, these are the future conditions social, demographics, environment, economy, policies, technology and shock events which are to be weighed.

Step 2: Set up the pairwise comparison matrix.

This includes future conditions (FC1 to FC7) populated as columns and rows. In this instance, there will be a 7x7 matrix i.e. 7 rows and 7 columns of future conditions (See Figure 4.9). The extra cells which duplicate the pair can be blanked. So for instance, in the table below, cell pair FC1 versus FC2 will contain the same result as the cell representing FC2 versus FC1. Similarly, alternatives do not compete themselves i.e. FC1 versus FC1 will not be of any use. Hence, the voter can eliminate these cells which represent same alternatives on the main diagonal. The remaining cells forms one triangle of the matrix where the voter is able to populate the results from ranking individual pair of alternatives.

	FC1	FC2	FC3	FC4	FC5	FC6	FC7
FC1	-	FC1 vs FC2	FC1 vs FC3	FC1 vs FC4	FC 1 vs FC5	FC 1 vs FC6	FC 1 vs FC7
FC2	-	-	FC2 vs FC3	FC 2 vs FC4	FC2 vs FC5	FC2 vs FC6	FC2 vs FC7
FC3	-	-	-	FC3 vs FC4	FC 3 vs FC5	FC 3 vs FC6	FC3 vs FC7
FC4	-	-	-	-	FC4 vs FC5	FC 4 vs FC6	FC 4 vs FC7
FC5	-	-	-	-	-	FC 5 vs FC6	FC 5 vs FC7
FC6	-	-	-	-	-	-	FC6 vs FC7
FC7	-	-	-	-	-	-	-

Figure 4.9: Pair wise comparison matrix.

Step 3: Compare Pairs of Future Conditions (FCs)

In the pair wise comparison matrix in figure 4.9 compare the FC in each row with relevant FCs in the columns. For example: The voter can compare FC1 and FC2. Based on which is a more important future condition for geotechnical solution or relevant to the requirements of the project, the result of this comparison is populated in the cell marked FC1 vs FC 2. Similarly, the voters can populate the remaining cells in the matrix. The result will appear like the figure 4.10.

	FC1	FC2	FC3	FC4	FC5	FC6	FC7
FC1	-	FC1	FC3	FC4	FC5	FC 1	FC 1
FC2	-	-	FC2	FC 2	FC5	FC6	FC2
FC3	-	-	-	FC3	FC5	FC6	FC3
FC4	-	-	-	-	FC5	FC 4	FC7
FC5	-	-	-	-	-	FC 5/ FC6	FC 5
FC6	-	-	-	-	-	-	FC6
FC7	-	-	-	-	-	-	-

Figure 4.10: Pair wise comparison matrix with voter results

This shows that in comparing the pair FC1 with FC2 the voter has ranked FC1 over FC2. Similarly, in FC1 vs FC3 comparison, the vote is for FC3. When there occurs a tie between the choice of future conditions, such as FC5 and FC6 when they are considered equally important for the voter, both the initials are written in the cell so that the tie is accounted for in the decision making.

Step 4: Creating the ranking for future conditions

We create a list of future conditions and write the number of points awarded to each future conditions. For every win the future condition gets a rank of 1 and 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 figure 4.11 provides the ranking of future conditions.

Future Conditions	Ranks
FC1	3
FC2	3
FC3	3
FC4	2
FC5	5.5
FC6	3.5
FC7	1

Figure 4.11: Ranking of Future Conditions

This shows that FC5 is highest rank, followed by FC6, followed by a tie between FC1, FC2 and FC3, followed by FC4 and finally lowest ranked future condition is FC1.

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 is out of 100 and it follows the qualitative ranking above.

$100 = 3x+3x+3x+2x+5.5x+3.5x+1x$ - Equation 1

$x = 100/21= 4.761904$

Thus the weightages (rounded to the nearest whole number) are as shown in figure 4.12 for this voter.

Future Conditions	Weights
FC1	14
FC2	14
FC3	14
FC4	10
FC5	26
FC6	17
FC7	5
Total	100

Figure 4.12: Weightages for future conditions

If we have 6 stakeholders and their weightings are considered, then we repeat the above exercise 6 times and group the rankings as shown in figure 4.13.

The final result can be shown in figure 4.13 as follows:

	Group A	Group B	Group C
Number of Votes	3	2	1
First	FC1	FC5	FC1
Second	FC3	FC2	FC2
Third	FC6	FC1	FC3
Fourth	FC7	FC4	FC4
Fifth	FC4	FC6	FC5
Sixth	FC5	FC7	FC6
Seventh	FC2	FC3	FC7

Figure 4.13: Summary of Ranking

The figure 4.13 shows that 3 stakeholders (Group A) have selected FC1 as most important giving it first rank followed by FC3 followed by FC6 followed by FC7 followed by FC4 followed by FC5 and FC2 is the least rank. Whereas 2 stakeholders' (Group B) opinion is FC5 is most important, therefore ranking FC5 as first followed by FC2 followed by FC1 followed by FC4 followed by FC6 followed by FC7 and FC3 is the least ranked. Finally only 1 stakeholder (Group C) has voted FC1 followed by FC 2 followed by FC3 followed by FC4 followed by FC5 followed by FC6 and FC7 as least ranked.

On comparing each pair of future conditions, there will be 21 pairs as shown in figure 4.14.

Pairs of Future Conditions					
FC1-Fc2	Fc2-FC3	FC3-FC4	FC4-FC5	FC5-FC6	FC6-FC7
FC1-FC3	Fc2-FC4	FC3-FC5	FC4-FC6	FC5-FC7	
FC1-FC4	Fc2-FC5	FC3-FC6	FC4-FC7		
FC1-FC5	Fc2-FC6	FC3-FC7			
FC1-FC6	FC2-FC7				
FC1-FC7					

Figure 4.14 – Comparison of Pairs of Future Conditions

For reference two pairs FC1 vs FC2 and FC1 vs FC3 are explained below. As seen in figure 4.13, three stakeholders (Group A) have voted FC1 more important than FC2. Two stakeholders (Group B) have voted FC2 more important than FC1 and finally one stakeholder (Group C) has voted FC1 more important than FC2.

For pair FC1 vs FC2:

FC1	FC2
3	2
1	

Thus the total votes of FC1 is 4 and FC2 is 2. Hence, FC1 wins compared to FC2 in this comparison and gets a score of 1.

Similarly, for FC1 vs FC3

FC1	FC3
6	0

FC1 has 6 votes compared to 0 votes for FC3. Hence, FC1 wins against FC3 in this comparison and is awarded 1 score.

Similarly, FC1 wins against FC4, FC5, FC6 and FC7 and therefore scores 1 point in each of those comparisons. Hence the total score of FC 1 is 6 i.e. it has ranked higher than its counterparts 6 times.

If we do this for all pairs of future conditions as shown in figure 4.14 bearing in mind that for every win the future condition is awarded 1 point and for every tie both the future conditions in that comparison are awarded 0.5 points, we get the following result.

Future Conditions	Total Score
FC1	6
Fc2	2
Fc3	5
Fc4	2.5
Fc5	1.5
Fc6	2.5
Fc7	1.5

Figure 4.15: Result of pair wise comparison

Thus from this exercise, we can say that FC1 is the highest ranking future condition, followed by FC3, followed by FC4 and FC6 (which share the rank), followed by FC2 followed by FC5 and FC7 (which share the rank).

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

100=6x+2x+5x+2.5x+1.5x+2.5x+1.5x - Equation 1

x = 4.76

Thus weightages are as follows:

- FC1-29%
- Fc2-10%
- Fc3-24%
- Fc4-12%
- Fc5-6.5%
- Fc6-12%
- Fc5-6.5%

This technique is used to derive the weightages in both the case studies discussed in chapter 5 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.

4.7. Summary

The Resilience Assessment Framework proposed in this research is a unique decision support tool. While there are a variety of long term asset management planning tools developing a futures based resilient assessment tool is novel in its own merit. The tool is intended for assessing the resilience of geotechnical assets on the highways network in the light of plausible future conditions likely to affect the transportation networks.

The framework provides tangible output for assessing resilience and comparing geotechnical solutions by providing a resilience score. The resilience score for a solution can be seen as a numeric value which serves as a comparator indicating whether a particular solution performs better or worse than the other alternatives proposed for that project. This chapter provides the detailed methodology which led to the design and development of the Resilience Assessment Framework through Design

Phase A, Design Phase B and Design Phase C and highlights the various iterations undertaken to produce the research output i.e. ‘Resilience Assessment Framework’.

Design Phase A describes the geotechnical assets and the critical factors affecting their performance which led to the development of Model 1. Design Phase B describes the future conditions affecting transportation network and the inter-relationship between the future conditions and critical factors which led to the development of Model 2. Design Phase C describes the development of the five staged resilience assessment framework and the associated scoring matrix. It also provides the detailed methodology of undertaking pair wise comparison technique for assigning weightages to the future conditions.

Chapter 5 provides an illustration of the ‘Resilience Assessment Framework’ with the help of two real case studies and discusses the associated findings and observations.

5. Research Findings and Discussions

5.1. Introduction

This chapter explains in detail the working of the 'Resilience Assessment Framework (RAF)' as per a five stage methodology with examples of two real case studies to illustrate its application on real projects. Observations made on the working of the tool and the discussions of the outputs of resilience assessment of these case studies are discussed in detail in Section 5.4.

5.2. Five-Stage Methodology

5.2.1. STAGE 1 (Steps 1-4) – Identify solution:

This forms the basis of any existing 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). In brief, this initial step identifies the goal and scope of the project (e.g. a road widening improvement scheme, a slope failure remediation scheme) and detailed aspects of asset inspection and current / previous condition. A gap analysis between the existing condition of the asset and the desired future level of service of the asset (in order to derive suitable design solutions) is proposed and options for design solutions identified. These steps are explained in this chapter in further detail (Shah et al. 2014). The Stage 1 incorporates 4 Steps of the Resilience Assessment Process as seen in Figure 4.7. The first sheet comprises of the index tab shown in figure 5.1 which showcases the overall resilience assessment framework with hyperlinks to each stage in the process.

> *For example:* A deteriorating road link to the city is assessed in terms of its existing condition. A series of cost-assigned recommendations are made for either its, renewal, maintenance or replacement (Shah et al. 2014).

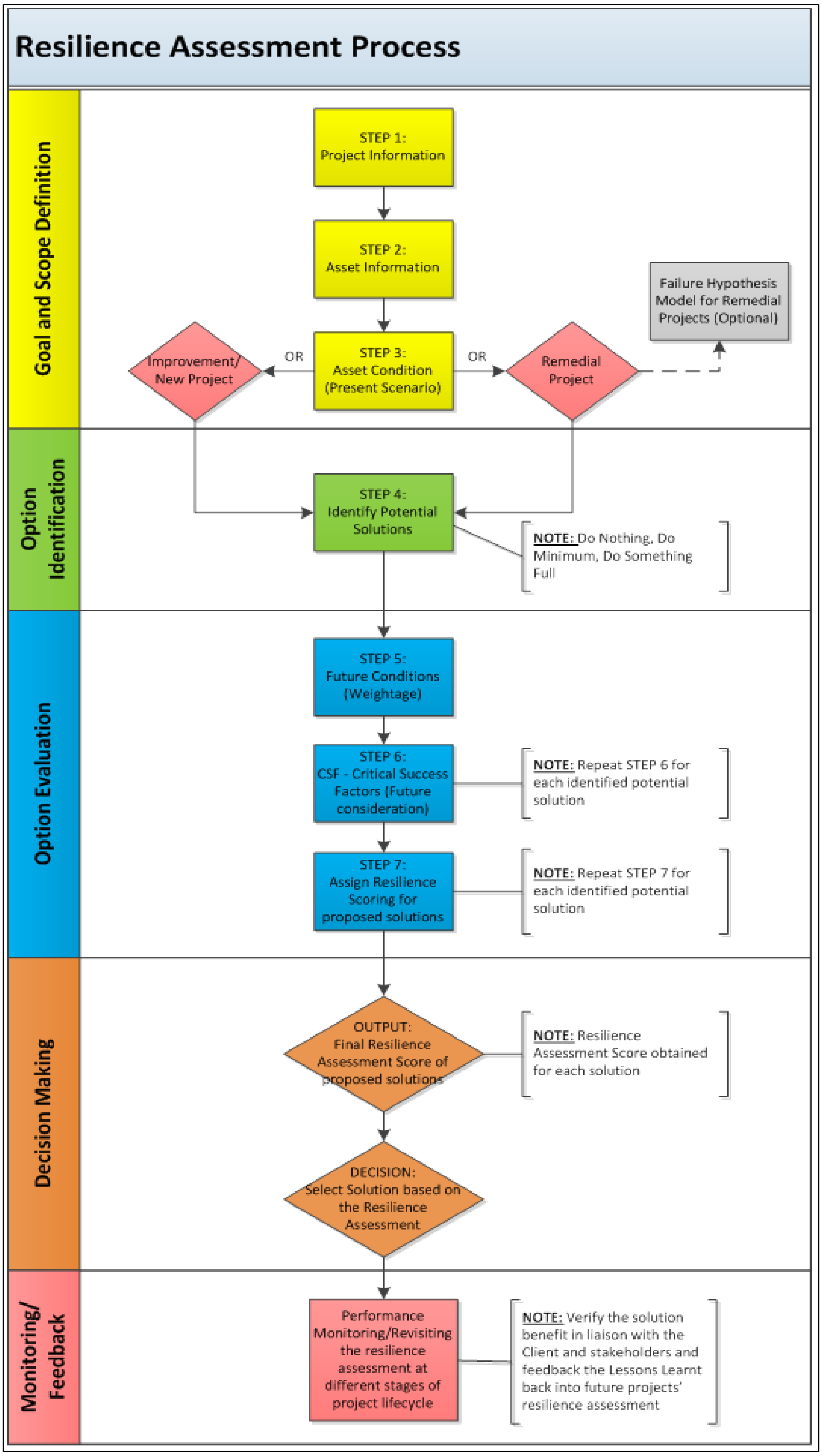


Figure 5.1: Index tab in the Resilience Assessment Tool

5.2.1.1 Step 1 - Project Information:

This is an input step, where the user provides details about the project and stakeholders involved. Information such as envisaged project start and end dates, preliminary assumptions/considerations, type of project, stage at which Resilience Assessment is undertaken etc. It is the second tab in the excel workbook (Figure 5.2).

For example: The project is regarding a deteriorated asset condition requiring remediation or it is an improvement scheme such as the Pinch point Project (i.e. strategic parts of network offered improvement budgets to reduce congestion and improve safety)

Project Name	
Projet Ref. No.	
Document Ref. No.	
Revision No.	
Date first prepared	
Date Updated	
Project Leader	
Project Manager	
Prepared by	
Checked by	
Approved by	

Project Description

Stakeholders Involved

Project Timescale	Project Start Date	Project End Date	Maintenance Schedule

Resilience Assessment Assumptions

Figure 5.2: Project information tab (STEP 1)

5.2.1.2 Step 2 – Asset Information:

In this step, asset information is collected and recorded (Figure 5.3). Information on the asset obtained from a preliminary desk study or ground investigation analysis is interpreted and presented here; this does not yet include the condition of the asset (STEP 4). It is the third tab in the excel workbook.

For Example: Details of asset type, age, surrounding conditions such as topography, geology, environmental conditions, hydrology and history. Typically these are classified as 'GATE2H' which is explained in the notes within the tab.

Asset type	Select
Topography	*Description of the asset and surrounding topography, e.g. height, slope angle, offsets, etc.*
Geology	*Solid -* *Drift -* *Artificial ground -* *Fearutes-*
Hydrogeology	*Waterbodies -* *Aquifers -* *Groundwater vulnerability -* *Flooding -*
Age	*Range from HAGDAMS*
Asset interaction	*Proximity with other assets:* *Structures -* *Pavement -* *Drainage -* *Furniture - (Street lights, cabinets, signs, fencing, safety barrier, etc.)* *Utilities -*
History	*Mining -* *Landfill -* *Previous use -* *Previous failures/remedial works -*
Environment	*Animal burrouwing -* *Vegetation -* *Sensitive Site Designation -* *Cultural Heritage -* *Pollution/Contamination -*
Histotic Information	*Previous reports -* *Boreholes -* *As-built records -* *Lab results -* *Design details -*
Geotechnical Information	*Recent Exploratory Holes -* *Ground Summary -* *Soil Parameters -*
Site Specific Constraints	*E.g. Room available at the toe, highway boundary, maintenance related constraints, environmental constraints, etc.*

Note: In this stage, asset information is collected and recorded. Information from a preliminary desk study or ground investigation analysis is interpreted and presented here. It does not suggest the condition of the asset, but provides information about the asset type and its age and also details related to its surroundings such as topography, geology and history.

The factors can be broadly classified into GATE2H.
Geology which will include solid and drift deposits and the soil fabric with geotechnical properties such as soil classification, design parameters such as density and angle of internal friction, youngs modulus etc and stresses and strains and consolidation and compression properties. It also accounts for details of geotechnical phenomena such as liquifaction and heave and creep if necessary.

Asset interaction implies the interaction and behavious of geotechnical assets with respect to other assets in the network in the vicnity. For example geotechnical asset slope interacts with drainage, highway furniture like street lights, foundations and utilities.

Topography includes the overall site conditions such as the height of the slope, angle of the slope, vegetation cover etc, setback distances between the asset, carriageway and asset owners land.

Environment includes the external enviornment surrounding the asset, such as the biodiversity, precipitation, climate change, flooding etc.

Hydrologeology is the presence of aquifers, ground water and pore water pressure

History includes the history of the asset in terms of its age, construction, design and maintenance records of historic site activity like mining etc and any historic ground improvement undertaken on the site, records of contamination etc is also incuded in this category.

The categories above are divided into more detailed elements representing critical factors that affects singularly or in conjunction with each other the performance of Geotechnical asset which directly affects the condition of the asset. This is discussed in the following tab.

Figure 5.3: Asset information tab (STEP 2)

A subjective assessment is also made of how the asset is likely to deteriorate over the next 5 years (Figure 5.4b) and therefore what Risk Class it may be located in at the end of that period. The period of 5 years is selected based on The Highways England's short-term risk assessment guidance as provided in HD 41/15 (the researcher has adopted the risk assessment technique based on Highways England's guidance HD41/15 and not developed a unique risk assessment strategy as it was not considered within the scope of this research). This is a basic condition assessment based on visual observation and does not currently involve any detailed deterioration modelling.

Reference for this is available in Highways England's Geotechnical Asset Management guidance document (HD 41/15) as a typical pro-forma for principal inspection regime for geotechnical inspections. It is the fourth tab in the excel workbook.

For Example: Presence of Vegetation, Presence of existing failure on or in the vicinity of the concerned asset.

5.2.1.3 Step 3 – Present Asset Condition and short term risk assessment:

In this step, critical factors that affect the current condition of the geotechnical assets are investigated and the user has to tick those applicable for the asset (Figure 5.4a). This records the findings (preferably) from visual inspections of the asset. Factors that are essential to decide the condition of the asset are listed in this step. It is the fourth tab in the excel workbook.

Ref.	Asset Condition	Sub-categories	✓	Description/Comments
1	Loading	Existing Loading Conditions depending on type of road		
2	Water Observation	Seepage		
		Marshy		
		Ponding		
		Erosion		
		Hydrophilic Vegetation		
		High Moisture Content		
3	Drainage	Lined Ditch, Unlined Ditch, Gravel, Pipe, Transverse, Herringbone, Kerb, Culvert, French, Reservation, Watercourse		
4	Pollution/Contamination	Evidence of Pollution/Contamination (BS suite test)		
5	Vegetation	Bare Ground		
		Grass		
		Brambles		
		Shrubs		
		Trees		
6	Animal Burrowing	Presence of Animal Burrowing		
7	Previous remedial works	Reinforced Earth, Existing Sheet Piles, etc.		
8	Interaction with other assets	Existing street furniture, utilities and other structures.		
9	Age			
10	Geology	Weak ground conditions, soil properties, soil fabric, stiffness, strength, stresses & strains		
11	Topography	Slope Height and Angle, location		
12	Soil Phenomena	Liquefaction, shrinkage & swelling, etc.		
13	Features	Soil Slip		
		Slope Bulge		
		Terracing		
		Tension Cracks		
		Dislocated Trees		
		Ravelling		
		Wedge/Block Failure		
		Planar Failure		
		Subsidence		
		Cracked Pavement		
		Dislocated Fence/Barrier		
		Distorted Structure		
		Leachate		
		Desiccation		
		Toe Debris		
		Other Feature		
14	Heave			
15	Creep			

(a) Asset condition

Overall Severity of Risk due to the Asset Condition	✓	Assessed Severity of Risk in 5 Years	✓
Severe		**Severe**	
High		**High**	
Medium		**Medium**	
Low		**Low**	
Negligible		**Negligible**	

(b) Short term risk assessment

Figure 5.4: Asset Condition and Risk assessment tab (STEP 3)

5.2.1.4 Step 4 – Potential Solutions:

Based on the asset information and the critical factors for current condition of the asset, the engineer can determine potential solutions for remediation or improvement depending on the nature of the asset and its condition (Figure 5.5). In this step, the user can record estimated cost(s) and anticipated project duration associated with the respective chosen solution obtained from other costing tools. For example for geotechnical solutions on highways network maintained by Highways England, the user can obtain the whole life cost and economic indicator from PEAT whole life costing tool and record here for the purpose of comparison of proposed solutions. This proposed tool enhances (rather than substitutes) the process of whole life costing, project planning and risk assessment undertaken during any construction scheme. This is the fifth tab in the excel workbook.

For Example: Potential Solutions could be a Do Something (Complete/Holding), Do Minimum or Do Nothing option.

Project Name	

Solution No. 1	
Geotechnical Solution Ref. no.	1
Description	
Solution Type	*e.g. Do Nothing, Do Minium, Do Something Full*
Project Duration	
Estimated Cost	
Comments	

Solution No. 2	
Geotechnical Solution Ref. no.	2
Description	
Solution Type	*e.g. Do Nothing, Do Minium, Do Something Full*
Project Duration	
Estimated Cost	
Comments	

Solution No. 3	
Geotechnical Solution Ref. no.	3
Description	
Solution Type	*e.g. Do Nothing, Do Minium, Do Something Full*
Project Duration	
Estimated Cost	
Comments	

Figure 5.5: Potential solutions tab (STEP 4)

5.2.2. STAGE 2 (Step 5) – Identifying Future Conditions (FC)

This step presents the list of Future Conditions and its impact on the transportation network and the geotechnical assets. This is the sixth tab in the excel workbook. These include aspects encapsulated within the following seven future conditions and are described in detail in Chapter 4 in section 4.3.1:

- FC1 – Demographics
- FC2 – Environmental
- FC3 – Social Changes
- FC4 – Economic Changes
- FC5 – Governance (policy drivers)
- FC6 – Technology / Innovation
- FC7 – Natural and man-made shocks.

