Highways Agency

A Risk-based framework for geotechnical asset management

Phase 2 Report

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Franklin, 1789

"in this world nothing can be said to be certain other than death and taxes"

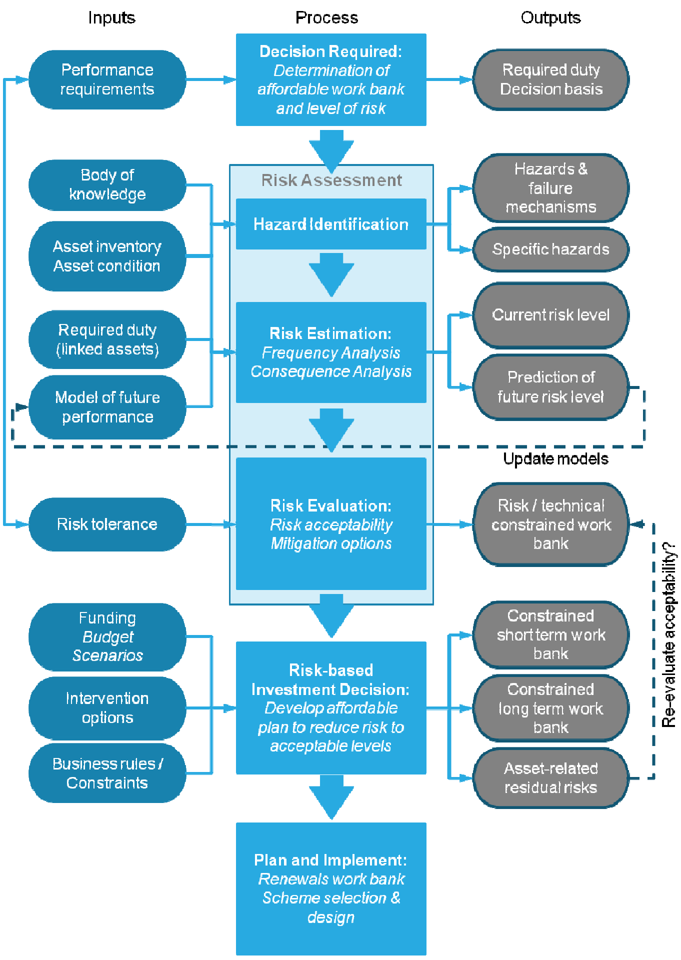
Risk

An uncertain events or set of events that, should it occur, will have an effect on the achievement of objectives. A risk is measured by a combination of the probability and the magnitude of its impact on objectives.

OGC: M_o_R®

This report presents a risk-based framework for the management of the Highways Agency's geotechnical assets. The principal reason that consideration of a risk-based framework is appropriate is the inherent uncertainty of future performance of geotechnical assets. The objective of a risk-based approach is to allow the allocation of limited resources using a rational basis for prioritisation.

The proposed framework, shown below, focuses on improving the definition of *likelihood* of a loss of performance of a geotechnical asset, and *consequences* of that loss of performance.



The general context for making **risk-based renewal and intervention decisions** about the Agency's geotechnical assets relates to the ongoing costs incurred repairing slope instabilities of approximately £20m per annum. The presence of *major defects* is used as the basis for decision making, based on the premise that these defects are indicative of the onset of loss of performance of the slope. It is proposed that decisions be made in the context of the *performance requirements* of the geotechnical assets, which are influenced by a number of different consequence components.

The first input to the framework is a definition of general **hazards and failure mechanisms** for different types of geotechnical assets, which will inform the asset management strategy.

The main step of the framework is the **estimation of risk**, based on an improved model of the future performance of geotechnical assets, from Task 651(666), to inform **likelihood**, and a more detailed breakdown of the different **consequence** components that link in to the performance requirements of the geotechnical assets, other assets, and the network as a system. A simple **risk matrix** is proposed, based on qualitative assessments of likelihood and consequence. Consequence may be an aggregated consequence rating based on all components, or individual elements of consequence can be considered if required. Within the decision making framework there is scope to undertake more complex quantitative risk assessments as the decision requires.

Risk evaluation separates assets into three main groups, *essential*, those that MUST be repaired, *high* and *moderate* priority, and *low priority* where no action is required. For those geotechnical assets in the middle category, which *should* or *could* be repaired, the decision should be optimised on the basis of a full understanding and communication of the risk. The output of the **risk evaluation** stage is an *unconstrained workbank* (in terms of budget) defined in terms of an indicated risk rating and a definition of the acceptability of that risk.

The **decision making** stage describes an Optimised Decision Making (ODM) process, based around decision rules and defined intervention and mitigation options. Where sufficient data are available and the decision to be made warrants it, a Quantitative Risk Assessment (QRA) tool can be implemented within the optimisation process.

The output from the framework is a clear route to prioritising decisions about renewals and interventions, with a clear communication of the risks as the reason for making the decisions, as well as the residual risks where a decision not to intervene is made.

The primary reason for proposing this risk-based framework for managing geotechnical assets is to improve budgeting decisions. The focus is on risks that could lead to unforeseen budgeting expenditures. Safety risks are included within the assessment but not explicitly stated.

1 Introduction

1.1 Task Brief

In November 2008, Arup, as part of the Séligere consortium, were commissioned though the HA SSR National Framework Contract for R&D Services (Contract 3/387) to undertake Task 580(387)ARPS *'Development of a Risk-based Approach to Geotechnical Asset Management'*. The Highways Agency Project Sponsor is David Gwede in Network Services.