Example: A change in demographics occurs that affects the transportation network that connects to the city. This could be attributed to a change in population density of an area, urbanisation patterns and an overall impact of globalisation that has an effect on the trade and migration patterns.

This step allows the asset managers and stakeholders using the tool to assign weights to the Future Conditions on the basis of the relevance of the conditions to the asset under consideration. The FC with the highest weight is clearly considered the most significant to the project. These weightages have significant influence on the overall resilience score; therefore, it is important that they are robust and judiciously assigned through effective stakeholder involvement.

The use of expert opinion for assigning of the weightages is beneficial for two reasons. Firstly, because these weightages are determined by the stakeholders using the tool, one can rest assured that these weightages are consciously chosen after a careful evaluation of the impact of future conditions as relevant to the project, and are duly justified. Secondly, as Costello et al., (2011) noted, most of the existing stochastic or deterministic approaches cannot be applied to the lifecycle planning of geotechnical assets because it is difficult to predict future changes in asset behaviour on the basis of its past performance. The involvement of experts, therefore, helps in overcoming problems associated with limited information. Their familiarity and expertise in dealing with similar assets enables them to offer deep and valuable advice on the asset and its management. The process of arriving at weightages involves in-depth discussions and may require iterative sessions amongst stakeholders. However, as this is a planning toolkit, this step allows for expert consultation and collaborative thinking on multiple agendas that are relevant to the project from the very beginning.

A snapshot from the tool is shown in Figure 5.6. Only one of the future conditions is shown for clarity.

Future Conditions (FC)	FC Ref.	Influencing factors to consider	Impact on infrastructure asset	*User considerations*	*User assigned Weighting %*
Demographics	**FC1**	Change in demographics could be attributed to: a change in population, density of an area, urbanisation patterns and an overall impact of globalisation that has an effect on the trade and migration patterns.	Changes in demography have a direct influence on the infrastructure network and in particular the use of transportation networks. Transportation assets are likely to be affected by usage, need and level of service expected.	The user should envisage the use and purpose of the network and the scale of demographic changes it intends to cater for in the future.	**25%**

Example(s)	Consideration(s)	Justification
Example 1: Imagine a strategic network of road(s) connecting a city with foreseen increasing density.	Consideration 1: the road will require to meet increased demands of traffic which puts additional pressure on the network. This in turn triggers a change in use of assets, resulting in an increased demand for multifunctionality and also increases the need for efficient interaction between different assets on the network.	Provide justification
Example 2: A decreased use of the network occurs due to emigration, poor economic conditions and / or susceptibility to environmental hazards such as floods etc.	Consideration 1: the solutions devised today may be over engineered for the needs of the future.	Provide justification

Figure 5.6: Future Conditions tab (STEP 5)

5.2.3. STAGE 3 (Step 6) – Identifying Critical Factors (CF)

In this part of the nested model, Critical Factors (CF) are identified that affect the performance, serviceability and stability requirements of the geotechnical asset base (Table 4.2). They are drawn from an extensive review of the literature, industrial experience and case studies discussed in Chapter 4 of this report. The list of CF's are defined in Figure 5.7. The user is required to deduce (from the available information they have provided) the relevant CF's that impact upon the chosen asset. They are subsequently categorised as 'relevant' or 'not relevant' in the 'Relevance' column. This is the seventh tab in the excel workbook. In order for the transportation network to perform satisfactorily the Critical Factors of the Geotechnical asset base are deemed critical.

> *Example:* For a slope, whose existing drainage is assessed to be in good condition, but the slope is envisaged to be exposed to increased loading due to change in traffic conditions, the CF1 'flexibility to allow loading variation' is going to be relevant whereas CF3 'drainage' is not relevant because is is not likely to be affected or impaired in this instance.

The derivation of the fixed score assigned to the CFs as seen in Figure 5.7 is explained in detail in STAGE 5 (Step 7) in section 5.2.4.

No.	Critical Factors (Future)	Description	Score (fixed)	Relevance
CF1	Flexibility to allow loading variation	Proposed solution's flexibility and ability to adapt to the loading variations (surcharge, change in use, etc.) causing increased demands and need for multi-functionality.	**8**	**Relevant**
CF2	Seepage Characteristics	Proposed solution's response to Seepage conditions in terms of nature of the material and influence on reducing groundwater and p.w.p.	**3**	**Relevant**
CF3	Effect on Drainage	Proposed solutions response to effectively drain the slope in the event of excessive precipitation and excessive storm water drainage in order to regulate groundwater.	**3**	**Not relevant**
CF4	Effect of Pollution/ Contamination	Effect of pollution and contamination due to triggering of contamination pathways or live traffic and spillages etc. on the solution and its applicability and fitness for purpose.	**7**	**Relevant**
CF5	Impact of Erosion	Proposed Solutions response to erosion caused by water or wind.	**3**	**Relevant**

No.	Critical Factors (Future)	Description	Score (fixed)	Relevance
CF6	Maintaining Bio-diversity	Solution should facilitate and enhance biodiversity	**5**	**Relevant**
CF7	Response to Extreme Climatic Conditions	Proposed Solutions response to extreme climatic events such as excessive snow, extreme temperatures, excessive precipitation causing flooding etc. Flexibility to accommodate increased and change in demands which may increase interaction with other assets.	**7**	**Relevant**
CF8	Flexibility for Interaction with Other Assets	Change in use and multi-functionality resulting from adaptation to increasing demands and changing conditions results in the need to have increased dependencies and interface between proposed solutions and other asset. Flexibility to asset interaction is quite essential in such a dynamic environment.	**8**	**Relevant**
CF9	Ease of Maintenance and Operation	Proposed Solution should be easy to maintain and operate with minimum disruption to road users and not jeopardise safety.	**8**	**Relevant**
CF10	Health & Safety consideration	Construction, Design, and Operation of the proposed solution should not affect health and safety of workers and live traffic.	**10**	**Relevant**
CF11	Flexibility of Use/Multi-functionality	Solutions flexibility to Use of the asset and adaptability to accommodate future expansions and modifications to the network.	**10**	**Relevant**
CF12	Obsolescence/Ease of disposal	Solutions ease of disposal on obsolescence or end of life should cause minimum waste generation and cost implications.	**10**	**Relevant**
CF13	Change in Standards & Policy	Flexibility to adapt to change in standards and policies with minimum modifications and waste.	**10**	**Relevant**
CF14	Whole Life Costing	Overall optimum costs throughout the life cycle of the asset right from material, transport, construction, maintenance and disposal of the solution,	**10**	**Relevant**
	Total		**100**	

Figure 5.7: Identifying Critical Factors (CF) tab (STEP 6)

5.2.4. STAGE 4 (Step 7) – Review of Proposed Remedial Solution

In light of the implications highlighted from STAGES 2 and 3, assessment is made of whether the solution is sufficiently flexible, fit-for-purpose and applicable both now and also in the future. Thus enabling engineers / users to undertake a sensitivity analysis of the different proposed design solution.

5.2.4.1 *Example 1 – 'Demographics'*

Geotechnical assets are likely to be affected by usage, need and level of service expected. An unforeseen increase in traffic density will put additional pressure on the network. This in turn triggers a change in use of the assets resulting in an increased demand for multi-functionality and an increase in the need for efficient interaction between different assets on the network.

Similarly a decrease in use for the network (perhaps due to emigration due to poor economic conditions or due to increased susceptibility to environmental hazards such as floods etc.) may mean the solution devised today may be over-engineered for the needs of the future.

5.2.4.2 *Example 2 – 'Economics'*

Elements such as the funding strategy, budgets (Capital expenditure / Operational expenditure) and its influence on the socio-economic credentials should be considered. Elements such as responsiveness to economic change (agility) is the need of the hour and is an attitude that is envisaged to be carried forward especially on projects where the return on investment is long term such as Private Finance Initiative (PFI) or Design Build Finance and Operate (DBFO) on transportation network. The user has to think along the lines of economic agility, change in funding patterns, whole life costing and its effect on need for multi-functionality, change of standards and policies and an overall attempt to improve the self-sufficiency and integration of the transportation network.

With the current condition of global finances, UK Department for Transport is working towards concerned about 'effectiveness' and 'efficiency' in road asset management specifically in determining what proportion of funding is required to improve the road condition to provide the desired level of service (Odoki et al., 2013). While the UK infrastructure is rapidly ageing and there is an increased need to provide an improved level of service with restricted budgets there are examples of economic agility required where government policies are emphasising on improving the socio-economic conditions of specific regions. Thereby, allocating additional funds for undertaking improvements works in such areas. There are a variety of short to medium term framework contracts commissioned by Highways England for maintaining their highways network such as the Managing Agent Contract (MAC) and Area Support Contract (ASC) contracts. Apart of these maintenance contracts, a separate pool of resources has been used (2013-14) to fund a programme of road improvement projects. These are referred to as the ‘Pinch Point Programme’ (PPP) which aims to improve (widening of roads) strategic junctions on motorway networks (http://www.highways.gov.uk/our-road-network/managing-our-roads/improving-our-network/pinch-point-programme/ accessed, November 2014). This demonstrates the change in economic spending over the years focussed on improving socio-economic conditions of the regions connected by the transport network. The user should think about the new trends such as the effect of global economy influencing local funding decisions. Change in funding policies may affect the budgets for maintenance for future hence requiring more robust solution with less Operational expenditure required in the future. Future discussions related to new policies suggesting privatisation of transportation network while keeping in mind the declining incomes needs to be accounted for.

From example 1, the inter-relationship between the future condition FC1 ‘Change in Demographics’ and critical factor CF1 ‘Flexibility to allow for loading variations’ is deemed important. Example 2 highlights an inter-relationship between the future condition FC4 ‘Economics’ and critical factor CF11 ‘Flexibility of use/multi-functionality’. A similar approach needs to be undertaken for determining the inter-relationships for all other future conditions and (relevant) critical factors as explained in Chapter 4 with examples [N.B. Interrelationships for each ‘Future Conditions’ and ‘Critical Factors’ is discussed in Section 4.3.3].

5.2.5. STAGE 5 (Step 7) – Application of scoring and weightings

In this step a multi-criteria decision analysis is developed for the proposed solution(s) with an intention to test their resilience. A scoring system is subsequently applied using an innovative matrix of future conditions (Table 5.1a), in line with Table 4.4 Only six of the fourteen critical factors are included for clarity.

Firstly, The future conditions receive a weighting (W) based on the requirements of relevant outlined users (e.g. asset owners, government organisations and other clients), engineers, subject matter experts, asset management professionals, etc.

substantial stakeholder liaison is required in order to discuss the importance of future conditions, for the project and depending on the priorities and requirements of these stakeholders, appropriate weightings can then be adopted. The user should be able to provide a justification for the choice of his/her weightings so that there is a justified rationale in the selection. A snapshot of the tab is shown in Figure 5.6 in the previous section. For the purpose of simplicity, only one Future Condition is shown in figure 5.6. It can be seen that, the FC is described in the first column; its impact on transportation network is explained in the subsequent column followed by user considerations and examples. There is also an option for giving all the future conditions (by default) equal weighting.

The Step 7 tab consists of the Resilience Scoring Matrix. As mentioned above, in this matrix, the weightings provided by the user in STEP 5 is automatically shown in the column adjacent to corresponding FC. Also predetermined scores for Critical Factors discussed in Step 6 are shown in the row below for the corresponding CFs. The project information is reflected and the preferred solution is shown in the top left of the worksheet. There are three separate matrices currently provided to be able to assess three proposed solutions. These can be further copied and expanded to include more options, as required.

Secondly, the asset design solution is assessed for each critical factor in the light of each relevant future condition to see if an interrelationship exists. Un-shaded cells represent the existence of an inter-relationship and shaded cells represent a non-existent or non-relevant inter-relationship (Table 5.1b). A Critical Factor score (Cx) is then calculated from Equation 2.

$C_x = A / B$ - Equation 2

Where,

- C_x = Critical Factor Score, where x is the column numbering within the matrix (e.g. C_1 in Figure 5.6)

- A = No. of un-shaded cells in each CF column (e.g. for column CF1, A = 6 in Table 5.1b)
- B = Total No. of un-shaded CF cells in all CF columns (e.g. B = 24 for Table 5.1b)

For example, in Table 5.1b, $C_1 = 6 / 24 = 0.25$

Thirdly, solution scores (S_{xy}) are assigned within un-shaded cells based on existence of an interrelationship within the matrix (example scoring is given in Table 5.1b to illustrate the process). Where x and y are used to define the intersection points within the matrix. Scores range from -3 (Least resilience potential) to +3 (Most resilience potential) - Table 5.2 shows an example of a clearly defined scoring key used for the purpose of this study. Lastly, a resilience score (RS) is calculated for each row according to Equation 3.

$$RS_y = W_y \sum (C_x \times S_{xy}) \qquad \text{- Equation 3}$$

Where,

- RS_y is the Resilience score
- W_y = Weighting (e.g. W_1 = 30 for FC2)

For example, in Table 15b, $RS_2 = 30 \times [(2 \times 0.25) + (-2 \times 0.125) + (-3 \times 0.208) + (2 \times 0.167)] = -1.3$

Table 5.1a: Innovative matrix of future conditions for an asset design solution (Illustration)

Future condition (FC)	Weighting (W)	Critical Factors (CF)						Resilience Score (RS)
		CF1	CS2	CF3	CF4	CF5	CF14	
		C_1	C_2	C_3	C_4	C_5	C_{14}	
FC1 - Demographics	W_1	S_{11}	S_{21}	S_{31}	S_{41}	S_{51}	S_{141}	RS_1
FC2 – Environment	W_2	S_{12}	S_{22}	S_{32}	S_{42}	S_{52}	S_{142}	RS_2
FC3 – Social	W_3	S_{13}	S_{23}	S_{33}	S_{43}	S_{53}	S_{143}	RS_3
FC4 – Economics	W_4	S_{14}	S_{24}	S_{34}	S_{44}	S_{54}	S_{144}	RS_4
FC5 – Governance	W_5	S_{15}	S_{25}	S_{35}	S_{45}	S_{55}	S_{145}	RS_5
FC6 - Tech/Innovation	W_6	S_{16}	S_{26}	S_{36}	S_{46}	S_{56}	S_{146}	RS_6
FC7 - Shock events	W_7	S_{17}	S_{27}	S_{37}	S_{47}	S_{57}	S_{147}	RS_7
							Total Resilience Score	RS_{total}

Table 5.1b: Example using Innovative matrix of future conditions for an asset design solution (Illustration)

Future condition (FC)	Weighting (W)	Critical Factors (CF)						Resilience Score (RS)
		0.250	0.083	0.125	0.208	0.167	0.167	
FC1 - Demographics	10	3						7.5
FC2 - Environment	30	2		-2	-3	2		-1.3
FC3 - Social	5	1				-1	-3	-2.1
FC4 - Economics	30	2		-2	1		-2	3.8
FC5 - Governance	10	-2	1		2	0		0.0
FC6 - Tech/Innovation	20	3		2.3	-1		2	23.3
FC7 - Shock events	5		1		3	0	0	3.5
							Total	34.7

Table 5.2: Example of scoring key

Score	Description
+3	Existing solution works with no change in design
+2	Existing solution works with minor amendments and cost and time implications
+1	Existing solution with room for improvement to design with time and cost implications

Table 5.2: Example of scoring key	
Score	**Description**
0	Neutral or Not Applicable
-1	Existing solution requires design changes with additional time and cost implications
-2	Existing solution requires substantial design amendments to its original form and surrounding area with time and cost implications
-3	Existing solution does not work and requires replacement with re-engineered solution having time and cost implications

Lastly, a Total Resilience Score (RS total) is found by summing all resilience scores in the column. In this example these total 34.7

Although, the final output is in the form of a total resilience score, it is also possible to see in which future condition is the solution most resilient (i.e. 'Technology / Innovation' in Table 5.1b) and in which is it least resilient (i.e. 'Social' in Table 5.1b).

5.2.6. Scoring

Ultimately, the resilience score for a solution can be seen as a numeric value that serves as a comparator, indicating whether a particular solution is better or worse than the other alternatives proposed. The purpose of the tool is not to ensure that a particular solution achieves a definitive or target score; however, the scoring mechanism provides a tangible measure of assessing if a solution may perform significantly better or worse than its alternatives in the long run. For instance, it is likely a solution that fares well on most the future conditions may receive a poor score on a critical future condition, with a high weight. This may suggest that the solution is not resilient with respect to that particular future condition from a long-term perspective.

This tool is a thinking tool to be used in the planning stage which enables the user to compare and appraise potential solutions from a long-term perspective. The proposed framework can be adopted at the 'options analysis' stage for asset management systems (strategic) or engineering design (operational) where different options are evaluated and a feasibility analysis is undertaken to select the most technically sound, cost effective and sustainable solution. Anyone can use the framework from the stakeholders to the client, project manager and the designer. The benefits are seen across the project.

> *Example:* For a strategic network of roads connecting a city with foreseen increasing density, the road will be required to meet increased demands for traffic, which will put additional pressure on the network (and geotechnical asset).
>
> For the Critical Factor 'Flexibility to allow variation in loading' (CF1), if the proposed solution is able to cope with changing loading patterns with minimal alteration and no changes to the design with the 'Change in Demographics' (FC1) then it is awarded a +3 (as assumed in Table 5.1b) suggesting it is a highly resilient solution for that future condition. On the other hand, if the proposed solution, was expected to be of no use under changing loading conditions to such an extent, that the existing solution would have to be demolished and replaced, imposing additional time and cost implication, it would have been given a -3.

Based on feedback from the initial test, one of the critical feedbacks was to introduce a mechanism in the tool where the total output of a project could be compared with other similar projects using a common benchmark. As a result, an additional step in the algorithm was introduced, which calculates the 'ideal' resilience score for each future condition. The ideal resilience score for a FC is calculated by assuming a weighting of 100% for that FC and a solution score (S) as +3 (i.e. most resilient) for all the corresponding relevant CFs. The resilience score (RS) when divided by this 'ideal' score provides the Resilience Future Condition Score (RF). Therefore, the ideal score becomes the benchmark against which all RS are compared. The summation of all RF scores for all future conditions gives the Total Resilience Score (TRS). The TRS is a score that is out of a total of 100 and hence is comparable unit of measurement of Resilience score for different projects. This is represented in Equation 4.

$$\sum \text{TRS} = \sum_{y=1}^{n} RF_y = \sum_{y=1}^{n} \left(\frac{RS_y}{ideal\ score_y} \times 100\right)$$ - Equation 4

Where,

- TRS = Total Resilience Score (out of a total of 100)
- RF_y is the Resilience Future Condition Score for each future condition
- RS_y is the Resilience Score for each future condition

5.2.6.1 Example for each Future Condition

Demographics:

Consider and embankment widening scheme on an urban road or a strategic motorway connecting busy cities: The proposed solutions are to widen the embankment with imported fill or by provision of sheet pile retaining wall at the toe. These solutions can be both technically sound and depending on site specific conditions viable for the proposed widening work. However, with changing demographics considering majority of population migrating towards cities may lead to an increase in the number of motorway users thereby increasing the usage of the network. This has an impact on the change in use of the network. Also, with increasing trade and demands more haulage and special vehicles may be used in the future hence arising the need to provide flexibility to account for increased loading due to this changing nature of network usage. Resilience Assessment for Sheet Pile Walls and Re-grading with imported fill is to be undertaken keeping in mind the aforementioned scenario.

With the need to accommodate increased traffic loading by provision of an additional lane there might be future widening works required along the same section of this strategic road network. If the additional loading is more than the inbuilt design capacity, amendments in the existing design solutions may be required. In such a case, the sheet pile walls option may need to be removed and replaced with a more fitting solution to account for the increased loading. It is also important to acknowledge that this will require major works and higher costs in removing the sheet piles. However, with the option of re-grading using imported fill, additional support reinforcements and strengthening works can be provided with minimal disruption to proposed solutions to account for such probable increased loadings. Hence for this example, a scoring of -2 is provided for sheet pile wall and +2 for re-grading with engineered fill.

For the same scenario due to the change in usage of the network additional widening works may be required to provide additional traffic lanes for increased volume of traffic. A similar principle can also be applied on this instance. Sheet Pile Walls are less flexible to allow accommodate additional earthwork widening whereas regarding with engineered fill can be cut back to appropriate design widths and can be incorporated as a part of new solutions such as provision of soil nails or other retaining structures. Hence, rendering a similar scoring of -2 and +2 for sheet pile wall and Re-grading respectively.

Social:

With recent increase in health and safety standards and importance, the Highways England's standard for safety barriers design (TD19/06) have amended (increased) their Working Width requirements behind safety barriers to a safer standard. Due to this, those safety barriers which were considered at risk are to be replaced with barriers as per latest standards and requirements. As a result, changes to existing earthworks supporting these carriageways are required. Imagine an embankment slope where proposed widening works to accommodate the new safety barrier and increased Working Width distance behind the barriers are to be undertaken. Due to site specific constraints of limited room at the toe of the embankment, retaining wall solution is proposed. Two solution options considered are Gabion Wall and Sheet Pile Wall.

In the future if considering the changing Social requirements of increased importance on improving and maintaining bio-diversity is laid, then a solution that offers the flexibility to grow vegetation or harbour nesting birds is much preferred than the once which doesn't. Hence, with Gabion Wall solution there is a possibility to grow vegetation and also possibility for provision of nests for species, if required, whereas, sheet pile walls provide limited flexibility to accommodate the same unless major changes are done to its existing slope profile. Hence for this scenario within this example, Gabion Wall can be scored as +2 while Sheet Pile Wall can be scored as -1 (considering some possible amendments in the future).

Environment:

Performance of the proposed solution under the influence of increased precipitation, extreme weather conditions, increased pollution/contamination, promoting bio-diversity, influencing waste-generation, conservation of Heritage and sensitive areas and promoting sustainability.

For example on a cutting slope, a slip failure has occurred due to increased precipitation, increased loading at the toe and existing drainage system unable to cope with the same. The remedial solutions considered are (1) re-grading the slope by replacing the slipped material with engineered fill (Do Minimum Option) and (2) remediate the slope by removal of slipped material and provision of counterfort drains, thereby improving the drainage capacity of the slope (Do Something Option).

Hence in this case, for the Environment Future Condition highlighting increased precipitation, flash flooding, geotechnical assets such as slopes have to deal with increased pressure on ‘drainage’ to keep them dry and release pore water pressures. Hence provision of counterfort drains (Solution 2) is a longer term solution than the replace and re-fill option (Solution 1), as it not only remediates the failed slope but also meets the needs of increased susceptibility to Environmental changes in the future. Hence in this case solution 2 would get a score of +3 because the solution will remain fit for purpose under the Environment FC with no changes to the design necessary. While, solution 1 would get a score of -1 because the solution will require design changes with additional time and cost implications.

Similarly for the CF of ‘Impact of Erosion’ and FC of ‘Environment’, the Solution 1 would get a score of -2 because the solution will require substantial design amendments to its original form and surrounding area with substantial time and cost implications. While, Solution 2 will get a score of +2 because the solution will allow for increased storm water drainage preventing erosion of the slope and may require minor amendments for future capacity improvement.

Governance:

Does the performance of the proposed solution rely on specific policies and regulations. Will change in governance (policies, security of funding etc.) have an effect on maintenance and operation of the proposed solution? Policies governing waste regulations may affect the operation and disposal of transportation assets and its interaction with other assets.

For example, consider a cutting that requires to be retained for provision of a pedestrian footpath for a road widening scheme. The proposed solutions are (1) Sheet Pile Wall with aesthetic painting and (2) Crib Wall with vegetation planting. In this case, the Sheet Pile walls will require regular maintenance for painting also generating waste from this. While the Crib Wall may require some vegetation maintenance, but very minimal and will not involve any waste generation. Hence, for the CF ‘Effect of Pollution/Contamination’ and FC ‘Governance’ considering that in the future the waste regulations change with stricter norms, the Solution 1 would get a score of -2 because paining the sheet pile wall every few years will generate pollutants, the disposal of which will have cost and environmental implications. While the Solution 2 in this case will get a score of +2 because it will in fact help in meeting the stricter regulations by no waste generation, but will still require some maintenance.

Similarly, for the CF of ‘Ease of Maintenance and Operation’ the Solution 1 will get a score of -2 because it will require substantial maintenance regime and costs and will also require disruption to the public during the maintenance. While solution 2 will get a score of +2 because it still requires some maintenance of vegetation, but it can be done relatively easily with minimal costs and disruption to the public.

Technology/Innovation:

Does the proposed solution offer innovative, leaner, efficient credentials. Does the solution offer flexibility to accommodate for future changes in technology. Does the solution allow multi-functionality?

For example, for a remediation of a cutting slope on the side of a strategic trunk road, the solution options being considered for the same are (1) Soil-nailing and (2) Re-graded Slope with new engineered fill. For the FC 'Technology/Innovation' consider the technological innovation in telecommunications requiring installation of substantial new utilities along the road. In this case, for the CF of 'Flexibility for Interaction with Other Assets', option 1 will score -2 because installation of the additional utilities will require substantial amendments to the soil nailed slope and hence disruption to the other surrounding assets; While, option 2 will score +2 because it will allow the flexibility to incorporate the installation of additional utilities with minimal changes to the design and minimal disruption to the interaction between these assets.

Shock Events:

Does the solution account for shock events in its design. Does the proposed solution provide redundancy in the event of extreme events without harming the society. Does the solution increase the inter-dependency or affect other surrounding assets. Does the proposed solution account for reasonable recovery of the network post an extreme event.

For example, for a flood bank protection scheme the options considered are (1) Gabion Walls and (2) Bio-Engineered slopes. For the FC 'Shock Events' consider the extreme shock event like large scale flooding due to storms, hurricanes (e.g. Sandy Hurricane in US in 2012) and/or flash flooding causing the failure of either of the solutions. In this case, for the CF of 'Response to Extreme Climatic Conditions', the Solution 1 will score -3 because post the event, the gabion wall will require full replacement. While for Solution 2 the score will be -1 because post the event, it will require some design changes but can be remediated with comparatively lesser cost implications.

5.2.7. Output and Decision tabs

Results from the Resilience Assessment Matrix (STEP 7) are recorded here in the Output tab (Figure 5.8). The results from STEP 7 automatically get fed in Resilience Score cell within this Tab. There is a column for comments which allows the user to provide comments on the output. Finally, in the Decision Sheet (which is a separate Tab, Figure 5.9), the user has to input his choice for considering the solution most resilient and provide reasons supporting the same.

OUTPUT - Final Resilience Assessment Score of proposed solutions

Project Name	
Solution No. 1	0.0
Geotechnical Solution Ref. no.	1.0
Description	0.0
Resilience Score	#VALUE!
Comments	

Solution No. 1	0.0
Geotechnical Solution Ref. no.	2.0
Description	0.0
Resilience Score	#VALUE!
Comments	

Solution No. 1	0.0
Geotechnical Solution Ref. no.	3.0
Description	0.0
Resilience Score	#VALUE!
Comments	

Figure 5.8: Output tab

DECISION - Select Solution based on the Resilience Assessment

Project Name	
Decision	
Solution No.	
Geotechnical Solution Ref. no.	
Description	
Resilience Score	
Comments	

Figure 5.9: Decision tab

5.3. Case Studies

This section discusses the case studies used for validating the research and the usability of the tool. The data for the two case studies considered, have been obtained from two actual sites in the UK: one remediation project and one improvement project (new build). The former is located on the northbound carriageway of the M42 between Marker post 22/5 and 22/7 near Coleshill in West Midlands and the latter at the junction 2 of motorway M5 in Birmingham in West Midlands These two projects are representative of the types of geotechnical asset management plans and decisions typically undertaken by the road and highway network authorities in the UK. The new build project addresses challenges encountered as part of a pinch-point programme (PPP), which is a government initiative to alleviate congestion and improve the economic growth of strategic locations. PPPs play a key role in furthering the socio-economic development of the communities accessing the asset, and the first case study has been selected with a view to exploring the viability of the decision-making tool in the execution of such critical asset management solutions. The second case study is a remediation project that is part of the ‘Smart Motorway Programme’, formerly known as ‘Managed Motorway Programme’, undertaken by Highways England to decongest environmentally sensitive areas during peak hours. This case study serves to illustrate the effectiveness of the decision-support tool in identifying an optimal solution under situations involving multiple constraints such as an SSSI area. It illustrates how the tool can assist managers in selecting solutions that balance maintenance and conservation. Data for both these case studies were collected through observation and from Highways Geotechnical Data Management System (HAGDMS). This 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, UK. The sponsoring organisation Amey and The Highways Agency (known as Highways England since April 2015) agreed to allow the researcher to access this information and use it in the study.

The information pertaining to the real projects considered in the case studies, are captured within the discussion and working of the case studies. While validating the tool through the workshop technique, the researcher used the expert knowledge inputs of the workshop attendees, comprising geotechnical experts, consultants, engineers, and project client, to arrive at the weightages for the future conditions. This process was chosen because it closely simulates the actual settings in which the tool is expected to be used.

5.3.1. Case Study 1:

This case study is an improvement scheme, as a part of the nation-wide pinch point programme (PPP). The scheme consists of undertaking an embankment widening on a strategic motorway in England. The pinch point programme was included as a part of the governments growth strategy in order to improve the strategic junctions of the road network which can help stimulate growth and development in the local economy while alleviating congestion and improving safety.

For the ease of representing the details of this case study and keep it concise without repeating the use of each Step of the tool, which is already discussed in Section 5.2 only 5 of the steps are explained below for providing information about the case study. These steps include Step 1 – Project Information, Step 2 – Asset information, Step 4 – Identify Potential Solutions, Step 5 – Future Conditions (Weightages) and Step 7 – Resilience Assessment Matrix.

5.3.1.1 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. It also includes resilience assessment assumptions for the proposed scheme, which should ideally be captured and recorded at the start of the project. The resilience assessment assumption for the proposed case study is:

‘The traffic in the local area, especially at this junction has already seen a significant increase during peak hours and is likely to continue this upward trend along with other developments nearby like retail park, shopping areas, etc. Hence this area will be of great socio-economic interest to the local community.’

See Figure 5.10 for the Project Information tab for Case Study 1.

Project Information

Pinch Point Programe	
Projet Ref. No.	Example 1
Document Ref. No.	Case study 1
Revision No.	A
Date first prepared	13-Apr-14
Date Updated	13-Apr-14
Project Leader	*Name*
Project Manager	*Name*
Prepared by	*Name*
Checked by	*Name*
Approved by	*Name*

Project Description
This is an improvement scheme consisting of embankment widening on a strategic motorway junction.

Stakeholders Involved
Asset Owner, Asset Managing Contractor and Designer and end-users

Project Timescale	Project Start Date	Project End Date	Comments
	13 October 2012	15 January 2013	

Resilience Assessment Assumptions
Improvement works are proposed as a part of the Pinch-point programme (PPP) which is a government initiative to alleviate congestion on strategic parts of the network and improve economic growth in the area. The traffic in the local area, especiialy at this junction has already seen a significant increase during peak hours and is liekly to continue this upward trend along with other developments nearby like retail park, shopping areas, etc. Hence this area will be of great socio-economic interest to the local community. This should be considered as a

Figure 5.10: Project Information tab for Case Study 1

5.3.1.2 Step 2 – Asset Information

The asset information collected and recorded in this step includes information from a preliminary desk study or ground investigation analysis is interpreted and presented here. It does not suggest the condition of the asset, but provides information about the asset type and its age and also details related to its surroundings such as topography, geology and history.

For this case study, the asset is an ‘Embankment’ having a maximum height of 5m and a slope angle of 26^{o}. The length of the earthwork widening scheme is approximately 200m. The geology comprises of glaciofluvial deposits overlying sandstone. There is a presence of a culvert within the slope along with a head wall. There are no records of any historical defects or previous remedial works in the vicinity of the proposed site. However, historic records suggest that the embankment was constructed using landfill material comprising of bricks, rubble, concrete, etc. this may have traces of contamination. There is limited room at the toe of the embankment within the asset owner's boundary and the proposed solution should take this into consideration.

The next step is to determine the asset condition. However, as this is an improvement scheme and no records of any defects were found. This is an improvement scheme and not a remedial scheme and hence the next Step 3 is not included in this case study description. See Figure 5.11 for a snapshot of the Asset Information tab for Case Study 1.

Asset Information

Asset type	Embankment
Topography	*There is a embankment with a maximum height of 5m and slope angle of 26 degree for a length of 200m. A culvert with headwall is present at mid way the length of the emabnkment. The adjacent earthwork is at grade on the north end and followed by a cutting.*
Geology	*Solid - Bridgenorth sandstone* *Drift - Glaciofluvial deposits* *Artificial ground - landfill material found* *Fearutes - no geological features present*
Hydrogeology	*Waterbodies - culvert with headwall present* *Aquifers - secondary* *Groundwater vulnerability - low* *Flooding - not in an area prone to flooding*
Age	*Range from HAGDMS - 50 - 70 years*
Asset interaction	*Proximity with other assets:* *Structures - headwall, supporting motorway carriageway.* *Pavement - yes.* *Drainage - yes, road drain at the crest of embankment and toe drain along with culvert.* *Furniture - (Street lights, cabinets, signs, fencing, safety barrier, etc.) ALL.* *Utilities - Refer to STATS plans. Cable Duct running at the crest of embankment.*
History	*Mining - not present* *Landfill - yes, comprising of asbestos, bricks, rubble, concrete, etc.* *Previous use - none* *Previous failures/remedial works - none*
Environment	*Animal burrouwing - not present* *Vegetation - present, but will be cleared as a part of the works* *Sensitive Site Designation - N/A* *Cultural Heritage - N/A* *Pollution/Contamination - contamination may be present due to landill material*
Histotic Information	*Previous reports - link provided* *Boreholes -* *As-built records -* *Lab results -* *Design details -*
Geotechnical Information	*Recent Exploratory Holes - link to Ground Investigation report* *Ground Summary -* *Soil Parameters -*
Site Specific Constraints	*Refer to General Arrangment drawing for details. Constrained space at the toe of embankment due to proximity of asset owner boundry*

Figure 5.11: Asset Information tab for Case Study 1

5.3.1.3 Step 4 – Identify Potential Solutions

Based on the site conditions the proposed remedial solutions for undertaking the embankment widening comprise of retaining wall solutions which can accommodate the widened earthwork within the site boundary. Hence the recommended solutions to be considered for this case study are, Sheet Pile Wall and Gabion Retaining Wall (See Figure 5.12). Considering the nature of the works it was not feasible to provide a 'Do minimum' option and hence bot options considered are 'Do something'.

Identify Potential Solutions

Pinch Point Programe	
Solution No. 1	Gabion Wall for supporting the Embankment widening
Geotechnical Solution Ref. no.	1
Description	Provision of Gabion Retaining wall using woven steel mesh at 6 degrees angle with and Class 6N backfill material. Refer to specifications and preliminary desgins for more details.
Solution Type	*Do Something*
Project Duration	6 months
Estimated Construction Cost for solution	*To be input from cost estimate*
Estimated Whole-life cost for solution	*To be input from whole life costing assessment*
Comments	Due to the presence of the landfill material at approximately 5m below the ground level (at toe wall), the formation level for Gabion wall should not be dug more than 3 m below ground level

Solution No. 2	Sheet Pile Wall
Geotechnical Solution Ref. no.	2
Description	Provision of embedded Steel Sheet Pile wall with Class 6N backfill material. Refer to specifications and preliminary desgins for more details.
Solution Type	*Do Something*
Project Duration	6 months
Estimated Construction Cost for solution	*To be input from cost estimate*
Estimated Whole-life cost for solution	*To be input from whole life costing assessment*
Comments	There is a presence of the landfill material at approximately 5m below the ground level (at toe wall).

Figure 5.12: Identify Potential Solutions tab for Case Study 1

The next Steps 5 and 6 are not explained in detail here as that will be a repeat of information from Section 5.2. However, the considerations are explained in some detail in the next Step 7 when explaining the Resilience Assessment scoring process

5.3.1.1 Step 5 – Future Conditions (Weightages)

The weightages for the future conditions are assigned using pair wise comparison technique and the methodology is explained in detail in section 4.6. The results from the stakeholder consultation used for the case study is shown in figure 5.13.

Future Conditions	Total Score
FC1	5
Fc2	2
Fc3	5
Fc4	4
Fc5	2
Fc6	1
Fc7	1

Table 5.13: Result of pair wise comparison for case study 1.

Thus from this exercise, we can say that FC 1 and FC 3 are the highest ranking future conditions, followed FC4 followed by FC2 and FC5 (share the rank) followed by FC6 and FC7 (share the rank).

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

$100 = 5x + 2x + 5x + 4x + 2x + 1x + 1x$ - Equation 5

$x = 5$

Thus weightages are as follows:

- FC1 – 25%
- FC2 – 10%
- FC3 – 25%
- FC4 – 20%
- FC5 – 10%
- FC6 – 5%
- FC7 – 5%

5.3.1.2 Step 7 – Resilience Assessment Scoring Matrix

Based on the explanation of the case study, the resilience assessment scoring is explained below for Future Conditions of Demographics, Social and Economics in Table 5.3, 5.4 and 5.5 respectively. Demographics, Social and Economy are three key FCs for this case study (high weightage and relevance) and hence these are considered for explaining the scoring process. Explanation of each FC with examples is provided in section 5.2.5.1 and hence in order to avoid repetition explanation of scoring is shown for three main FC important for this case study. The scoring for solution number 1 and 2 is shown in Figure 5.14 and Figure 5.15 respectively.

Table 5.3: Resilience Assessment for FC1 Demographics

Critical Factor (CF)	Scoring and Reasoning
Flexibility to allow loading variation	With the need to accommodate increased traffic loading in the future due to foreseen development of the surrounding area and overall urbanisation, provision of an additional lane there might lead to future widening works. If the additional loading is more than the inbuilt design capacity, amendments in the existing design solutions may be required. In such a case, the sheet pile walls option may need to be removed and replaced with a more fitting solution to account for the increased loading. It is also important to acknowledge that this will require major works and higher costs in removing the sheet piles. However, with the replacement of Gabion Wall it is also will require major works but the costs of may not be as high as the Sheet Pile Wall replacement. Hence for this example, a scoring of -3 is provided for sheet pile wall and -1 for Gabion Wall.
Effect of Pollution/Contamination	Not applicable for both the solutions, unless the contamination gets a pathway from gabion foundation which is unlikely. Hence the score for both solutions is 0.

Table 5.3: Resilience Assessment for FC1 Demographics	
Critical Factor (CF)	**Scoring and Reasoning**
Maintaining Bio-diversity	Gabion wall provides flexibility to allow for vegetation and animal habitats. This is not possible with sheet pile wall. This is important from the perspective of increasing urbanisation as Bio-diversity maybe given more importance in the future. Hence a score of +2 and -1 is given to gabion and sheet pile walls respectively.
Flexibility for interaction with other assets	Both solutions do not offer flexibility to accommodate new utilities, drains, etc. and hence a score of -3 is given to both of them. However, if an option of 'embankment construction using engineered fill' was an option, then this would allow the flexibility to accommodate new asset installation with minimal design changes and hence this would have offered a positive score.
Ease of operation and Maintenance	In the light of increasing demographics and hence increasing traffic conditions, it is preferable if the solutions need less maintenance, as this would reduce the number of interventions and therefore reduce disruption to traffic. Sheet pile wall may require occasional re-painting, but gabion walls do not require maintenance. But both these options require monitoring. Hence a score of -1 for Sheet Pile Wall and +3 for gabion wall is given.
Health & Safety consideration	Both the options require hardly any maintenance and solutions do not pose any H&S risks. In fact, they improve the H&S credential of the network by allowing improvement works and hence both will get a score of +3 as compared to a 'Do nothing' or a 'Do minimum' options which in the future may have a potential of posing H&S risk.
Flexibility of use and multi-functionality	Due to increased demographics the solutions are required to offer more multi-functionality. Both the solutions provide flexibility to offer multi-functionality hence both options are assigned a score of +2 as this is possible with minimal changes to the solutions.
Obsolescence and Ease of Disposal	If the demographics increase, and retaining wall needs replacing, the gabion fill material can be re-used, whereas steel sheet pile walls only provides scrap value. Hence a score of +2 for gabion wall and +2 for sheet pile wall is given.
Change in Standards and Policies	Increase in demographics/increase in use may result in introduction of policies (funding) leading to additional improvement works. Hence requiring flexibility to allow changes and expansion. Also, in an event where increase in the design loading is not significantly high, we may be able to reinforce the existing gabion wall to support increased loading by increasing a level of gabion basket. Such flexibility is not allowed by Sheet Pile Wall. Hence for this example, a scoring of -2 is provided for sheet pile wall and -1 for Gabion Wall.
Whole Life Costing	Due to the required maintenance regime and construction cost for sheet pile wall, the whole life cost for this options will be more than gabion wall. Hence the score of -1 and +2 is given to sheet pile and gabion wall respectively. The score of +2 is because there is also a cost associated to the disposal of the wall material.

Table 5.4: Resilience Assessment for FC3 Social	
Critical Factor (CF)	**Scoring and Reasoning**
Flexibility to allow loading variation	With the need to accommodate increased loading due to change in social needs of increased haulage and safety. If the additional loading is more than the inbuilt design capacity, amendments in the existing design solutions may

Table 5.4: Resilience Assessment for FC3 Social	
Critical Factor (CF)	**Scoring and Reasoning**
	be required. In such a case, the sheet pile walls option may need to be removed and replaced with a more fitting solution to account for the increased loading. It is also important to acknowledge that this will require major works and higher costs in removing the sheet piles. However, with the replacement of Gabion Wall it is also will require major works but the costs of may not be as high as the Sheet Pile Wall replacement. Hence for this example, a scoring of -3 is provided for sheet pile wall and -1 for Gabion Wall.
Effect of Pollution and Contamination	Due to change in social behaviours in the future there may be increased contamination/pollution. In this case, the gabion wall may act as a potential pathway for contamination, while sheet pile will is not likely to do the same. Hence, sheet pile option will get a score of 0 as it is not applicable while gabion wall will get a score of -2.
Maintaining Bio-diversity	Gabion wall provides flexibility to allow for vegetation and animal habitats. This is not possible with sheet pile wall. This is important from the perspective of increasing urbanisation as Bio-diversity maybe given more importance in the future. Hence a score of +2 and -1 is given to gabion and sheet pile walls respectively.
Response to Extreme Climatic Conditions	In the event of an extreme climatic event like flash floods, etc. sheet pile walls are more stable than gabion walls as they are embedded deep into the soil. Hence for this FC, the sheet pile wall option will get a score of +2 while gabion wall option will get a score of -2. It is important that the solution should be able to respond to what the society expects, in the form of an increased level of service, requiring a network that is accessible and operational also during extreme climatic events.
Ease of operation and Maintenance	In the light of increasing constraints due to social requirements in the future, it is preferable if the solutions need less maintenance, as this would reduce the number of interventions and therefore reduce disruption to road users. Sheet pile wall may require occasional re-painting, but gabion walls do not require maintenance. But both these options require monitoring. Hence a score of -1 for Sheet Pile Wall and +3 for gabion wall is given.
Health & Safety consideration	Both the options require hardly any maintenance and solutions do not pose any H&S risks. In fact, they improve the H&S credential of the network by allowing improvement works and hence both will get a score of +3 as compared to a 'Do nothing' or a 'Do minimum' options which in the future may have a potential of posing H&S risk.
Flexibility of use and multi-functionality	If due to increased social requirements in the future of providing and using cycle-ways and walkways, both the solutions provide the possibility to install a hand rail in the future to accommodate the same. Hence providing multi-functionality rendering both options getting a score of +2 as this is possible with minimal changes to the solutions.
Obsolescence and Ease of Disposal	In this case the explanation will be similar to that of the aforementioned 'Demographics' FC. Hence if the retaining wall needs replacing due to changes in social requirements, the gabion fill material can be re-used, whereas steel sheet pile walls only provides scrap value. Hence a score of +2 for gabion wall and +2 for sheet pile wall is given.

Table 5.4: Resilience Assessment for FC3 Social	
Critical Factor (CF)	**Scoring and Reasoning**
Change in Standards and Policies	If due to changing social requirements there is a change in standards or policies demanding improved safety considerations, the gabion wall provides some flexibility in terms of reinforcing its strength by addition of an additional layer of gabion. However this is not possible with sheet pile wall options. This renders a score of -2 to sheet pile wall as it will require substantial changes while gabion will get a score of -1 as it requires lesser changes for the same.
Whole Life Costing	Due to the required maintenance regime and construction cost for sheet pile wall, the whole life cost for this options will be more than gabion wall. Hence the score of -1 and +2 is given to sheet pile and gabion wall respectively. The score of +2 is because there is also a cost associated to the disposal of the wall material.

Table 5.5: Resilience Assessment for FC4 Economics	
Critical Factor (CF)	**Scoring and Reasoning**
Flexibility to allow loading variation	Gabion wall is envisaged to be more economical than sheet pile walls for enabling future improvement works (if required). Hence for this example, a scoring of -2 is provided for sheet pile wall and -1 for Gabion Wall.
Flexibility of interaction with other assets	Both solutions do not offer flexibility to accommodate new utilities, drains, etc. and hence a score of -3 is given to both of them as they both will require significant changes which will have economic implications.
Health and Safety Considerations	Both the options require hardly any maintenance and solutions do not pose any H&S risks. In fact, they improve the H&S credential of the network by allowing improvement works and hence also increase the economic credentials of the network (by improving trade and commerce in the area). Thus, both will get a score of +3 as compared to a 'Do nothing' or a 'Do minimum' options which in the future may have a potential of posing H&S risk which may mean more disruption to traffic and increased interventions which has increased economic implications.
Flexibility of Use and Multi-functionality	Under the consideration of economic agility in the future, the gabion wall provides more flexibility and multi-functionality than sheet pile wall. Hence a score of +1 for gabion wall while a score of -1 for sheet pile wall will be given.
Obsolescence and Ease of Disposal	If due to improved economic conditions the retaining wall needs replacing, the gabion fill material can be re-used, whereas steel sheet pile walls provide scrap value. Hence a score of +2 for gabion wall and +2 for sheet pile wall is given.
Changes in Standards and policies	Asset owners' funding and spending reviews which promotes 'Do Minimum' as a preferred option, which means the solution should be able to provide longevity in its useful service life. Both these options provide high economic credentials in the long term as they require minimal maintenance and less disposal costs. However in the event of offering flexibility to interact with new assets, these

Table 5.5: Resilience Assessment for FC4 Economics	
Critical Factor (CF)	**Scoring and Reasoning**
	solutions may have cost implications. Hence a score of +2 is provided for both the solutions.
Whole Life Costing	Due to the required maintenance regime and construction cost for sheet pile wall, the whole life cost for this options will be more than gabion wall. Considering a change in funding scenario in the future this leads to score of -1 and +2 for sheet pile and gabion wall respectively. The score of +2 is because there is also a cost associated to the disposal of the wall material.

Resilience Assessment Tool - Scoring Matrix

Project	Pinch Point Programe
Project Ref.	Example 1

Proposed Geotechnical Solution 1	
Proposed Geotechnical Solution	Gabion Wall for supporting the Embankment widening
Geotechnical Solution Ref. no.	1
Document Ref.	Case study 1
Document Revision	A
Date First Prepared	13/04/2014
Date Updated	13/04/2014

Scoring Key	
Score	**Description**
+3	Existing solution works with no change in design
+2	Existing solution works with minor amendments and cost and time implications
+1	Existing solution with room for improvement to design with relatively reasonable time and cost implications
0	Neutral or Not Applicable
-1	Existing solution requires design changes with additional time and cost implications
-2	Existing solution requires substantial design amendments to its original form and surrounding area with relatively higher time and cost implications
-3	Existing solution does not work and requires replacement with re-engineered solution have major time and cost implications

Future Conditions (FC)			Critical Factors (CF) - Future Consideration															Resilience Score		
Description	**FC Ref**	**FC Weitage (%)**	***Factor***	**Flexibility to allow loading variation**	**Seepage Characteristics**	**Effect on Drainage**	**Effect of Pollution/ Contamination**	**Impact of Erosion**	**Maintaining Bio-diversity**	**Response to Extreme Climatic Conditions**	**Flexibility for Interaction with Other Assets**	**Ease of Maintenance and Operation**	**Health & Safety consideration**	**Flexibility of Use/Multi-functionality**	**Obsolescence/ Ease of disposal**	**Change in Standards & Policy**	**Whole Life Costing**	**FC Score**	**Resilience FC Score**	**Total Resilience Score**
			Factor Score (Fixed to a total of 100)	**9**	**3**	**3**	**7**	**3**	**6**	**6**	**9**	**6**	**10**	**10**	**10**	**10**	**10**			
Demographics	FC1	25%		-1			0		2		-3	3	3	2	2	-1	2	**18.6**	**14.6**	**34.6**
Environment	FC2	10%			2	2	-2	-2	2	-2	1		-2	2	2	-1	2	**3.0**	**2.4**	
Social	FC3	25%		-1			-2		2	-2		3	3	2	2	-1	2	**18.6**	**9.0**	
Economics	FC4	20%		-1							-3		3	1	2	2	2	**13.1**	**8.1**	
Governance	FC5	10%		-1			2		2	-1	-3	3	3	0	2	0	2	**7.3**	**2.7**	
Technology/ Innovation	FC6	5%		-1							-3		-2	-2	2	2	2	**-0.7**	**-0.3**	
Shock Events	FC7	5%		-1	2	2	-2	-2		-2	-3	-3	-3	-2	2	-2	2	**-5.1**	**-1.9**	

Figure 5.14: Resilience Assessment Tool with solved Case Study 1 – Solution 1

Resilience Assessment Tool - Scoring Matrix

Project	Pinch Point Programe
Project Ref.	Example 1

Proposed Geotechnical Solution 2	
Proposed Geotechnical Solution	Sheet Pile Wall
Geotechnical Solution Ref. no.	2
Document Ref.	Case study 1
Document Revision	A
Date First Prepared	13/04/2014
Date Updated	13/04/2014

Scoring Key

Score	Description
+3	Existing solution works with no change in design
+2	Existing solution works with minor amendments and cost and time implications
+1	Existing solution with room for improvement to design with relatively reasonable time and cost implications
0	Neutral or Not Applicable
-1	Existing solution requires design changes with additional time and cost implications
-2	Existing solution requires substantial design amendments to its original form and surrounding area with relatively higher time and cost implications
-3	Existing solution does not work and requires replacement with re-engineered solution have major time and cost implications

Future Conditions (FC)			Critical Factors (CF) - Future Consideration														Resilience Score		
Description	FC Ref	FC Weitage (%)	Factor	Flexibility to allow loading variation	Seepage Characteristics	Effect on Drainage	Effect of Pollution/ Contamination	Impact of Erosion	Maintaining Bio-diversity	Response to Extreme Climatic Conditions	Flexibility for Interaction with Other Assets	Ease of Maintenance and Operation	Health & Safety consideration	Flexibility of Use/Multi-functionality	Obsolescence/ Ease of disposal	Change in Standards & Policy	Whole Life Costing	FC Score	Resilience FC Score	Total Resilience Score
			Factor Score (Fixed to a total of 100)	9	3	3	7	3	6	6	9	6	10	10	10	10	10			
Demographics	FC1	25%		-3			0		-1		-3	-1	3	2	2	-2	-1	-5.7	-4.5	-1.9
Environment	FC2	10%			1	-2	2	2	-1	2	-3		2	-1	2	2	-1	3.7	3.0	
Social	FC3	25%		-3			0		-1	2		-1	3	2	2	-2	-1	3.6	1.7	
Economics	FC4	20%		-2							-3		3	-1	2	2	-1	1.4	0.9	
Governance	FC5	10%		-3			2		-2	-2	-2	1	2	-2	2	-2	-1	-5.6	-2.1	
Technology/ Innovation	FC6	5%		-3							-2		-2	-2	2	-2	-1	-4.6	-2.2	
Shock Events	FC7	5%		2	1	-2	2	2		2	-2	2	2	-2	2	2	-1	3.5	1.3	

Figure 5.15: Resilience Assessment Tool with solved Case Study 1 – Solution 2

5.3.2. Observations from Case Study 1:

For this case study, Gabion Wall solution is more resilient than the Sheet Pile Wall solution on the give project. The main reasons observed for this are:

- Weightages assigned to future conditions has a significant impact on the total resilience score. Demographics and Social have highest weightings from stakeholder consultation and project specific conditions. Hence it is evident, for 'Demographics' future condition, the scorings for 'Sheet Pile Wall' solution is significantly lower than the 'Gabion Wall' solution and affects its' total resilience scores.
- Performance of solutions on for critical factors are highlighted. For example: The trend observed for 'Maintaining Bio-diversity', gabion wall performs significantly better than the sheet pile wall solution. This observation highlights that the resilience scoring matrix provides an ability to spot such trends between solution types.

5.3.3. Case Study 2

This case study is a remediation scheme on a cutting slope, located along a strategic motorway which is a part of the 'Smart Motorway Programme' formerly known as 'Managed Motorway Programme' undertaken by the Highways Agency (known as Highways England since April 2015) to use hard-shoulders during peak hours to reduce congestion. A slip failure has occurred due to increased precipitation, increased loading at the toe and existing drainage system being unable to cope with the same.

For the ease of representing the details of this case study and keep it concise without repeating the use of each Step of the tool, which is already discussed in section 5.2, only 6 of the steps are explained below for providing information about the case study. These steps include Step 1 – Project Information, Step 2 – Asset information, Step 3 – Asset condition, Step 4 – Identify Potential Solutions, Step 5 – Future Conditions (weightages) and Step 7 – Resilience Assessment Matrix.

5.3.3.1 Step 1 – Project Information

The resilience assessment assumption for the proposed case study is:

'The remedial works is a part of the 'Smart Motorway Programme' formerly known as 'Managed Motorway Programme' undertaken by the Highways Agency (known as Highways England since April, 2015) to use hard-shoulders during peak hours to reduce congestion. The surrounding area is prone to increased precipitation, extreme weather conditions and also has an area of SSSI in close proximity (within 300m of the site). The pavement condition report identified no signs of defect in the road structure and carriageway drainage. The report has suggested that the upgraded road construction is adequate. Hence, this is not considered to be the cause of failure of the slope. However, the existing slope drainage showed signs of not functioning effectively. Hence the slope drainage along with the topography is considered to be the likely cause of failure.

See Figure 5.16 for a snapshot of the Project Information tab for Case Study 2.

Project Information

Remediation Scheme - Smart Motorways	
Projet Ref. No.	Example 2
Document Ref. No.	Case study 2
Revision No.	A
Date first prepared	13-Apr-14
Date Updated	13-Apr-14
Project Leader	*Name*
Project Manager	*Name*
Prepared by	*Name*
Checked by	*Name*
Approved by	*Name*

Project Description
This is a remediation scheme on a cutting slope, located along a strategic motorway which. A slip failure has occurred due to increased precipitation, increased loading at the toe and existing drainage system being unable to cope with the same.

Stakeholders Involved
Asset Owner, Asset Managing Contractor and Designer and end-users

Project Timescale	Project Start Date	Project End Date	Comments
	13 October 2012	15 January 2013	

Resilience Assessment Assumptions
The remedial works is a part of the 'Smart Motorway Programme' formerly known as 'Managed Motorway Programme' undertaken by Highways Agency to use hard-shoulders during peak hours to reduce congestion. The surrounding area is prone to increased precipitation, extreme weather conditions and also has an area of SSSI in close proximity.

Figure 5.16: Project Information tab for Case Study 2

5.3.3.2 Step 2 – Asset Information

For this case study, the asset is a ‘Cutting’ having a maximum height of 10m and a slope angle of 260. The length of the remediation work is approximately 200m. The geology comprises of glacial till deposits overlying Mercia mudstone. There is a presence of utilities within the slope and lighting columns at the toe of the slope along with presence of communication cabinets. The slope has shown evidence of progressive slip failures along this section. Historic as-built drawings suggest presence of herring bone drains in the adjacent slope.

There is a presence of ground water table at 4-5m below ground level. Perched water tables may be present in the glacial till deposits which has shown evidence of intermediate bands of sand layer and may vary seasonally with higher ground water tables expected during periods of heavy rainfall.

Any further movement of the slope will result in slope material slipping on the live lane which will pose a threat to the stability of lighting columns and affect the safety of the road users. See Figure 5.17 for a snapshot of the Asset Information tab for Case Study 2.

Asset Information

Asset type	Cutting
Topography	*The cutting is with a maximum height of 10m and slope angle of 26 degree for a length of 200m. Signs of progressive slip-failure has been observed with a slope bulge and backscar affecting the stability of the slope and any further movement could result in slope material potentially encroaching on running lane. The adjacent earthwork is cutting.*
Geology	*Solid - Mercia mudstone* *Drift - Glacial Till* *Artificial ground - none* *Fearutes - no geological features present*
Hydrogeology	*Waterbodies - culvert with headwall present* *Aquifers - secondary* *Groundwater vulnerability - low* *Flooding - not in an area prone to flooding* *Groundwater level - presence of gwt at 4-5m below ground level. Perched water tables may be present in the glacial till deposits which has shown evidence of intermediate bands of sand layer and may vay seasonally. With higher ground water tables expected during periods of heavy rainfall.*
Age	*Range from HAGDMS - 50 - 70 years*
Asset interaction	*Proximity with other assets:* *Structures - Gantry* *Pavement - yes. Hard Shoulder to be used as live lane.* *Drainage - yes, road drain at the toe of cutting slope. Historic evidence of drainage in the adjacent slope.* *Furniture - (Street lights, cabinets, signs, fencing, safety barrier, etc.) Any further movement of the slope material can affect the lighting columns at the toe of the slope and safety of road users.* *Utilities - Refer to STATS plans.*
History	*Mining - not present* *Landfill - Not present* *Previous use - none* *Previous failures/remedial works - yes, presence of progressive slip failures along the cutting slope.*
Environment	*Animal burrouwing - not present* *Vegetation - present, but will be cleared as a part of the works* *Sensitive Site Designation - N/A* *Cultural Heritage - N/A* *Pollution/Contamination - N/A*
Histotic Information	*Previous reports - link provided* *Boreholes -* *As-built records -* *Lab results -* *Design details -*
Geotechnical Information	*Recent Exploratory Holes - link to Ground Investigation report* *Ground Summary -* *Soil Parameters -*
Site Specific Constraints	*Refer to General Arrangment drawing for details. Presence of utilities on the slope and lighting cables at the toe of the slope and the hardshoulder used as live lanes during peak hours.*

Figure 5.17: Asset Information tab for Case Study 2

5.3.3.3 Step 3 – Asset Condition

As this is a remediation scheme, it is important to determine the asset condition. The snapshot of the Step 3 of the resilience assessment tool (Figure 5.18) shows the asset condition.

The observations made on the condition of the cutting slope are:

1. The cutting slope has shown signs of slip failure with slope bulging at the toe with a backscar.
2. Its soil material has high moisture content and comprises of glacial till material with intermediate sand layers.
3. There is presence of carriageway drainage at the toe of the cutting which is in serviceable condition
4. There is presence of shrubs on the slope which will be removed for the remediation works
5. There is presence of lighting columns at the toe of the embankment whose stability may be affected by any further movement of the slope material.

Asset Condition (Present Scenario)-Based on Visual Inspection

Ref.	Asset Condition	Sub-categories	✔	Description/Comments
1	Loading	Existing Loading Conditions depending on type of road	✔	Motorway subject to HA Loading standards. AADT, Hardshoulder used a live lanes during peak hours + 3 lanes
2	Water Observation	Seepage		Refer to the Geotechnical Investigation Report for the details of the asset condition
		Marshy		
		Ponding		
		Erosion		
		Hydrophilic Vegetation		
		High Moisture Content	✔	
3	Drainage	Lined Ditch, Unlined Ditch, Gravel, Pipe, Transverse, Herringbone, Kerb, Culvert, French, Reservation, Watercourse	✔	
4	Pollution/Contamination	Evidence of Pollution/Contamination (BS suite test)		
5	Vegetation	Bare Ground		
		Grass		
		Brambles		
		Shrubs	✔	
		Trees		
6	Animal Burrowing	Presence of Animal Burrowing		
7	Previous remedial works	Reinforced Earth, Existing Sheet Piles, etc.		
8	Interaction with other assets	Existing street furniture, utilities and other structures.	✔	
9	Age	30 years		
10	Geology	Weak ground conditions, soil properties, soil fabric, stiffness, strength, stresses & strains	✔	
11	Topography	Slope Height and Angle, location	✔	
12	Soil Phenomena	Liquefaction, shrinkage & swelling, etc.		
13	Features	Soil Slip	✔	
		Slope Bulge	✔	
		Terracing		
		Tension Cracks		
		Dislocated Trees		
		Ravelling		
		Wedge/Block Failure		
		Planar Failure		
		Subsidence		
		Cracked Pavement		
		Dislocated Fence/Barrier		
		Distorted Structure	✔	
		Leachate		
		Desiccation		
		Toe Debris		
		Other Feature		
14	Heave			
15	Creep			

Figure 5.18: Asset Condition tab for Case Study 2

5.3.3.4 Step 4 – Identify Potential Solutions

Based on the site conditions and asset condition the recommended solutions to be considered for this case study are (1) re-grading the slope by replacing the slipped material with engineered fill (Do Minimum Option) and (2) remediate the slope by removal of slipped material and provision of counterfort drains, thereby improving the drainage capacity of the slope (Do Something Option). See Figure 5.19 for details.

Identify Potential Solutions

Remediation Scheme - Smart Motorways	
Solution No. 1	Re-grading
Geotechnical Solution Ref. no.	1
Description	Re-grading the slope by replacing the slipped material with engineered fill
Solution Type	*Do Minimum*
Project Duration	3 months
Estimated Construction Cost for solution	To be input from cost estimate
Estimated Whole-life cost for solution	To be input from whole life costing assessment
Comments	

Solution No. 2	Installation of Counterfort drains
Geotechnical Solution Ref. no.	2
Description	Remediate the slope by removal of slipped material and provision of counterfort drains, thereby improving the drainage capacity of the slope
Solution Type	Do Something
Project Duration	3 months
Estimated Construction Cost for solution	To be input from cost estimate
Estimated Whole-life cost for solution	To be input from whole life costing assessment
Comments	

Figure 5.19: Identify Potential Solutions tab for Case Study 2

5.3.3.5 Step 5 – Identifying Future Conditions

The weightages for the future conditions are assigned using pair wise comparison technique and the methodology is explained in detail in section 4.6. The results from the stakeholder consultation used for the case study is shown in figure 5.20.

Future Conditions	Total Score
FC1	4
FC2	4
FC3	3
FC4	4
FC5	1
FC6	3
FC7	1

Figure 5.20: Result of pair wise comparison for case study 2

Thus from this exercise, we can say that FC1, FC2 and FC4 (share the rank) are the highest ranking future conditions, followed by FC3 and FC6 (share the rank) followed by FC5 and FC7 (share the rank).

Using equation 6 these scores can be converted into weightages as seen below:

$$100 = 4x + 4x + 3x + 4x + 1x + 3x + 1x \qquad \text{- Equation 6}$$

$x = 5$

Thus weightages are as follows:

- FC1-20%
- FC2-20%
- FC3-15%
- FC4-20%
- FC5-5%
- FC6-15%
- FC7-5%

5.3.3.6 Step 7 – Resilience Assessment Scoring Matrix

Based on the explanation of the case study, the resilience assessment scoring is explained below for Future Conditions Environment and Technology/Innovation in Table 5.6 and 5.7 respectively. Explanation of each FC with examples is provided in section 5.2.5.1. Environment and Technology/Innovation are two key FCs for this case study (high weightage and relevance) and hence these are considered for explaining the scoring process. The scoring for solution number 1 and 2 is shown in Figure 5.21 and Figure 5.22 respectively.

Table 5.6: Resilience Assessment for FC2 Environment

Critical Factor (CF)	Scoring and Reasoning
Seepage Characteristics and Effect on Drainage	In this case, the increased precipitation, flash flooding, geotechnical assets such as slopes have to deal with increased pressure on 'drainage' to keep them dry and release pore water pressures. Hence, provisions of counterfort drains (Solution 2) is a longer term solution than the replace and re-fill option (Solution 1), as it not only remediates the failed slope but also meets the needs of increased susceptibility to Environmental changes in the future. Hence in this case Solution 2 would get a score of +3 because the solution will remain fit for purpose in the future with no changes to the design necessary. While, option 1 would get a score of -1 because the solution will require some design changes with additional time and cost implications.
Effect of Pollution/Contamination	In this case the solution 2 can become a pathway for contamination in the future while this is not possible with solution 1. Hence in this case, they would get a score of -2 and +2 respectively.
Impact on Erosion	The Solution 1 would get a score of -2 because the solution will require substantial design amendments to its original form and surrounding area with substantial time and cost implications. While, Solution 2 will get a score of +2 because the solution will allow for increased storm water drainage preventing erosion of the slope and may require minor amendments for future capacity improvement.
Maintaining Bio-diversity	Both the solutions have equal potential for providing good potential for maintaining bio-diversity. Hence they will both get a score of +1, as this may require some additional work to be done for this.
Response to Extreme Climatic Conditions	In this case the explanation and scoring will be the same as 'Seepage Characteristics' and 'Effect on Drainage' as the solution 2 will be better at dealing with extreme climatic conditions, for e.g. excessive precipitation. So the scores will be +3 for solution 2 and for Solution 2 the score will be -2 because it will require substantial works if failure occurs post extreme climatic event.
Flexibility of interaction with other assets	Option 2 will score -2 because installation of the additional utilities will require substantial amendments to the counterfort drains; While, option 1 will score +1 because it will allow the flexibility to

Table 5.6: Resilience Assessment for FC2 Environment	
Critical Factor (CF)	**Scoring and Reasoning**
	incorporate the installation of additional utilities with changes to the design and minimal disruption to the interaction between these assets.
Health and Safety Considerations	Both the options do not pose any health and safety risk during its operation and also as it does not require any maintenance and hence a score of +1 will be given to both these options, as they are both favourable for the future.
Flexibility of Use/Multi-functionality	In this case the use of free draining material used as engineered fill in replace and refill option, is not only is a slope remediation solution but also acts as a drainage medium and improves the slope drainage there provides additional use and multi-functionality. Hence a score of +2 will be given to solution 1. Solution 2 also provides this multi-functionality of slope stability with drainage. However, it does not provide any additional multi-functionality like provision of vegetation which I possible with Solution 1. So the Solution 2 will get a score of +1.
Obsolescence and Disposal	Both the options will be scores 0 as they both can remain in place and even if they become obsolete
Change in Standards and Policies	Any change in standards and policies in terms of the environment, will not have any effect on either of the options. However, both the options provide flexibility for incorporating any additional changes fairly easily if any future environmental policies lead to changes. Hence both options will get a score of +2.
Whole Life Costing	The whole life costing score for solution 1 is low as it requires negligible maintenance and and only regular inspection and monitoring as per the maintenance regime.Hence the option will get +2. Whereas, solution 2 requires regular on-going maintenance and hence get a score of -1.

Table 5.7: Resilience Assessment for FC6 Technology and Innovation	
Critical Factor (CF)	**Scoring and Reasoning**
Flexibility to allow loading variation	Regarding with engineered fill is a slope stabilisation technique which improves the strength of the slope mostly by addition of material with high strength properties whereas counterfort drains are essentially aimed at improving the drainage properties of the slope. Hence the load carrying capacity is likely to be higher in option 1 giving it score of +1 than option 2 which may require additional strengthening works in the future for increased loading rendering it a score of -2.
Flexibility of interaction with other assets	In this case option 2 will score -2 because installation of additional equipment due to improved technology in the future (e.g. telecommunications, utilities, etc.) will require substantial amendments to the counterfort drains; While, option 1 will score +1 because it will allow the flexibility to incorporate the installation of any additional equipment with changes to the design and minimal disruption to the interaction between these assets.

Table 5.7: Resilience Assessment for FC6 Technology and Innovation	
Critical Factor (CF)	**Scoring and Reasoning**
Health and Safety Consideration	Innovation and Technology may improve the road users' safety and operative's safety; the solution should allow inclusion of any innovative systems. Hence, in this case the requirement for the options is similar to the case above i.e. 'flexibility of interaction with other assets'. Hence the scoring will also be the same i.e. option 1 and option 2 with scores of +1 and -2 respectively.
Flexibility of Use and Multi-functionality:	In this case, both the options do not offer multi-functionality or flexibility of use for technological future consideration, but may not require complete disposal in the future. Hence a score of -2 will be given to both the options.
Obsolescence and Ease of Disposal	Even with change in technology in the future, the material in both the solutions can be re-used or kept in place. Hence rendering a score of +1 for both.
Change in Standards and Policies	Considering the aforementioned factors, the solutions will offer certain advantages such as flexibility to allow loading and interaction with other assets. Hence in the light of changing policies due to technological advancement, both the solutions get a score of +1 as it has some flexibility to accommodate changes in standards and policies.
Whole Life Costing	The whole life costing for both the options is similar as they both require negligible maintenance and only regular inspection and monitoring as per the maintenance regime. So both options will get +2.

Resilience Assessment Tool - Scoring Matrix

Project	Remediation Scheme - Smart Motorways
Project Ref.	Example 2

Proposed Geotechnical Solution 1	
Proposed Geotechnical Solution	Replace and re-fill using engineered material
Geotechnical Solution Ref. no.	1
Document Ref.	Case study 2
Document Revision	A
Date First Prepared	13/04/2014
Date Updated	13/04/2014

Scoring Key	
Score	**Description**
+3	Existing solution works with no change in design
+2	Existing solution works with minor amendments and cost and time implications
+1	Existing solution with room for improvement to design with relatively reasonable time and cost implications
0	Neutral or Not Applicable
-1	Existing solution requires design changes with additional time and cost implications
-2	Existing solution requires substantial design amendments to its original form and surrounding area with relatively higher time and cost implications
-3	Existing solution does not work and requires replacement with re-engineered solution have major time and cost implications

Future Conditions (FC)			Critical Factors (CF) - Future Consideration														Resilience Score		
Description	**FC Ref**	**FC Weitage (%)**	***Factor***	**Flexibility to allow loading variation**	**Seepage Characteristics**	**Effect on Drainage**	**Effect of Pollution/ Contamination**	**Impact of Erosion**	**Maintaining Bio-diversity**	**Response to Extreme Climatic Conditions**	**Flexibility for Interaction with Other Assets**	**Ease of Maintenance and Operation**	**Health & Safety consideration**	**Flexibility of Use/Multi-functionality**	**Obsolescence/ Ease of disposal**	**Change in Standards & Policy**	**Whole Life Costing**	**FC Score**	**Resilience FC Score**	**Total Resilience Score**
			Factor Score (Fixed to a total of 100)	**9**	**3**	**3**	**7**	**3**	**6**	**6**	**9**	**6**	**10**	**10**	**10**	**10**	**10**			
Demographics	FC1	20%		1			2		1		2	2	1	-2	1	1	2	**17.4**	**13.7**	**42.5**
Environment	FC2	20%			-1	-1	2	-2	1	-1	1		1	2	0	2	2	**16.3**	**13.2**	
Social	FC3	15%		1			2		1	-2		2	1	-2	1	1	2	**8.8**	**4.3**	
Economics	FC4	20%		1							1		1	-1	2	1	2	**13.4**	**8.3**	
Governance	FC5	5%		1			0		1	-2	1	2	1	-1	1	1	2	**3.1**	**1.2**	
Technology/ Innovation	FC6	15%		1							1		1	-2	1	1	2	**7.1**	**3.4**	
Shock Events	FC7	5%		-2	-2	-2	0	-2		-2	-2	-2	-1	-2	-1	1	2	**-4.2**	**-1.6**	

Figure 5.21: Resilience Assessment Tool with solved Case Study 2 – Solution 1

Resilience Assessment Tool - Scoring Matrix

Project	Remediation Scheme - Smart Motorways
Project Ref.	Example 2

Proposed Geotechnical Solution 2	
Proposed Geotechnical Solution	Installation of Counterfort drains
Geotechnical Solution Ref. no.	2
Document Ref.	Case study 2
Document Revision	A
Date First Prepared	13/04/2014
Date Updated	13/04/2014

Scoring Key	
Score	**Description**
+3	Existing solution works with no change in design
+2	Existing solution works with minor amendments and cost and time implications
+1	Existing solution with room for improvement to design with relatively reasonable time and cost implications
0	Neutral or Not Applicable
-1	Existing solution requires design changes with additional time and cost implications
-2	Existing solution requires substantial design amendments to its original form and surrounding area with relatively higher time and cost implications
-3	Existing solution does not work and requires replacement with re-engineered solution have major time and cost implications

Future Conditions (FC)			**Critical Factors (CF) - Future Consideration**															**Resilience Score**		
Description	**FC Ref**	**FC Weitage (%)**	***Factor***	**Flexibility to allow loading variation**	**Seepage Characteristics**	**Effect on Drainage**	**Effect of Pollution/ Contamination**	**Impact of Erosion**	**Maintaining Bio-diversity**	**Response to Extreme Climatic Conditions**	**Flexibility for Interaction with Other Assets**	**Ease of Maintenance and Operation**	**Health & Safety consideration**	**Flexibility of Use/Multi-functionality**	**Obsolescence/ Ease of disposal**	**Change in Standards & Policy**	**Whole Life Costing**	**FC Score**	**Resilience FC Score**	**Total Resilience Score**
			Factor Score (Fixed to a total of 100)	**9**	**3**	**3**	**7**	**3**	**6**	**6**	**9**	**6**	**10**	**10**	**10**	**10**	**10**			
Demographics	FC1	20%		-2			-2		1		-2	2	1	-2	1	1	2	**-0.3**	**-0.2**	**16.5**
Environment	FC2	20%			3	3	-2	2	1	3	-2		1	1	0	2	2	**14.9**	**12.1**	
Social	FC3	15%		-2			-2		1	3		2	2	-2	1	1	2	**6.4**	**3.1**	
Economics	FC4	20%		-2							-2		2	-2	1	1	2	**1.1**	**0.7**	
Governance	FC5	5%		-2			2		1	2	-2	2	2	-2	1	1	2	**2.4**	**0.9**	
Technology/ Innovation	FC6	15%		-2							-2		-2	-2	1	1	2	**-5.1**	**-2.5**	
Shock Events	FC7	5%		0	3	3	-2	2		2	2	2	2	2	1	1	2	**6.4**	**2.4**	

Figure 5.22: Resilience Assessment Tool with solved Case Study 2 – Solution 2

5.3.4. Observations from Case Study 2:

For this case study, it is evident that the 'Replace and re-fill' solution is more resilient than the 'Counterfort Drains' solution. However the difference in the overall score is not as significant as seen in the previous Case Study 1. The main reasons observed for this difference in scoring are:

1. For this case study Demographics, Social and Economics are given highest weightings based on stakeholder consultation and project specific conditions. As a result the scorings for these future conditions influence the overall resilience score.
2. It is evident, the resilience scoring for the 'Demographics' and 'Social' FC are not very different for both the solutions. However, especially for the 'Economic' future condition, the difference in scorings for both solutions is significant. As an example, this can be partly attributed to difference in scoring for the 'Flexibility for interaction with other assets' CF.
3. Similarly, another observation that can be made is that for the Critical Factor 'Flexibility to allow loading variation', the scoring for all future conditions is very low for the 'Counterfort Drains' solution, whereas the score is relatively higher for the 'Replace and Re-fill' solution. On the contrary, it can be observed that for 'Counterfort Drains' score higher than the 'Replace and Re-fill' solution for the CFs 'Seepage' and 'Drainage'. But because the CF Score for 'Flexibility to allow loading variation' is a lot more than the 'Seepage' and 'Drainage' CFs, this has minimal effect on the overall resilience score.
4. It is evident that the FC score for 'Shock Event' is negative for 'Replace and re-fill' solution and positive for 'Counterfort Drain' solution. This is because the latter would better respond to a shock event than the former solution. This also clearly indicates that if the 'Shock Event' FC was to have critical importance for the asset owners, then the Counterfort Drains would have been a preferable solution.

5.3.5. Observations made while using the Resilience Assessment Tool

There were a few observations made while using the tool to influence decision making for the appropriate resilient solutions in Case studies 1 and 2. These are:

1. The use of the ‘Resilience Assessment Tool’ can be seen as a planning toolkit within Asset Management process
2. Within Asset management phases, it can be used in the feasibility and/or decision making stages. The output from the tool can be re-visited throughout the asset lifecycle to check the success of the assumptions made during the initial assessment and ‘lessons learnt’ can be recorded from any deviations or successes of the assessment. This is because the tool allows recording of all the information from the asset condition and assumptions made for the future by stakeholders at the time of the assessment.
3. The weightings have significant influence on the overall resilience score and hence it is critical that the weightings are robust and judiciously assigned through effective stakeholder involvement.
4. The sensitivity of the overall resilience score to the individual scoring is very limited. It only has an effect on the overall score in a cumulative manner.
5. It can be observed in both the case studies described previously, that the resilience scores for some CFs remain similar for all FCs. This is because the behaviour of the solution will be the same for a particular CF for all FCs. This is true in some cases but not all. For example, under CF ‘Health and Safety consideration’, the response of a solution tends to remain the same irrespective of the FC but for CF such as ‘Flexibility of interaction with other assets’ the response of the same solution changes depending on the corresponding FC.
6. The user can specifically observe the performance of the solution for each FC and ascertain in which FC the solution will behave particularly poorly and choose to address the risks associated to the same. It allows the user to spot such trends.
7. The main purpose of the tool is to enable the user to judiciously think along the lines of long-term performance of asset solutions in the light of future conditions. Therefore, enables embedding resilience planning in asset management. This therefore, allows next generation of asset management systems and tools to be developed further enabling improved decision making for future of asset management.
8. It is not only possible to compare the overall resilience score for asset management solutions, but also possible to spot trends and hot-spots for the solutions. For

example, if a solution scores particularly low in a specific FC or CF, it may be possible to spot the trend and take specific measures to improve the solution.

5.4. Discussion

Transportation infrastructure plays a significant role in the social, economic and environmental progress of a region and a nation, at large. While the development of an effective transportation network is always a key point in the political agenda of policymakers, an equally important aspect is the maintenance and management of these assets. Within the UK, governmental and private organisations undertake massive planning and development activities, requiring enormous investments of time and funds, to maximize the strategic value of these assets. Typically, asset managers rely on theoretical and practical asset management advice available in the form of literature (Snaith et al., 1998) and standards such as PAS55 and ISO 55000. These help authorities streamline their planning efforts by identifying the critical stages in an asset's lifecycle: design, acquisition, construction, commissioning, utilisation or operation, maintenance, renewal, modification and/or ultimate disposal. Naturally, each stage brings with it a unique set of challenges and decisions, which are influenced by factors related to the asset, its location, the future changes that may affect it, the costs and funds available, and a whole host of other factors. Recently, given the changing climatic conditions and extreme weather events that have been experienced globally, a growing concern for asset managers in the UK has been the long-term maintenance of the asset i.e. over a period of 20 to 30 years. A report released by the Highways Agency in 2011 identifies long-term 'resilience' of the infrastructure network against climate change as the need of the hour.

Achieving Research Objectives 1 & 2: Objective 1 – To review the state- of – the-art asset management systems and practices for transportation network in the UK and around the world including geotechnical assets. Objective 2 – To examine the long term planning needs and resilience assessment in asset management within the road transportation infrastructure (with focus on geotechnical) industry.

The goal of this study was to develop a planning and decision-support tool that allows asset managers to determine the resilience of asset management solutions for geotechnical assets, such as slopes, embankments and tunnels, which support existing infrastructural assets. To this end, the researcher first conducted a critical literature analysis, reviewing existing approaches, frameworks, tools and systems used within the transport sector for the management of assets, both within and outside the UK. The analysis revealed that the existing decision-support tools and planning frameworks are directed towards the development of asset management solutions for pavements and structures, but not geotechnical assets. Further, toolkits and frameworks currently in use do not enable planners to account for a robust resilience assessment, which considers asset behaviour under all plausible future conditions; most of the tools focus on identifying the best possible solution under the given budget constraints. Thus, by fulfilling the first two objectives of the study—(1) reviewing asset management systems and practices for transportation networks and (2) examining the need for long-term planning and resilience assessment in asset management, the researcher has validated the need for a tool tailored to the resilience assessment of geotechnical assets. One of the major advantages of this tool is that it allows for an all-round evaluation of resilience as against other tools or frameworks that focus exclusively on one or two facets such as life-cycle costing (Costello et al., 2005 and Geiger et al., 2005).

Achieving Research Objectives 3 & 4: objective 3 – To study the ground structure interaction and determine the factors affecting the performance of geotechnical assets including groundwater, seepage, soil properties, geology and hydrogeology. Objective 4 – to classify and evaluate the plausible future conditions relevant to the road transport network and the associated geotechnical assets.

Another important contribution of this thesis is the plotting of the interrelationships between critical factors (CFs) that influence the performance of geotechnical assets and the future conditions that may affect their performance. Using a combination of expert consultation and literature review, the researcher developed a list of 14 critical factors that are vital to the management of all geotechnical assets, thus fulfilling the third objective of the research: determine factors affecting the performance of the geotechnical assets including groundwater, seepage, soil properties, geology and hydrogeology. With the help of cross impact analysis technique (Richards and Pherson, 2011), these critical factors, which have been further classified as triggered and triggering, were linked to all the plausible future conditions that can affect the performance of the geotechnical assets in the long term. It is interesting to note that the unlike most impact analysis results, which are presented in the form of a matrix, the output of this analysis is presented in the form of a rose diagram. The rose diagram, which is often used in geological studies, is better suited to help planners visualize the inter-linkages between the triggered factors, the triggering factors and the future conditions that impact it. The diagram facilitates the development of a failure hypothesis of a geotechnical asset, by illustrating the interrelation between the triggering (external) and triggered (internal) factors to highlight the most likely failure path. It directs planners to move from the circle (e.g. climate change) through the middle circle (e.g., pore water pressure changes) and to finally the central circle (e.g. asset failure). In this way, a hypothesis is laid out establishing the critical factors that led to the asset failure. Through this diagram, the research achieves the fourth objective of the study i.e. to evaluate the plausible future conditions that are relevant to the transportation network and therefore geotechnical assets.

Achieving Research Objectives 5 and 6: Objective 5 – to develop a resilience-based geotechnical asset management framework for use in the planning stage of an asset management lifecycle and to develop a tool to support these assessment. Objective 6 – to test the framework 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 resilience geotechnical asset management framework and a decision-support tool to be used in the planning stage of an asset management lifecycle; and validation of the tool through the use of real life (not hypothetical) case studies. To allow asset managers and stakeholders to compare multiple solutions in the light of plausible future conditions that can impact the performance of geotechnical assets, the researcher developed an Excel-based spreadsheet model, with the 14 critical factors on the row and the plausible future conditions on column. The users assessing an geotechnical asset solution are required to provide a resilience score on a 6-point Likert-type scale from, ranging from –3 to +3, where –3 indicates considerable re-engineering needed with high time and cost implications, and +3 indicates that the existing solution works without any change in design.

An interesting aspect of the tool is that it allows the asset managers or stakeholders using the tool to attach weights to the future conditions on the basis of the relevance of the conditions to the asset under consideration. The future condition with the highest weight is clearly considered the most significant to the project. These weightages have significant influence on the overall resilience score; therefore, it is important that they are robust and judiciously assigned through effective stakeholder involvement. Because, the overall sum of the individual scores (ranging from -3 to +3) is multiplied by the percentage weight attached to each future condition, the weights play an important role in the overall score. The resilience score is derived using an algorithm explained in Chapter 5 and equations 2, 3 and 4 of the thesis. The findings of the two case studies also attest to the importance of the weightings in the final calculation of the resilience score. For instance, in case study 1, which covered a new build project, demographics (25%) social factors (25%) and economic factors (20%) were identified key future conditions and assigned the highest weightage by the stakeholders. On the other hand, shock events and technology were assigned the least weightages (5%). Individual scores yield a negative or a positive resilience score; however, the magnitude of the total score is influenced by the weightages assigned to the future conditions. This is evident when we observe the first solution under case study 1, where the overall resilience score is negative for shock events, not because the individual scores are collectively negative but because the magnitude is low (-5.1). This is the weightage assigned to shock events as a future condition is low, i.e. 5%. A similar result can be observed with the first solution discussed under case study 2. Case study 2 is a remediation scheme,   in which the future conditions were assigned the following weightages: demographics (20%), environment (20%), and technology/innovation (15%). These weights were influenced by the nature of the project and its proximity to a flood prone area. As a result, the final resilience score is higher for these future conditions compared to the others. However, there might be certain cases where the cumulative scorings for a future condition might be very low, and despite high weightage assigned to a future condition, the resilience score may be low. This was observed in case study 2, where although economic factors (20%) was assigned the highest weightage, the individual scores were lower and the net effect was of a smaller magnitude.

Ultimately, the resilience score for a solution can be seen as a numeric value that serves as a comparator, indicating whether a particular solution is better or worse than the other alternatives proposed. The purpose of the tool is not to ensure that a particular solution achieves a definitive or target score; however, the scoring mechanism provides a tangible measure of assessing if a solution may perform significantly better or worse than its alternatives in the long run. For instance, it is likely a solution that fares well on most the future conditions may receive a poor score on a critical future condition, with a high weight. This may suggest that the solution is not resilient with respect to that particular future condition from a long-term perspective. This is a clear advantage of this tool over other tools that only focus on short-term planning objectives and over those which provide planning strategies focussing mainly on budgets versus asset performance (Ruitenburg, et al., 2014). This tool acts as a thinking tool used in the planning stage which enables the user to compare potential solutions from a long-term perspective. It uses qualitative data to identify the resilience potential of geotechnical solutions in the light of future conditions. As a differentiator, the tool allows the user to think about the impact of multiple future conditions and its relationship with the critical factors affecting the asset and not just the impact of any one factor in significant detail (such as cost or environment) and therefore takes a more strategic view of multiple factors and their inter-relationships which can provide a wider perspective on the resilience of the asset.

The use of expert opinion for assigning of the weightages is beneficial for two reasons. Firstly, because these weightages are determined by the stakeholders using the tool, one can rest assured that these weightages are consciously chosen after a careful evaluation of the impact of future conditions as relevant to the project, and are duly justified. Secondly, as Costello et al., (2011) noted, most of the existing stochastic or deterministic approaches cannot be applied to the lifecycle planning of geotechnical assets because it is difficult to predict future changes in asset behaviour on the basis of its past performance. The involvement of experts, therefore, helps in overcoming problems associated with limited information. Their familiarity and expertise in dealing with similar assets enables them to offer deep and valuable advice on the asset and its management.

Lastly, like most other user-centric toolkits (e.g. HMEP), this tool uses MS Excel and not some proprietary software. The use of MS Excel ensure that the tool can be used by individuals without any prior training or knowledge. The researcher believes that the tool can be used by geotechnical asset managers, planners and engineers across the world who intend to undertake resilience assessment of their proposed geotechnical solutions. This tool can used at the feasibility stage of the project, where solutions are compared on the strength of their technical soundness, costs and risks. This tool can contribute to this stage by introducing a long-term perspective to the selection of the asset management solution. Although this work focuses on geotechnical assets on the road network, the researcher is confident that the tool can be used for similar assets on any other infrastructural network and can be adapted to other assets. For instance, to use this tool for pavement assets, factors affecting the performance of pavements will need to be determined and linked to the future conditions already captured by the tool. The research framework is robust enough to enable the generic use of the tool by varied managers, planners and stakeholders.

5.5. Limitations

The deployment of the resilience assessment framework developed in this work requires extensive stakeholder engagement for the assignment of robust weightages to future conditions, which is a critical step in the overall resilience assessment planning and the calculation of the resilience score of the solution. However, the involvement of stakeholders is a de facto step for effective decision making within the asset management domain (Ruitenburg et al., 2014). This encourages early involvement and effective communication between 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).

During the tool validation process, one of the aspects highlighted by the experts was the considerable investment of time required for the deployment of the tool. However, the researcher believes that this is not a significant drawback as most planning tools, especially tools such as these that require collaborative decision-making, are known to be heavy in terms of time investment. At the same time, the researcher does acknowledge that the tool requires additional time and commitment from strategic decision makers and asset owners. The process of arriving at weightages involves in-depth discussion and may be require iterative sessions among the stakeholders. Conflicting opinions and biases may impede appropriate assignment of weightages to the FCs. However, one can also argue the planning stage of the project is ideal for such a discussion as it allows for the inclusion of multiple agendas that are relevant to the project.

This tool cannot replace existing risk management, deterioration modelling and whole life costing methodologies, which provide information in relation to risk management strategies and potential asset performance in the light of available budgets and treatment strategies which aids in effective asset management. However it allows for supporting decision making at the planning stage of asset management by providing a systematic and consistent framework in relation to future conditions pertaining to the project and the geotechnical solutions. Whilst it is not a risk management tool and does not use sophisticated data or algorithms to generate a fix if the asset may fail to perform in the future it does allow asset managers and planners to explore the impact of difference future conditions on various solutions and so allows an objective assessment of their ultimate resilience. The objective of the researcher was to adopt an exploratory approach to analysing impact of future conditions on geotechnical assets and to examine their impacts on different solutions. In fact, one of the research gaps that the study attempts to fulfil is to provide a basis for comparing potential solutions, based on the long-term performance, as opposed to identifying solutions, which has been the focus of many contemporary asset management tools. Second, almost all the models and the tools discussed above assist decision makers in identifying solutions given the budgetary constraints. This tool is slightly different in that it enables senior managers identify the best solution by appraising them in terms their responsiveness to changes in the future asset conditions. It offers a snapshot view of the diverse future conditions that may affect the performance of the geotechnical asset and allows for the selection of the most resilient solution. In that sense, this decision-support tool can be viewed as complementing some of the models and systems discussed above.

Although this is not a standalone decision-support tool that estimates all the future uncertainties or vulnerabilities of geotechnical assets, it provides a systematic framework to compare geotechnical solutions that address a wide range of plausible changes in the future, which can affect the network, asset behaviour and its use. For instance, in conflict- or disaster-prone areas, this tool may need to be used in conjunction with others more tailored to the needs of such environments. However, the strength of this tool lies in its ability to provide a macro-level overview of plausible conditions that affect the transportation network at a planning stage. While the tool does not provide an action plan to mitigate such risks, it enables the identification of patterns where one solution performs more or less favourably than its alternatives, in the light of the interaction between critical factors and future conditions. These patterns can be used in devising appropriate mitigation actions.

Lastly, a long-term forward-looking strategy may not always be available with assets owners and hence the tool’s capabilities may not be fully utilised. However, the methodology encourages asset owners to develop such strategies. It offers a starting point to identify options should a future condition arise.

In summary, it is important to add that despite these limitations, this research is significant for its theoretical and practical contributions to the literature on asset management. By identifying and addressing the need for planning resilient geotechnical assets and conceptualising resilience comprehensively through its assessment framework, this work empowers asset managers and planners to design, build and maintain long-lasting public assets.

6. Conclusions

Key environmental impacts such as changes in the global climate in addition to changes in the global economic, social and political factors have challenged infrastructural asset owners—both governmental and private—to re-think the conventional approaches to asset management. Asset planners have come to realise that to ensure the longevity of an asset, it is important to assess the impact of the changing conditions on asset behaviour and develop plans that integrate resilience in long term planning and decision making. It has become imperative for asset owners and managers to consider resilience as a vital component of long term planning in asset management. In light of this need, this research makes two important contributions to the discipline of asset management: it embeds resilience assessment into the long-term planning stage of asset management for road transportation infrastructure, and it offers a geotechnical asset management framework to evaluate the resilience of asset management solutions.

The detailed critical review of existing asset management literature establishes the value of geotechnical assets in the maintenance of the road transport network, the critical factors that influence or indicate its performance and future conditions that are likely to affect the performance of the geotechnical assets.

The two diagrammatic models (Models 1 & 2) that map the interrelationships between the critical factors as well as between the critical factors and the future conditions allow asset planners to develop sound failure hypotheses for assets. These aids are valuable for analysing the resilience of assets at the planning stage; geotechnical asset managers can use these models to guide their investigation of assets and develop assessment for geotechnical asset performance instead of only relying on their judgement or previous knowledge.

The main contribution of this work is the geotechnical asset management planning framework that allows asset managers to appraise geotechnical asset solutions on the basis of their resilience. By carefully assessing the impact of future conditions on the asset performance in the long term, it facilitates a comprehensive evaluation of resilience of geotechnical assets. The Excel-based tool drives the selection of geotechnical asset solutions that is resilient to the plausible future conditions likely to affect the transportation network and thereby helps in the long-term planning of geotechnical assets. The resilience assessment framework has been tested and the tool is validated using real case studies by geotechnical engineers and asset management experts.

This step wise methodology of the tool provides a structured and consistent approach in assessing the geotechnical solution’s potential to continue being serviceable and fit for purpose even under the changing future conditions. Further, the tool is designed to facilitate the selection of an asset solution that offers flexibility and multi-functionality to cater for changing conditions in a sustainable and cost effective manner. Given that the UK road infrastructure is accessed by many on a daily basis, in the light of changing social, economic and environmental conditions, a resilient geotechnical asset can deliver longer term advantages to its adjoining regions than a non-resilient one. The tool therefore facilitates the process of translating resilience strategies into tangible deliverables.

The proposed framework (and associated tool) encourages the implementation, management and integration of resilience at the asset management planning stage and promote wider uptake of the concept in the asset management industry. The tool also encourages increased involvement and collaborative working with the asset managers and strategic decision makers.

6.1. Future Work

This research work provides a good starting point and basis for further development in asset management and ‘resilience’. Some of the suggested future work is listed as follows:

1. The tool can be adapted and developed for different types of assets and not only geotechnical assets. Hence, the critical factors studied in the research for geotechnical assets can be replaced by identifying the critical factors (key performance measures) which affect the performance of other transportation

assets like pavements, structures, drainage etc. The performance of these assets in the light of changing futures can then be studied using this methodology to determine the resilience of solutions for those assets.

2. It can be expanded on a network wide level to compare a portfolio of projects to obtain a strategic view on the resilience of transportation network. Hence, solutions that can be adopted across the network due to similar conditions and challenges can be compared for providing a resilient asset management solution throughout the network.
3. Model 1 proposed in this research can be developed further and incorporated as a part of a risk management technique for geotechnical assets. Model 1 provides a process of identifying the critical factors and failure path for geotechnical assets. This can be used in combination with existing risk assessment tools to identify risk factors along with the probability and severity of failure for a range of geotechnical assets on a network. This will provide a comprehensive risk assessment along with likely failure hypothesis for different assets at risk.
4. This tool can be developed further in detail and made as a web-based application using systems engineering.
5. The use and application of the tool can be broadened by developing it for other areas such as built environment, urban planning and development and transport planning. The tool is a matrix of critical factors (which affects the performance of asset solutions) and future conditions. Factors which influence the choice of solutions for urban planning or solutions adopted for enhancing the use of built environment or improved solutions for transport planning can be studied in the light of changing futures using a similar methodology to develop a resilience assessment tool for built environment, urban planning and transport planning.

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Appendices

Appendix A – Alpha Test Feedback

1. For Models 1 & 2

Alpha Test Feedback of Models 1 & 2

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Attendees:	Position:	Date of alpha test:
Attendee 1	Geotechnical Engineer	August 8, 2012
Attendee 2	Senior Geotechnical Engineer	August 8, 2012
Attendee 3	Principal Geotechnical Engineer	August 8, 2012
Attendee 4	Geo-environmental Engineer	August 21, 2012
Attendee 5	Engineering Geologist	August 21, 2012
Attendee 6	GIS specialist	August 21, 2012

1. Subjective Assessment for Model 1 – Critical Factors Affecting Geotechnical Assets

Elements	Subjective Assessment/ Feedback	Actions
Geotechnical Assets and typical failure features covered.	i. Common agreement that the geotechnical assets on the highway network are covered and the typical failure features identified. ii. Some questioned whether sub-grade is a core geotechnical asset	i. N/A ii. Because the sub-grade is usually maintained along with pavements and considering this feedback, sub-grade was not included in the study.
Review of Critical Factors – i.e. do they encompass the key factors which affect geotechnical asset performance?	i. Don't call it critical success factors. They are essentially KPIs. When you suggest success it gives an impression that the solution is successful. ii. Include 'seepage' as one of the factors as it is different to drainage and it is important in case of slopes. iii. Overall feedback was that the factors were well covered	i. Feedback considered and the model was modified to indicate the factors as 'Critical Factors' ii. Seepage included as one of the critical factors iii. N/A
Classification of the critical factors as 'external' & 'internal' and their inter-relationship	i. Appreciate the logic between calling the factors as external and internal. However, they could be better represented as 'Triggering' and 'Triggered' factors instead of external and internal.	i. Feedback accepted and incorporated in the study.
Overall presentation and Layout	i. Make each cell different color so that it is easy to identify. ii. Drawings failure paths on the model can become complicated and can make the tool look messy if there are combinations of factors.	i. Feedback accepted and incorporated ii. To simplify this, the critical factors were given a unique ID so the failure path could be represented in an effective manner.

Alpha Test Feedback – August 2012 1

2. Subjective Assessment Model 2 – Future Conditions and their inter-relationship with the Critical Factors affecting Geotechnical Assets

Elements	Subjective Assessment/Feedback	Actions
List of Future Conditions	i. Common agreement that the future conditions considered broadly covers the future conditions that affect the transportation network and hence the geotechnical assets in this study	i. N/A
Inter-relationship between Critical Factors and Future Conditions	i. The logic is right. ii. Based on the discussion, it was clear that only first level inter-relationships should be considered and not second tier relations. This would make it very complex and not be logical.	i. N/A ii. This feedback was incorporated when finalising the exact inter-relationships between the Future conditions and critical factors.
Extension to combine Model 1 and Model 2	i. Agreeable initially on the logical extension to combine Models 1 and 2. However, representing multiple inter-relationships and combination of critical factors to show the analysis of the geotechnical problem and preferred solution will not be possible. So, it was suggested to keep both Models separate as they individually add value and serve different purposes.	i. Feedback accepted and the Models 1 and 2 kept separate.
Overall Presentation and Layout	i. The Models 1 and 2 diagrams are easy to read and understand. ii. Initial option was discussed whether it is better to represent the models in the form of tables and it was unanimously agreed that a 'rose diagram' with concentric circles was a better representation.	i. N/A ii. Feedback accepted and the Models 1 and 2 represented as rose diagrams

2. For the Tool

Alpha Test Feedback of the Tool

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Attendees:	Position:	Date of alpha test:
Attendee 1	Geotechnical Engineer	December 10, 2012
Attendee 2	Senior Geotechnical Engineer	December 10, 2012
Attendee 3	Principal Geotechnical Engineer	December 10, 2012
Attendee 4	Geo-environmental Engineer	December 10, 2012
Attendee 5	Engineering Geologist	December 10, 2012
Attendee 6	GIS specialist	December 10, 2012
Attendee 7	Asset Management Expert	December 10, 2012
Attendee 8	Asset Management Expert (Client)	December 14, 2012

1. Subjective assessment of Resilience Assessment Framework

Elements	Subjective Assessment/ Feedback	Actions
Scoring System for Resilience Assessment of proposed solution	i. Instead of ranking use weightages. So the user can assign equal weightages to conditions equally important to them. ii. What about considering one for the short term and one for the long term. For example – for a scheme economy is very important now but for long term environment is more important. Can they analyze both conditions? iii. Is it possible to compare the score with an ideal case in order to obtain a score out of 100? This would make it easy to compare one project with another on a like for like basis.	i. This feedback was incorporated in the final version of the tool ii. If we include the long-term and short-term aspects, the assessment would become a tedious process and also adds an additional dimension to the tool for the user to think about and making it complex and limiting its use. Hence only long-term view has been included as a principle because it ties in with the research objectives. iii. This feedback was incorporated in the final algorithm of the tool to ensure that he final resilience score is calculated out of a total of 100.
Development/ Presentation of the Tool	i. Use of Arrow Diagram. Use of Step wise representation of the tool. ii. In the matrix use the similar color code as in the models 1 and 2 for drawings reference iii. However the tool looks too colorful. Most professional tools are colored as shaded and unshaded depending on whether an input is required in the cell or not. iv. It is evident that if all triggering and triggered factors are going to be used in the tool, it will be too onerous and may even loose the essence of analysis. Hence, all these factors should be clubbed into KPI (Critical Factors) which directly	i. This feedback was incorporated and a vertical flow diagram was created to represent the stepwise working of the tool. ii. This feedback was not incorporated as the action iii below was incorporated. iii. It was considered more appropriate to have shaded cells for the irrelevant input cells and un-shaded for the input cells. iv. All the feedback was considered and was incorporated in the development of the final version of the tool.

Alpha Test Feedback – December 2012 1

Elements	Subjective Assessment/ Feedback	Actions
	influence the performance of the asset. For example: Previous remedial works and Interaction of other assets can be clubbed because the solutions response to interacting with a previously built wall and another asset such as a structure will perhaps be the same. You can either work around it or not. Also, animal infestation and vegetation can be clubbed together to Biodiversity. v. Risk assessment and asset management can be removed because these are strategic decisions which will affect the construction and maintenance of the asset. However, the overall purpose of the KPIs is to include the factors that directly affect the performance of geotechnical solutions.	v. The feedback was incorporated in the final version of the tool
Adoption of Model 1 elements and principles in the tool	i. Can be used for risk assessments but is not essential for undertaking resilience assessment. ii. Critical factors are too many and they can be clubbed together to cover the key factors on which the success of the solution can be assessed.	i. The Model has been retained at the back of the assessment tool for developing failure hypothesis before identifying technically sound design solutions. ii. This feedback was taken on board and the final tool is devised using key critical factors (some of critical factors are grouped together in the final version).
Adoption of Model 2 elements and principles in the tool	i. Explains clearly the inter-relationship and should be retained in the tool for reference.	i. A snapshot of the model 2 was retained in the tool.

Appendix B – Resilience Assessment Tool Validation

Validation 1:

Resilience assessment Tool Validation

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Attendee:	Position:	Date of validation:
Attendee 1	Geo-environmental Engineer	November 12, 2013

1. Manual (Overall Score between 1 and 4 – 4 being Very Good)

☐ 1 ☐ 2 ☑ 3 ☐ 4

1a. Content Quality - Score between 1 and 4 (4 being Very Good)

☐ 1 ☐ 2 ☑ 3 ☐ 4

1b. Clarity - Score between 1 and 4 (4 being Very Clear)

☐ 1 ☑ 2 ☐ 3 ☐ 4

1c. Ease of Navigation - Score between 1 and 4 (4 being Very Easy)

☐ 1 ☑ 2 ☐ 3 ☐ 4

1d. Comments

In the Manual there is no clear contents page this would be useful for troubleshooting or referencing.
The manual has some excessive language used to describe principles that could be summed up concisely

2. Resilience Assessment Tool (Overall Score between 1 and 4 – 4 being Very Good)

☐ 1 ☐ 2 ☐ 3 ☑ 4

2a. Ease of Use - Score between 1 and 4 (4 being Very Easy)

☐ 1 ☐ 2 ☑ 3 ☐ 4

2b. Presentation/Aesthetics - Score between 1 and 4 (4 being Very Good)

☐ 1 ☐ 2 ☑ 3 ☐ 4

Resilience Assessment Tool Validation • November 12, 2013 1

2c. Logic/Workflow - Score between 1 and 4 (4 being Very Logical)

☐ 1 ☐ 2 ☑ 3 ☐ 4

2d. Subjective Assessment for Each Step of the Tool

STEP	Subjective Assessment/Feedback
STEP 1 - Project Information	Easy to understand sensible layout. Similar to other database entry systems. A hyperlink for when you complete the page would be useful to take you to step 2. (like on the process steps page)
STEP 2 - Asset Information	Could the Asset information guides be locked into the cells i.e. not deletable?
STEP 3 - Present Asset Condition and short term risk assessment	Simple page used for logging on site information. Could do with a drop down tick box menu instead of user typing it in every stage.
STEP 4 - Potential Solutions	Standard page only inclusion should be a next step button to take you to the next page/step.
STEP 5 - Future Conditions	It is a large page difficult to see all of the Future conditions and text at once. A total Percentages tab which goes red if over 100% weightages may be useful for this tab. The pairwise comparison method of assigning ranking and weightages was not clear to begin with, but as the process went ahead, it was straightforward and logical to follow.
STEP 6 - Critical Success Factors	Selectable relevance tabs within the sheet is useful. Not clear why the fixed score references the next Step. It would be useful but not essential to lock all of the cells that do not require input so that they cannot be edited. If possible make all cells that need to be edited one colour throughout the tool. This step is useful for a reminder/indicator of future conditions if not already previously considered.
STEP 7 - Scoring Matrix	Within the scoring matrix it would be useful to have all of the boxes that don't apply locked. Total Resilience score would be more useful if it had a comparison to the perfect score. Formulas for FC score are for each of the inputs in the row despite if some of them are greyed out. At present I am able to enter any number into the cells. A drop down menu +3 to -3 would be very helpful and lower risk of error here.
STEP 8 - Output and Decision	The output and decision tables does not carry across the score generated in the Step 7 Scoring Matrix. Seems to be an error in the merged cell reference. If referencing a single cell it works. It would be excellent to have a comparison to the ideal scenario so you can compare your Total resilience score with a 'perfect rating'. This might be used when more than one scheme and several solutions are being compared. I.e. 70/114

Resilience Assessment Tool Validation • November 12, 2013 2

3. *Decision Support*

3a. Applicability of the tool - Score between 1 and 4 (4 being Very Applicable)

☐ 1 ☐ 2 ☑ 3 ☐ 4

3b. Does this meet the objectives of the tool as promised - Score between 1 and 4 (4 being Meets Objectives Completely)

☐ 1 ☐ 2 ☑ 3 ☐ 4

4. *Any other Comments / Testimonial:*

This tool has clear applicability in terms of assessing an asset for future applicability. It could be refined with ease of use for the end user in mind. It can be refined to make boxes locked with the user only able to enter in fields that are all the same colour no matter the tool step.

Validation 2:

Resilience assessment Tool Validation

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Attendee:	**Position:**	**Date of validation:**
Attendee 2	Technical Director (Geotechnical)	November 12, 2013

1. Manual (Overall Score between 1 and 4 – 4 being Very Good)

☐ 1 ☐ 2 ☑ 3 ☐ 4

1a. Content Quality - Score between 1 and 4 (4 being Very Good)

☐ 1 ☐ 2 ☑ 3 ☐ 4

1b. Clarity - Score between 1 and 4 (4 being Very Clear)

☐ 1 ☑ 2 ☑ 3 ☐ 4

1c. Ease of Navigation - Score between 1 and 4 (4 being Very Easy)

☐ 1 ☑ 2 ☑ 3 ☐ 4

1d. Comments

Manual is clear. Examples are easy to follow and have a logical approach.

2. Resilience Assessment Tool (Overall Score between 1 and 4 – 4 being Very Good)

☐ 1 ☐ 2 ☐ 3 ☑ 4

2a. Ease of Use - Score between 1 and 4 (4 being Very Easy)

☐ 1 ☐ 2 ☑ 3 ☐ 4

2b. Presentation/Aesthetics - Score between 1 and 4 (4 being Very Good)

☐ 1 ☐ 2 ☑ 3 ☐ 4

2c. Logic/Workflow - Score between 1 and 4 (4 being Very Logical)

☐ 1 ☐ 2 ☑ 3 ☐ 4

Resilience Assessment Tool Validation • November 12, 2013 1

2d. Subjective Assessment for Each Step of the Tool

STEP	Subjective Assessment/Feedback
STEP 1 - Project Information	Easy to understand sensible layout. Follows a logical approach
STEP 2 - Asset Information	Could the Asset information be input from other sources of information? For example a hyperlink to an existing report etc.
STEP 3 - Present Asset Condition and short term risk assessment	Again a hyperlink to existing reports could be handy. Technically sound. Covers all aspects used in Highways Transportation Geotechnical asset Management system used in the industry based on guidance from HA documents.
STEP 4 - Potential Solutions	Here the costs could be whole life cycle costs and not just estimated costs.
STEP 5 - Future Conditions	Quite a lot of information. However, with the help of manual and cited examples it is easy to follow. A lot of this information can be obtained from strategic documents from asset owners when they are planning network wide programs and allocating funding decisions and hence these should be referenced/hyperlinked if necessary by the user. The tool should allow doing that. The pairwise comparison technique used for ranking provided an objective and systematic way of assigning weightages. One of the biggest advantages is that it includes input from all involved stakeholders in an objective manner, making it easier to justify the weightages and making it more representative.
STEP 6 - Critical Success Factors	Fixed scores are clear. Having a relevance tab is not essential, as far as the tool allows the user to proceed without having to tick every box in this tab, this is fine.
STEP 7 - Scoring Matrix	A scoring between +3 and -3 is very useful. The scoring key makes it easier to interpret. However, whole life costing should be ticked in every FC because irrespective of the FC, choosing an economically efficient solution is always great value. Same applied to H&S consideration. Recommend that in each cell where the user has to input score, there is a one line example of how the CF and FC are interconnected and performance of the solution is gauged. This will enable the user to not have to refer to the manual repeatedly. The approach of having a benchmark score is good. The algorithm is not clear from the excel sheet and the manual should make it clear.
STEP 8 - Output and Decision	The output and decision tables do not carry across the score generated in the Step 7 Scoring Matrix. Needs revisiting the cell entry. Overall appreciated efforts. The final tab should also show the costs so that the user can compare the resilience score with the whole life cycle costs for each solution.

3. *Decision Support*

3a. Applicability of the tool - Score between 1 and 4 (4 being Very Applicable)

☐ 1 ☐ 2 ☑ 3 ☐ 4

3b. Does this meet the objectives of the tool as promised - Score between 1 and 4 (4 being Meets Objectives Completely)

☐ 1 ☐ 2 ☐ 3 ☑ 4

4. *Any other Comments / Testimonial:*

Using this tool for assessing resilience can be the next step in asset management and can be used as a bolt on service to existing feasibility studies example Value Management etc. However, this has the potential to be used in more strategic Asset Management such as planning and decision making.

Validation 3:

Resilience assessment Tool Validation

Amey

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Attendee:	Position:	Date of validation:
Attendee 3	Principal Geotechnical Engineer	November 12, 2013

1. Manual (Overall Score between 1 and 4 – 4 being Very Good)

☐ 1 ☐ 2 ☑ 3 ☐ 4

1a. Content Quality - Score between 1 and 4 (4 being Very Good)

☐ 1 ☐ 2 ☑ 3 ☐ 4

1b. Clarity - Score between 1 and 4 (4 being Very Clear)

☐ 1 ☑ 2 ☑ 3 ☐ 4

1c. Ease of Navigation - Score between 1 and 4 (4 being Very Easy)

☐ 1 ☑ 2 ☑ 3 ☐ 4

1d. Comments

Manual is clear. Use of examples for understanding the concept is helpful.

2. Resilience Assessment Tool (Overall Score between 1 and 4 – 4 being Very Good)

☐ 1 ☐ 2 ☐ 3 ☑ 4

2a. Ease of Use - Score between 1 and 4 (4 being Very Easy)

☐ 1 ☐ 2 ☑ 3 ☐ 4

2b. Presentation/Aesthetics - Score between 1 and 4 (4 being Very Good)

☐ 1 ☐ 2 ☑ 3 ☐ 4

2c. Logic/Workflow - Score between 1 and 4 (4 being Very Logical)

☐ 1 ☐ 2 ☑ 3 ☐ 4

Resilience Assessment Tool Validation • November 12, 2013 1

2d. Subjective Assessment for Each Step of the Tool

STEP	Subjective Assessment/Feedback
STEP 1 - Project Information	Clear
STEP 2 - Asset Information	Clear
STEP 3 - Present Asset Condition and short term risk assessment	Clear but should allow hyperlinking the sheet with existing information and reports.
STEP 4 - Potential Solutions	Clear. The advantages of the first 4 steps are that it includes key steps in geotechnical asset management feasibility works. It is a good representation of putting the key processes together in the form of a framework. Watertight application.
STEP 5 - Future Conditions	Lot of information. Weightings is a sensible way forward. The pairwise comparison provides an opportunity to include all stakeholders' views. However, it may be difficult with a much larger audience to consolidate results. Also, there needs to be a good understanding of the Future Conditions and what is important to the stakeholders to make an informed assessment.
STEP 6 - Critical Success Factors	This tab should state that it is for information only.
STEP 7 - Scoring Matrix	Use of grey locked cells where the scores are not to be assigned. When discussed, it is argued; that the tool should not allow the user to assign scores in every cell but stick to the interpreted logic of correlation between FC and CF. This would result in establishing a clear first level co-relation only. Explanation in each cell of the scoring would be useful. Algorithm clear from understanding but not evident on the tool/manual. Scoring Key should be on each of the matrix not just at the top.
STEP 8 - Output and Decision	Clear and good for comparison.

3. *Decision Support*

3a. Applicability of the tool - Score between 1 and 4 (4 being Very Applicable)

☐ 1 ☐ 2 ☑ 3 ☐ 4

3b. Does this meet the objectives of the tool as promised - Score between 1 and 4 (4 being Meets Objectives Completely)

☐ 1 ☐ 2 ☑ 3 ☐ 4

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4. *Any other Comments / Testimonial:*

The tool is useful in feasibility studies and planning frameworks. However, in the presentation it was recommended that anyone can use the tool from engineers to strategic decision makers. Personally, it is recommended that in order that the tool is used for the right level of strategic decision making, it should be used by PMs and Strategic decision makers. Within the tool, highlight the co-relation between CF and FC for ease of scoring.

Validation 4:

Resilience assessment Tool Validation

Amey

amey

UNIVERSITY OF BIRMINGHAM

Attendee:	**Position:**	**Date of Validation:**
Attendee 4	Asset Management Expert (Director)	November 12, 2013

1. Manual (Overall Score between 1 and 4 – 4 being Very Good)

☐ 1 ☐ 2 ☑ 3 ☐ 4

1a. Content Quality - Score between 1 and 4 (4 being Very Good)

☐ 1 ☐ 2 ☑ 3 ☐ 4

1b. Clarity - Score between 1 and 4 (4 being Very Clear)

☐ 1 ☑ 2 ☐ 3 ☐ 4

1c. Ease of Navigation - Score between 1 and 4 (4 being Very Easy)

☐ 1 ☐ 2 ☑ 3 ☐ 4

1d. Comments

Manual can do with some overarching reference to strategic documents. It should be a short paper showing how it works and its applications.

2. Resilience Assessment Tool (Overall Score between 1 and 4 – 4 being Very Good)

☐ 1 ☐ 2 ☑ 3 ☑ 4

2a. Ease of Use - Score between 1 and 4 (4 being Very Easy)

☐ 1 ☐ 2 ☑ 3 ☐ 4

2b. Presentation/Aesthetics - Score between 1 and 4 (4 being Very Good)

☐ 1 ☐ 2 ☑ 3 ☐ 4

2c. Logic/Workflow - Score between 1 and 4 (4 being Very Logical)

☐ 1 ☐ 2 ☑ 3 ☐ 4

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2d. Subjective Assessment for Each Step of the Tool

STEP	Subjective Assessment/Feedback
STEP 1 - Project Information	This is good. But there should be a more conceptual and generic model
STEP 2 - Asset Information	OK
STEP 3 - Present Asset Condition and short term risk assessment	OK
STEP 4 - Potential Solutions	OK -this could be expanded to suit a more network wide plan or solution not just an asset solution. For example- A new road construction with multiple assets.
STEP 5 - Future Conditions	Is this level of information readily available with the asset owners for stakeholder engagement to be able to conclude the right level of weightages? There are other ways as well. You can choose to provide the user with a series of questions for each FC and based on those subjective assessments, you can derive a weightage for each FC. An alternative method is to give ranking between 1 to 'n' to all FC and then each ranking is equivalent to a range of weightages. However this may add another step to the process but can minimize the extent of information on this sheet. However, the Pairwise comparison method used for assigning weightages was fair, inclusive and objective. However, in the first instance it may need detailed explanation from the presenter if any of the stakeholders haven't used this method before. But once it has been used, it is simple to follow.
STEP 6 - Critical Success Factors	These should be called as 'Key Performance Measures' or 'Critical Factors' because the term Success may give a mixed message.
STEP 7 - Scoring Matrix	Scoring process may be considered as cumbersome for smaller scale projects. The tool is logical and can be useful to provide better client service
STEP 8 - Output and Decision	OK- overall the tool is useful.

3. *Decision Support*

3a. Applicability of the tool - Score between 1 and 4 (4 being Very Applicable)

☐ 1 ☐ 2 ☑ 3 ☐ 4

3b. Does this meet the objectives of the tool as promised - Score between 1 and 4 (4 being Meets Objectives Completely)

☐ 1 ☐ 2 ☑ 3 ☐ 4

-

4. *Any other Comments / Testimonial:*

The tool has clear applicability for long term planning in asset management where clients and stakeholders are interested want supporting mechanisms and data to enable them to make long term decisions.

Validation 5:

Resilience assessment Tool Validation

Amey

UNIVERSITY OF BIRMINGHAM

Attendee:	Position:	Date of Validation:
Attendee 5	Asset Management Expert (Manager)	November 12, 2013

1. Manual (Overall Score between 1 and 4 – 4 being Very Good)

☐ 1 ☐ 2 ☑ 3 ☐ 4

1a. Content Quality - Score between 1 and 4 (4 being Very Good)

☐ 1 ☐ 2 ☑ 3 ☐ 4

1b. Clarity - Score between 1 and 4 (4 being Very Clear)

☐ 1 ☑ 2 ☐ 3 ☐ 4

1c. Ease of Navigation - Score between 1 and 4 (4 being Very Easy)

☐ 1 ☐ 2 ☑ 3 ☐ 4

1d. Comments

Manual can do with some overarching reference to strategic documents. It should be a short paper showing how it works and its applications.

2. Resilience Assessment Tool (Overall Score between 1 and 4 – 4 being Very Good)

☐ 1 ☐ 2 ☑ 3 ☐ 4

2a. Ease of Use - Score between 1 and 4 (4 being Very Easy)

☐ 1 ☐ 2 ☑ 3 ☐ 4

2b. Presentation/Aesthetics - Score between 1 and 4 (4 being Very Good)

☐ 1 ☐ 2 ☑ 3 ☐ 4

2c. Logic/Workflow - Score between 1 and 4 (4 being Very Logical)

☐ 1 ☐ 2 ☐ 3 ☑ 4

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2d. Subjective Assessment for Each Step of the Tool

STEP	Subjective Assessment/Feedback
STEP 1 - Project Information	OK
STEP 2 - Asset Information	OK
STEP 3 - Present Asset Condition and short term risk assessment	OK
STEP 4 - Potential Solutions	OK – a probable list of solutions could be useful but not necessary as assumption is it will be used by experts in the field
STEP 5 - Future Conditions	There is a lot of information to follow and may need pre-preparation with the stakeholders to digest the information. But the information and examples are self-explanatory and easy to understand. Pairwise comparison method was systematic.
STEP 6 - Critical Success Factors	OK – a comprehensive list.
STEP 7 - Scoring Matrix	It is a time consuming process. The scoring may need long sessions for more complex solutions and also get relevant stakeholder approval.
STEP 8 - Output and Decision	OK- overall the tool is useful and puts us in the forward direction towards the changing trend in asset management.

3. Decision Support

3a. Applicability of the tool - Score between 1 and 4 (4 being Very Applicable)

☐ 1 ☐ 2 ☐ 3 ☑ 4

3b. Does this meet the objectives of the tool as promised - Score between 1 and 4 (4 being Meets Objectives Completely)

☐ 1 ☐ 2 ☑ 3 ☐ 4

4. Any other Comments / Testimonial:

None

Validation 6:

Resilience assessment Tool Validation

Amey

UNIVERSITY OF BIRMINGHAM

Attendee:	**Position:**	**Date of Validation:**
Attendee 6	Principal Geologist	November 12, 2013

1. Manual (Overall Score between 1 and 4 – 4 being Very Good)

☐ 1 ☐ 2 ☑ 3 ☐ 4

1a. Content Quality - Score between 1 and 4 (4 being Very Good)

☐ 1 ☐ 2 ☐ 3 ☑ 4

1b. Clarity - Score between 1 and 4 (4 being Very Clear)

☐ 1 ☐ 2 ☑ 3 ☐ 4

1c. Ease of Navigation - Score between 1 and 4 (4 being Very Easy)

☐ 1 ☐ 2 ☑ 3 ☐ 4

1d. Comments

None

2. Resilience Assessment Tool (Overall Score between 1 and 4 – 4 being Very Good)

☐ 1 ☐ 2 ☑ 3 ☐ 4

2a. Ease of Use - Score between 1 and 4 (4 being Very Easy)

☐ 1 ☐ 2 ☑ 3 ☐ 4

2b. Presentation/Aesthetics - Score between 1 and 4 (4 being Very Good)

☐ 1 ☐ 2 ☑ 3 ☐ 4

2c. Logic/Workflow - Score between 1 and 4 (4 being Very Logical)

☐ 1 ☐ 2 ☑ 3 ☐ 4

2d. Subjective Assessment for Each Step of the Tool

STEP	Subjective Assessment/Feedback
STEP 1 - Project Information	OK
STEP 2 - Asset Information	OK – adequate to provide comprehensive information in a single place even for future reference
STEP 3 - Present Asset Condition and short term risk assessment	OK – matches the asset condition assessment method used for asset inspection regime on strategic highways and motorways
STEP 4 - Potential Solutions	OK
STEP 5 - Future Conditions	Information took time to be well understood. But this may be due to the newness of the concept and exercise. Pairwise comparison method for weightages was objective and structured
STEP 6 - Critical Success Factors	OK
STEP 7 - Scoring Matrix	Initially found it difficult to think in multiple directions but once understood the principles it was down to experience and professional judgement. The scoring output and the final scores provided a good way to compare solutions easily and see hotspots that could be addressed
STEP 8 - Output and Decision	OK

3. *Decision Support*

3a. Applicability of the tool - Score between 1 and 4 (4 being Very Applicable)

☐ 1 ☐ 2 ☑ 3 ☐ 4

3b. Does this meet the objectives of the tool as promised - Score between 1 and 4 (4 being Meets Objectives Completely)

☐ 1 ☐ 2 ☑ 3 ☐ 4

4. *Any other Comments / Testimonial:*

None

Appendix C – Manual used for Validation

Manual – Resilience Assessment Tool for Geotechnical Solutions

1. Resilience Assessment Tool- Answers the 'What'

The overarching aim of this research project is to produce a resilience assessment decision support tool that assesses the resilience of potential geotechnical solutions in the light of future changing socio-economic, environmental and technological conditions.

The tool described in this manual aims to identify the resilience of proposed geotechnical solutions for UK transportation assets in the light of the foreseeable future conditions that geotechnical assets are likely to be exposed to during their design life.

The assessment tool is in the form of a matrix that provides a resilience score for proposed geotechnical solution(s). It provides decision support framework which can be applied during the feasibility stage of construction projects. By using whole life cycle costing it provides a holistic assessment which helps to determine effective solutions with maximum benefits (e.g. returns on tax payer's money).

The manual described herein facilitates the designer/engineer to develop an overall understanding of the elements of the assessment matrix adopted within the tool and the underlying principles used therein. .

2. Need – Answers the 'Why'

Geotechnical solutions provided today are designed for a minimum of 60 years design life. However, the conditions facing the geotechnical assets, along with the overall transportation network, are changing exponentially altering their role and purpose. This necessitates these solutions not only to be technically sound but also to offer flexibility, be fit-for-purpose and resilient. In so doing they can continue to perform with minimal changes in the design under a range of changing conditions. Hence embedding these requirements into a Geotechnical Asset Management framework (i.e. the tool described herein) achieves this aim. .

The tool can be adopted at the 'Design options analysis' stage where engineering options are evaluated and a feasibility analysis is undertaken to select the most technically sound, cost effective (and sustainable) geotechnical solution. Resilience

Assessment does not replace any of the above assessment processes. The resilience assessment is a form of acid test on the proposed solution(s) considering its applicability and flexibility under changing future conditions such as environment, economy, social, political and technological and hence provides an outlook on adopting a solution which gives ‘more for less’.

3. Geotechnical Assets

The tool has been developed for application on geotechnical earthwork solutions, but can be adopted for other geotechnical assets. The Geotechnical assets considered for the scope of this research are

- Foundations
- Slopes/Earthworks (Embankments and Cuttings)
- Retaining structures
- Subgrade underlying and supporting Carriageways.

4. Typical Failure Modes/Symptoms

The failure modes considered for the aforementioned geotechnical assets includes cognisance of their performance, serviceability, safety and stability.

5. Principles behind the Tool

The main principles behind developing this tool are three fold

- To determine the critical factors which lead to (or trigger) the failure of geotechnical assets.
- To establish an interrelation between these critical factors and future conditions (Social, Economic, Environment, Political, Technology and Shock Events such as Manmade and Natural Hazards)
- To facilitate testing the resilience of the proposed geotechnical solution(s) in the light of plausible changing future conditions.

6. WHO can use the tool and WHEN should it be applied?

Anyone can use the tool from the stakeholders to the client, project manager and designer. The benefits are seen across the project. The proposed tool can be mainly adopted at the feasibility stage where engineering options (in this case a geotechnical solution) are evaluated for technical soundness, cost effectiveness and sustainability. This assessment can form part of an overall lifecycle analysis or be adopted within a risk assessment framework where critical factors affecting geotechnical assets can be drawn up (e.g. during Value Management Workshops for The Highways Agency (known as Highways England since April 2015) on ASC contracts or Optioneering Stage in Railway Projects).

7. Methodology – How to use the tool.

The tool is in the form of an Excel based workbook which comprises 8 logical steps outlined below. An example is provided for ease of understanding for potential users. Each step is located on different hyperlinked tabs (2 to 10). Tab 1 provides a flow diagram showing the chronological sequence of the resilience assessment process

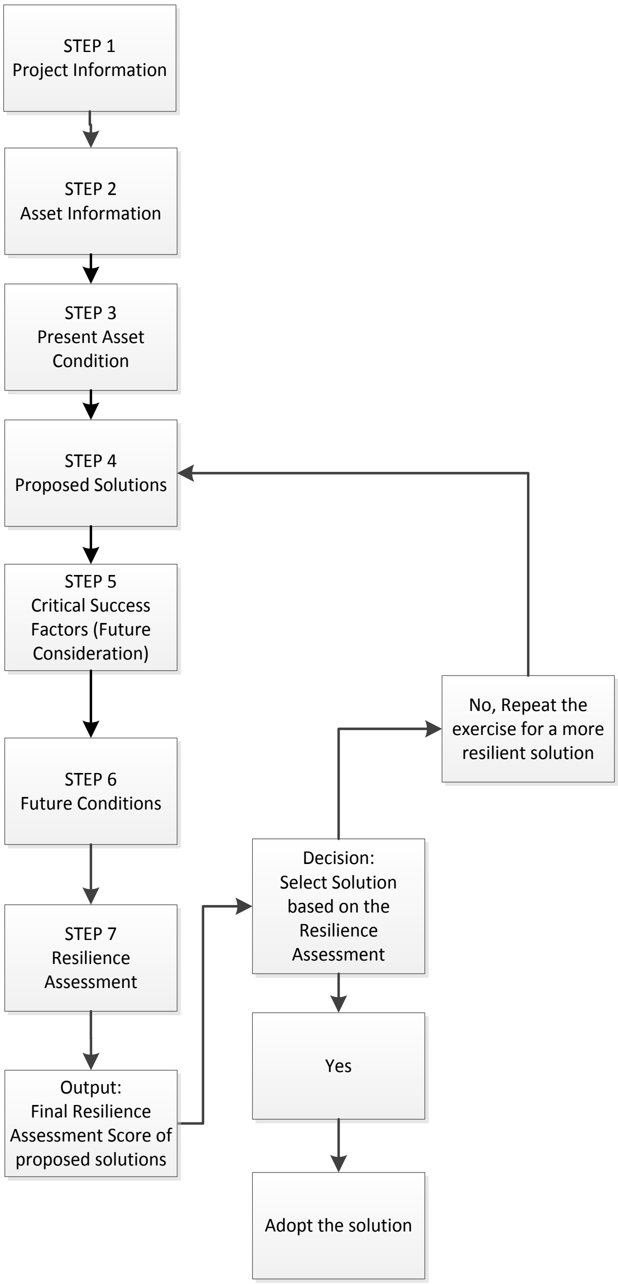

Figure 1: 8 steps adopted in the Assessment tool

STEP 1 – Project Information (Tab 2): This is an input step, where the user provides details about the project and stakeholders involved (Table 2). Information such as envisaged project start and end dates, preliminary assumptions/considerations, type of project, stage at which Resilience Assessment is undertaken etc.

<u>For example</u>: The project is regarding a deteriorated asset condition requiring remediation or it is an improvement scheme such as the Pinch point Project (i.e.

strategic parts of network offered improvement budgets to reduce congestion and improve safety)

Project Name	
Projet Ref. No.	
Document Ref. No.	
Revision No.	
Date first prepared	
Date Updated	
Project Leader	
Project Manager	
Prepared by	
Checked by	
Approved by	

Project Description

Stakeholders Involved

Project Timescale	Project Start Date	Project End Date	Maintenance Schedule

Resilience Assessment Assumptions

Figure 2: Project information (STEP 1)

STEP 2 – Asset Information (Tab 3): In this step, asset information is collected and recorded (Figure 3). Information on the asset obtained from a preliminary desk study or ground investigation analysis is interpreted and presented here; this does not yet include the condition of the asset (STEP 4).

<u>For Example</u>: Details of asset type, age, surrounding conditions such as topography, geology, environmental conditions, hydrology and history. Typically these are classified as 'GATE2H' which is explained in the notes within the tab.

Asset type	Select
Topography	*Description of the asset and surrounding topography, e.g. height, slope angle, offsets, etc.*
Geology	*Solid -* *Drift -* *Artificial ground -* *Fearutes-*
Hydrogeology	*Waterbodies -* *Aquifers -* *Groundwater vulnerability -* *Flooding -*
Age	*Range from HAGDAMS*
Asset interaction	*Proximity with other assets:* *Structures -* *Pavement -* *Drainage -* *Furniture - (Street lights, cabinets, signs, fencing, safety barrier, etc.)* *Utilities -*
History	*Mining -* *Landfill -* *Previous use -* *Previous failures/remedial works -*
Environment	*Animal burrouwing -* *Vegetation -* *Sensitive Site Designation -* *Cultural Heritage -* *Pollution/Contamination -*
Histotic Information	*Previous reports -* *Boreholes -* *As-built records -* *Lab results -* *Design details -*
Geotechnical Information	*Recent Exploratory Holes -* *Ground Summary -* *Soil Parameters -*
Site Specific Constraints	*E.g. Room available at the toe, highway boundary, maintenance related constraints, environmental constraints, etc.*

Note: In this stage, asset information is collected and recorded. Information from a preliminary desk study or ground investigation analysis is interpreted and presented here. It does not suggest the condition of the asset, but provides information about the asset type and its age and also details related to its surroundings such as topography, geology and history.

The factors can be broadly classified into GATE2H.
Geology which will include solid and drift deposits and the soil fabric with geotechnical properties such as soil classification, design parameters such as density and angle of internal friction, youngs modulus etc and stresses and strains and consolidation and compression properties. It also accounts for details of geotechnical phenomena such as liquifaction and heave and creep if necessary.

Asset interaction implies the interaction and behavious of geotechnical assets with respect to other assets in the network in the vicnity. For example geotechnical asset slope interacts with drainage, highway furniture like street lights, foundations and utilities.

Topography includes the overall site conditions such as the height of the slope, angle of the slope, vegetation cover etc, setback distances between the asset, carriageway and asset owners land.

Environment includes the external enviornment surrounding the asset, such as the biodiversity, precipitation, climate change, flooding etc.

Hydrologeology is the presence of aquifers, ground water and pore water pressure

History includes the history of the asset in terms of its age, construction, design and maintenance records of historic site activity like mining etc and any historic ground improvement undertaken on the site, records of contamination etc is also incuded in this category.

The categories above are divided into more detailed elements representing critical factors that affects singularly or in conjunction with each other the performance of Geotechnical asset which directly affects the condition of the asset. This is discussed in the following tab.

Figure 4: Asset information (STEP 2)

A subjective assessment is also made of how the asset is likely to deteriorate over the next 5 years (Figure 5b) and therefore what Risk Class it may be located in at the end of that period. This is a basic condition assessment based on visual observation and does not currently involve any detailed deterioration modelling.

Reference for this is available in Highways England's Geotechnical Asset Management guidance document (HD 41/15) as a typical pro-forma for principal inspection regime for geotechnical inspections.

<u>For Example</u>: Presence of Vegetation, Presence of existing failure on or in the vicinity of the concerned asset.

STEP 3 – Present Asset Condition and short term risk assessment (Tab 4): In this step, critical factors that affect the current condition of the geotechnical assets are investigated and the user has to tick those applicable for the asset (Figure 5a). This records the findings (preferably) from a walk over survey or regular inspections of the asset. Factors that are essential to decide the condition of the asset are listed in this step.

Ref.	Asset Condition	Sub-categories	✔	Description/Comments
1	Loading	Existing Loading Conditions depending on type of road		
2	Water Observation	Seepage		
		Marshy		
		Ponding		
		Erosion		
		Hydrophilic Vegetation		
		High Moisture Content		
3	Drainage	Lined Ditch, Unlined Ditch, Gravel, Pipe, Transverse, Herringbone, Kerb, Culvert, French, Reservation, Watercourse		
4	Pollution/Contamination	Evidence of Pollution/Contamination (BS suite test)		
5	Vegetation	Bare Ground		
		Grass		
		Brambles		
		Shrubs		
		Trees		
6	Animal Burrowing	Presence of Animal Burrowing		
7	Previous remedial works	Reinforced Earth, Existing Sheet Piles, etc.		
8	Interaction with other assets	Existing street furniture, utilities and other structures.		
9	Age			
10	Geology	Weak ground conditions, soil properties, soil fabric, stiffness, strength, stresses & strains		
11	Topography	Slope Height and Angle, location		
12	Soil Phenomena	Liquefaction, shrinkage & swelling, etc.		
13	Features	Soil Slip		
		Slope Bulge		
		Terracing		
		Tension Cracks		
		Dislocated Trees		
		Ravelling		
		Wedge/Block Failure		
		Planar Failure		
		Subsidence		
		Cracked Pavement		
		Dislocated Fence/Barrier		
		Distorted Structure		
		Leachate		
		Desiccation		
		Toe Debris		
		Other Feature		
14	Heave			
15	Creep			

(a) Asset condition

Overall Severity of Risk due to the Asset Condition	✔	Assessed Severity of Risk in 5 Years	✔
Severe		**Severe**	
High		**High**	
Medium		**Medium**	
Low		**Low**	
Negligible		**Negligible**	

(b) Short term risk assessment

Figure 5: Asset Condition and Risk assessment (STEP 3)

STEP 4 – Potential Solutions (Tab 5): Based on the asset information and the critical factors for current condition of the asset, the engineer can determine potential solutions for remediation or improvement depending on the nature of the asset and its condition (Figure 6). This step allows the user to record estimated cost(s) and anticipated project duration associated with the respective chosen solution. This proposed tool enhances (rather than substitutes) the process of whole life costing, project planning and risk assessment undertaken during any construction scheme. .

For Example: Potential Solutions could be a Do Something (Complete/Holding), Do Minimum or Do Nothing option.

Project Name	

Solution No. 1	
Geotechnical Solution Ref. no.	1
Description	
Solution Type	*e.g. Do Nothing, Do Minium, Do Something Full*
Project Duration	
Estimated Cost	
Comments	

Solution No. 2	
Geotechnical Solution Ref. no.	2
Description	
Solution Type	*e.g. Do Nothing, Do Minium, Do Something Full*
Project Duration	
Estimated Cost	
Comments	

Solution No. 3	
Geotechnical Solution Ref. no.	3
Description	
Solution Type	*e.g. Do Nothing, Do Minium, Do Something Full*
Project Duration	
Estimated Cost	
Comments	

Figure 6: Potential solutions (STEP 4)

STEP 5 – Future Conditions Filter (Tab 6): The Future Conditions (FC's) are explored in more detail through the use of scenarios filter Figure 7. The scenario based description provides the user with a filter/picture of how the FC's could be triggered influencing their choice of selection of geotechnical solution. The user should think along these lines and then can assign ranking/weightages as per their priority and importance. The sum total of the weightings should be 100.

Future Conditions (FC)	FC Ref.	Influencing factors to consider	Impact on infrastructure asset	*User considerations*	*User assigned Weighting %*
Demographics	FC1	Change in demographics could be attributed to: a change in population, density of an area, urbanisation patterns and an overall impact of globalisation that has an effect on the trade and migration patterns.	Changes in demography have a direct influence on the infrastructure network and in particular the use of transportation networks. Transportation assets are likely to be affected by usage, need and level of service expected.	The user should envisage the use and purpose of the network and the scale of demographic changes it intends to cater for in the future.	10%

Figure 7: Future conditions filter (STEP 5)

The user should be able to provide a justification for the choice of his/her weightings so that there is a justified rationale in the selection. A snapshot of the tab is shown below. For the purpose of simplicity, only one Future Condition is shown below. It can be seen that, the FC is described in the first column; its impact on transportation network is explained in the subsequent column followed by user considerations and examples. If the user wishes to skip this stage, then all the future conditions (by default) get equal weighting.

For Example:

(1) Change in 'Demographics' – affects the transportation network. This could be attributed to a change in population, density of an area, urbanisation patterns and an overall impact of globalisation that has an effect on the trade and migration patterns. This has a direct influence on the infrastructure network and in particular the use of transportation network. Transportation assets are likely to be affected by usage, need and level of service expected.

Imagine a strategic network of road connecting a city with forecast increasing density, the road will require to meet increased demands of traffic which puts additional pressure on the network. This in turn triggers a change in use of assets, results in an increased demand for multi-functionality and also increases the need for efficient interaction between different assets on the network. Similarly a decreased use of the network for any reason such as emigration due to poor economic conditions or *susceptibility to environmental hazards such as floods etc. may mean the solutions devised today may be over engineered for the needs of the future. The user should think along these lines to envisage the use and purpose of the network and the scale of demographic changes it intends to cater in the future. Hence the asset owner or Engineer should determine the appropriate weightage depending on the importance and/or relevance of the Future Condition.*

(2) *'Economics' - elements such as the funding strategy, budgets (Capex/Opex) and its influence on the socio-economic credentials should be considered. Elements such as responsiveness to economic change (agility) is the need of the hour and is an attitude that is envisaged to be carried forward especially on projects where the return on investment is long term such as PFIs or DBFOs on transportation network. The user has to think along the lines of economic agility, change in funding patterns, whole life costing and its effect on need for multi-functionality, change of standards and policies and an overall attempt to improve the self-sufficiency and integration of the transportation network.*

As an instance of economic agility, most of UKs infrastructure is rapidly ageing and funds allocated for maintenance schemes are also increasing with time. Within the MAC and ASC contracts operated by The Highways Agency (known as Highways England since April 2015), a separate pool of resources is currently (2013-14) used to fund PPP i.e. Pinch Point Programme which aims to improve (widen) specific junctions on strategic motorway networks. This demonstrates the change in economic spending over the years. The user should think about the new trends such as the effect of global economy influencing local funding decisions. Change in funding policies may affect the budgets for maintenance for future hence requiring more robust solution with less Opex required in the future. Future discussions related to new policies suggesting privatisation of transportation network while keeping in mind the declining incomes needs to be accounted for.

STEP 6 – Critical Success Factors and Future Conditions (Tab 7):

Critical success factors (CSF) are those key factors which when triggered affect the performance of geotechnical assets. These include, but are not limited to such factors as loading, changing ground water condition etc. Solutions provided today have to be acceptable and fit for purpose under the impact of various combinations of these factors both now and in the future. Their ability to do this effectively, defines the resilience of these solutions.

The seven future conditions considered here (i.e. Demographics, Environmental Changes, Changes in Social Behaviour, needs and attitudes, Political changes (Governance), Economic Changes and implications, Technological changes and innovations and finally manmade and natural shock events) are directly or indirectly applicable to Infrastructure (mainly transportation) networks and geotechnical assets.

The list of CSF's are defined in Figure 8. The user is required to deduce (from the available information they have provided) the relevant CSF's that impact upon the chosen asset. They are subsequently categorised as 'relevant' or 'not relevant' in the 'Relevance' column. .

The inter-relationship between the CSF and the seven FC's is represented in the CSF score pre-determined using Equation 1.

$$Score(CSFn) = \frac{No.of\ RFC_n}{Total\ no.of\ FC} \times \frac{100}{\sum_{n=1}^{n=14}\left(\frac{No.of\ RFC_n}{Total\ no.of\ FC}\right)} \qquad \text{Equation 1}$$

Where:

- Future Condition (FC). Total number of FC's considered in this study (i.e. Demographics, Social, Environment, Economic, Governance, Technology and Shock Events) = 7.
- Critical Success Factors (CSF)= Total No of CSF from Figure 7 = 14.
- Relevant Future Conditions (RFC) User specifies how many FC's are relevant for a specific CSF.

- The CSF Score (CSF n) determined from Equation 1.

For Example:

CSF1 (i.e. Flexibility to allow for loading) is important in the following FC's: Demographics, Social, Governance, Technology and Shock Events. Hence forCSF1, RFC= 5, FC=7. Therefore CSFn =5/7. **Therefore, the critical factor that is likely to get triggered in most future conditions is given highest score. The diagrammatic representation of this correlation between FC and CSF is shown in the Resilience Assessment Tool presented in Appendix A.**

The justification behind deriving the inter-relationship between the CSF and FCs is described in detail in Step 6.

No.	Critical Success Factors (Future)	Description	Score (fixed)	Relevance
CSF1	Flexibility to allow loading variation	Proposed solution's flexibility and ability to adapt to the loading variations (surcharge, change in use, etc.) causing increased demands and need for mutlifunctionality.	8	
CSF2	Seepage Characteristics	Proposed solution's response to Seepage conditions in terms of nature of the material and it's influnce on reducing groundwater and p.w.p.	3	
CSF3	Effect on Drainage	Proposed solutions response to effectively drain the slope in the event of excessive precipitation and excessive storm water drainage in order to regulate groundwater.	3	
CSF4	Effect of Pollution/Contamination	Effect of pollution and contamination due to triggering of contamination pathways or live traffic and spillages etc. on the solution and its applicability and fitness for purpose.	8	
CSF5	Impact of Erosion	Proposed Solutions response to erosion caused by water or wind.	3	
CSF6	Maintaining Bio-diversity	Solution should facilitate and enhance biodiversity	6	
CSF7	Response to Extreme Climatic Conditions	Proposed Solutions response to extreme climatic events such as excessive snow, extreme temperatures, excessive precipitation causing flooding etc. Flexibility to accommodate increased and change in demands which may increase interaction with other assets.	8	
CSF8	Flexibility for Interaction with Other Assets	Change in use and multifunctionality resulting from adaptation to increasing demands and changing conditions results in the need to have increased dependencies and itnerface between proposd solutions and other asset. Flexibility to asset interaction is quite essential in such a dynamic environment.	10	
CSF9	Ease of Maintenance and Operation	Porposed Solution should be easy to maintain and operate with minimum disruption to road users and not jeopardise safety.	10	
CSF10	Health & Safety consideration	Construction, Design,Maintenance and Operation of the proposed solution should not affect health anss safety of workers and live traffic.	6	
CSF11	Flexibility of Use/Multi-functionality	Solutions flexibility to Use of the asset and adapatability to accommodate future expansions and modifications to the network.	10	
CSF12	Obsolecence/Ease of disposal	Solutions ease of disposal on obscolescence or end of life should cause minimum waste generation and cost implications.	10	
CSF13	Change in Standards & Policy	Flexbility to adapt to change in standards and policies with minimum modifications and waste.	11	
CSF14	Whole Life Costing	Overall optimum costs throughtout the life cycle of the asset right from material, transport, construction, maintenance and disposal of the solution,	5	
	Total		**100**	

Figure 8: Critical success factors (STEP 6)

STEP 7 – Scoring Matrix (Tab 8): This tab consists of the Resilience Scoring Matrix. In this matrix, the weightings provided by the user in STEP 5 is automatically shown in the column adjacent to corresponding FC. Also predetermined scores for Critical Success Factors discussed in STEP 6 are shown in the row below for the corresponding CSFs. The project information is reflected and the preferred solution is shown in the top left of the worksheet. There are three separate matrices currently provided to be able to assess 3 proposed solutions. These can be further copied and expanded to include more options, as required.

The cells which represent the inter-relationship between the CSF and FC are highlighted with the same colour coding used within the Resilience Assessment Model. It is in this cell, that the resilience scores assigned for the preferred geotechnical solution are input by the user. The scoring system is in the range of -3 to +3, where -3 is lowest and +3 is best vis-à-vis the solution with most resilience potential is scored +3 and the one with least flexibility to be resilient is scored -3. If the solution is envisaged as over-engineered for the future conditions, a negative score can be assigned. If the solution is neutral or not applicable then a score of 0 can be provided.

Resilience Assessment Tool - Scoring Matrix

Project	0
Project Ref.	0

Proposed Geotechnical Solution 1	
Proposed Geotechnical Solution	0
Geotechnical Solution Ref. no.	0
Document Ref.	0
Document Revision	0
Date First Prepared	0
Date Updated	0

Future Conditions (FC)			**s Factors (CSF) - Future**		**Resilience Score**		
Description	**FC Ref**	**FC Weitage (%)**	***Factor***	**Flexibility to allow loading variation**	**FC Score**	**Resilience FC Score**	**Total Resilience Score**
			Factor Score (Fixed to a total of 100)	**8**			
Demographics	FC1	10%		2	11.0	8.7	**8.7**
Environment	FC2	20%			0.0	0.0	
Social	FC3	30%		0	0.0	0.0	
Economics	FC4	10%			0.0	0.0	
Governance	FC5	10%		0	0.0	0.0	
Technology/ Innovation	FC6	10%		0	0.0	0.0	
Shock Events	FC7	10%		0	0.0	0.0	

Scoring Key	
Score	**Description**
+3	Existing solution works with no change in design
+2	Existing solution works with minor amendments and marginal cost and time implications
+1	Existing solution with room for improvement to design with reasonable time and cost implications
0	Neutral or Not Applicable
-1	Existing solution requires design changes with additional time and cost implications
-2	Existing solution requires substantial design amendments to its original form and surrounding area with substantial time and cost implications
-3	Existing solution does not work and requires replacement with re-engineered solution have major time and cost implications

Figure 9: Resilience Scoring Matrix (STEP 7)

<u>*For Example:*</u>

(1) ***Demographics:*** *Consider and embankment widening scheme on an urban road or a strategic motorway connecting busy cities: The proposed solutions are to widen the embankment with imported fill or by provision of sheet pile retaining wall at the toe. These solutions can be both technically sound and depending on site specific conditions viable for the proposed widening work. However, with changing demographics considering majority of population migrating towards cities may lead to an increase in the number of motorway users thereby increasing the usage of the network. This has an impact on*

the change in use of the network. Also, with increasing trade and demands more haulage and special vehicles may be used in the future hence arising the need to provide flexibility to account for increased loading due to this changing nature of network usage. Resilience Assessment for Sheet Pile Walls and Re-grading with imported fill is to be undertaken keeping in mind the aforementioned scenario.

With the need to accommodate increased traffic loading by provision of an additional lane there might be future widening works required along the same section of this strategic road network. If the additional loading is more than the inbuilt design capacity, amendments in the existing design solutions may be required. In such a case, the sheet pile walls option may need to be removed and replaced with a more fitting solution to account for the increased loading. It is also important to acknowledge that this will require major works and higher costs in removing the sheet piles. However, with the option of regrading using imported fill, additional support reinforcements and strengthening works can be provided with minimal disruption to proposed solutions to account for such probable increased loadings. Hence for this example, a scoring of -2 is provided for sheet pile wall and +2 for regrading with engineered fill.

For the same scenario due to the change in usage of the network additional widening works may be required to provide additional traffic lanes for increased volume of traffic. A similar principle can also be applied on this instance. Sheet Pile Walls are less flexible to allow accommodate additional earthwork widening whereas regarding with engineered fill can be cut back to appropriate design widths and can be incorporated as a part of new solutions such as provision of soil nails or other retaining structures. Hence, rendering a similar scoring of -2 and +2 for sheet pile wall and Re-grading respectively.

(2) ***Social:*** *With recent increase in health and safety standards and importance, the Highways Agency (now referred as the Highways England since April 2015) standard for Safety Barriers Design (TD19/06) have amended (increased) their Working Width requirements behind safety barriers to a*

safer standard. Due to this, those safety barriers which were considered at risk are to be replaced with barriers as per latest standards and requirements. As a result, changes to existing earthworks supporting these carriageways are required. Imagine an embankment slope where proposed widening works to accommodate the new safety barrier and increased Working Width distance behind the barriers are to be undertaken. Due to site specific constraints of limited room at the toe of the embankment, retaining wall solution is proposed. Two solution options considered are Gabion Wall and Sheet Pile Wall.

In the future if considering the changing Social requirements of increased importance on improving and maintaining bio-diversity is laid, then a solution that offers the flexibility to grow vegetation or harbour nesting birds is much preferred than the once which doesn’t. Hence, with Gabion Wall solution there is a possibility to grow vegetation and also possibility for provision of nests for species, if required, whereas, sheet pile walls provide limited flexibility to accommodate the same unless major changes are done to its existing slope profile. Hence for this scenario within this example, Gabion Wall can be scored as +2 while Sheet Pile Wall can be scored as -1 (considering some possible amendments in the future).

(3) ***Environment:*** *Performance of the proposed solution under the influence of increased precipitation, extreme weather conditions, increased pollution/contamination, promoting bio-diversity, influencing waste-generation, conservation of Heritage and sensitive areas and promoting sustainability.*

For example on a cutting slope, a slip failure has occurred due to increased precipitation, increased loading at the toe and existing drainage system unable to cope with the same. The remedial solutions considered are (1) re-grading the slope by replacing the slipped material with engineered fill (Do Minimum Option) and (2) *remediate the slope by removal of slipped material and provision of counterfort drains, thereby improving the drainage capacity of the slope (Do Something Option).*

Hence in this case, for the Environment Future Condition highlighting increased precipitation, flash flooding, geotechnical assets such as slopes have to deal with increased pressure on 'drainage' to keep them dry and release pore water pressures. Hence provision of counterfort drains (Solution 2) is a longer term solution than the replace and re-fill option (Solution 1), as it not only remediates the failed slope but also meets the needs of increased susceptibility to Environmental changes in the future. Hence in this case option 2 would get a score of +3 because the solution will remain fit for purpose under the Environment FC with no changes to the design necessary. While, option 1 would get a score of -1 because the solution will require design changes with additional time and cost implications.

Similarly for the CSF of 'Impact of Erosion' and FC of 'Environment', the Solution 1 would get a score of -2 because the solution will require substantial design amendments to its original form and surrounding area with substantial time and cost implications. While, Solution 2 will get a score of +2 because the solution will allow for increased storm water drainage preventing erosion of the slope and may require minor amendments for future capacity improvement.

(4) ***Governance:*** *Does the performance of the proposed solution rely on specific policies and regulations. Will change in governance (policies, security of funding etc.) have an effect on maintenance and operation of the proposed solution? Policies governing waste regulations may affect the operation and disposal of transportation assets and its interaction with other assets.*

For example, consider a cutting that requires to be retained for provision of a pedestrian footpath for a road widening scheme. The proposed solutions are (1) Sheet Pile Wall with aesthetic painting and (2) Crib Wall with vegetation planting. In this case, the Sheet Pile walls will require regular maintenance for painting also generating waste from this. While the Crib Wall may require some vegetation maintenance, but very minimal and will not involve any waste generation. Hence, for the CSF 'Effect of Pollution/Contamination' and FC 'Governance' considering that in the future the waste regulations change with stricter norms, the Solution 1 would get a score of -2 because paining the sheet pile wall every few years will generate pollutants, the disposal of which will have cost and environmental implications. While the Solution 2 in this case will get a score of +2 because it will in fact help in meeting the stricter regulations by no waste generation, but will still require some maintenance.

Similarly, for the CSF of 'Ease of Maintenance and Operation' the Solution 1 will get a score of -2 because it will require substantial maintenance regime and costs and will also require disruption to the public during the maintenance. While solution 2 will get a score of +2 because it still requires some maintenance of vegetation, but it can be done relatively easily with minimal costs and disruption to the public.

(5) ***Technology/Innovation:*** *Does the proposed solution offer innovative, leaner, efficient credentials. Does the solution offer flexibility to accommodate for future changes in technology. Does the solution allow multi-functionality?*

For example, for a remediation of a cutting slope on the side of a strategic trunk road, the solution options being considered for the same are (1) Soil-nailing and (2) Re-graded Slope with new engineered fill. For the FC 'Technology/Innovation' consider the technological innovation in telecommunications requiring installation of substantial new utilities along the road. In this case, for the CSF of 'Flexibility for

Interaction with Other Assets', option 1 will score -2 because installation of the additional utilities will require substantial amendments to the soil nailed slope and hence disruption to the other surrounding assets; While, option 2 will score +2 because it will allow the flexibility to incorporate the installation of additional utilities with minimal changes to the design and minimal disruption to the interaction between these assets.

(6) ***Shock Events:*** *Does the solution account for shock events in its design. Does the proposed solution provide redundancy in the event of extreme events without harming the society. Does the solution increase the inter-dependency or affect other surrounding assets. Does the proposed solution account for reasonable recovery of the network post an extreme event.*

For example, for a flood bank protection scheme the options considered are (1) Gabion Walls and (2) Bio-Engineered slopes. For the FC 'Shock Events' consider the extreme shock event like large scale flooding due to storms, hurricanes (e.g. Sandy Hurricane in US in 2012) and/or flash flooding causing the failure of either of the solutions. In this case, for the CSF of 'Response to Extreme Climatic Conditions', the Solution 1 will score -3 because post the event, the gabion wall will require full replacement. While for Solution 2 the score will be -1 because post the event, it will require some design changes but can be remediated with comparatively lesser cost implications.

STEP 8 – Output and Decision (Tabs 9 & 10): Results from the Resilience Assessment Matrix (Tab 8) are recorded here. The results from Tab 8 automatically get fed in Resilience Score cell within this Tab. There is a column for comments which allows the user to provide comments on the output. Finally, in the Decision Sheet (which is a separate Tab), the user has to input his choice for considering the solution most resilient and provide reasons supporting the same.

OUTPUT - Final Resilience Assessment Score of proposed solutions

Project Name	

Solution No. 1	0.0
Geotechnical Solution Ref. no.	1.0
Description	0.0
Resilience Score	#VALUE!
Comments	

Solution No. 1	0.0
Geotechnical Solution Ref. no.	2.0
Description	0.0
Resilience Score	#VALUE!
Comments	

Solution No. 1	0.0
Geotechnical Solution Ref. no.	3.0
Description	0.0
Resilience Score	#VALUE!
Comments	

DECISION - Select Solution based on the Resilience Assessment

Project Name	

Decision	
Solution No.	
Geotechnical Solution Ref. no.	
Description	
Resilience Score	
Comments	