The task objective is to:

Develop a coherent quantitative risk assessment approach to prioritising maintenance of the geotechnical asset. The approach should complement the ongoing work by Networks Operations Directorate under the Integrated Asset Management (IAM) Programme.

The particular needs to be addressed by the Task are:

1. To introduce quantification to the engineering processes of scheme selection and evaluation of maintenance, where the existing approach as prescribed in HD41/03 (HA, 2003) is largely qualitative.
2. To enable smarter communication of risks to the business decision process.

1.2 Task approach

The task has been carried out in a phased approach. The initial phase of the project was to undertake a scanning study to advise and determine the programme of activities for the subsequent stages of the work. This was reported in the *Scanning Study Report* (Arup, June 2009).

The second phase of the project, described in this report, takes the recommendations of the *Scanning Study Report* and develops them into a coherent framework, with specific guidance and recommendations.

1.3 Document purpose and structure

This document summarises the findings of Phase 2 of the task, and presents clear and practical recommendations for moving towards a risk-based approach.

Section 2 summarises the background information relevant to this report.

Section 3 summarises the scope of work and the methodology adopted to develop the framework.

Section 4 presents the recommended framework for risk-based geotechnical asset management.

Sections 5 to 9 cover the five components of the framework as follows:

- Section 5 describes the context of the risk-based asset management decision;

- Section 6 discusses hazards that have the potential to cause a loss of performance of geotechnical assets;
- Section 7 describes approaches for Risk Estimation, including identifying the frequency of occurrence of possible events, and their consequence;
- Section 8 presents the techniques for evaluating risks and defining their acceptability criteria; and,
- Section 9 summarises the process for evaluating options and making decisions.

Section 10 contains conclusions and a series of recommendations.

A glossary of terms is presented in Appendix A.

2 Background

2.1 The need for a risk-based approach

A unique aspect of geotechnical assets, as opposed to pavements or bridges for example, is their inherent variability. Even if our information and knowledge of future performance were perfect (which it never is), there would still be a variability associated with our future predictions, related to the uncertain behaviour of geological materials. The behaviour of geotechnical assets is also affected by environmental conditions notably surface water and groundwater including rainfall events, which are also uncertain. Thus a risk-based approach is essential to understand this variability, and to assign probabilities to future behaviour rather than presenting future behaviour as if it were certain.

The additional information pertaining to likelihood and consequences of uncertain future events should provide an invaluable basis to understand, communicate and evaluate risk within the asset management decision-making process. As described by Woodhouse (2001), decision-making in asset management requires understanding and resolution of cost, risk and performance aspects. This is also echoed in PAS55-2: 2008, the publicly available specification for asset management.

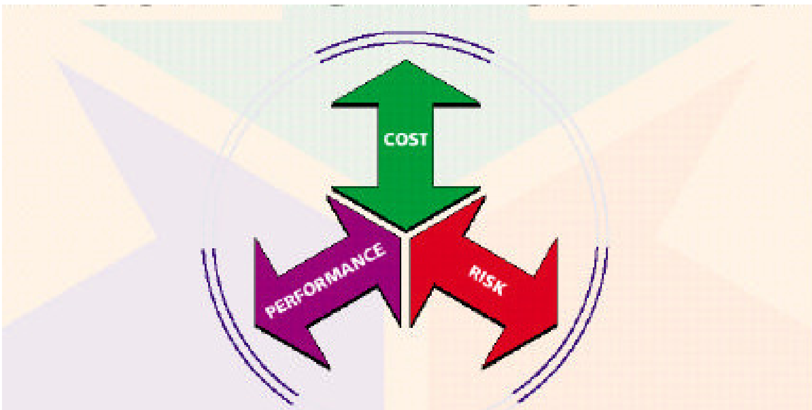


Figure 1: Balancing the needs of cost, risk and performance (Woodhouse, 2001)

The primary output of a risk-based approach will be the ability to make informed budget allocation decisions with a proper understanding of the associated risk. A full approach will also include appreciation of future changes in environment and asset duty. For the geotechnical asset this would include further uncertainty such as climate change.

The current approach for managing geotechnical assets, as documented in HD41/03, is already risk-based. A risk rating is allocated to geotechnical assets during inspection based on observed condition and their proximity to the running lanes or significant structures. Therefore the framework developed in this report is not a fundamental change of approach; rather it is a way of making the risk assessment more systematic and less subjective, by improving on the existing approach.

The over-arching issues covered by this approach are:

- The need for a practical aid to decision making

- The fact that decision making in asset management requires resolution of cost, risk and performance.
- The inherent variability of geological materials and geotechnical asset performance.
- The ability to provide compatible information between different asset classes and different decisions.

2.2 Sources and types of risk

In the context of geotechnical assets within an infrastructure system, *Risk* can be broadly defined as the probability of loss of performance (in terms of safety, reliability, serviceability etc.) due to an event. The event may be a slope failure, a rock fall, a settlement, or some other mode of ground movement, and the loss of performance may range from closure of a running lane, to excessive tilting of a road sign.

The reason these are *risks* defined in terms of their probability is that the occurrence of the event is **not certain**. Where we have certainty, there is no risk.

Reasons for the uncertain future behaviour of geotechnical assets come from two principal sources:

- **Lack of knowledge** (also known as *epistemic* uncertainty)

  Ground conditions are never known with complete certainty, and most of our understanding of geotechnical behaviour is induced from limited observations and information, used to derive a model which only approximates reality.

  Inputs to a model contain sample uncertainties due to accuracy of measurements or validity of the sample, and data uncertainties due to interpolation or extrapolation.

  Future events that may affect stability are not known with complete certainty, such as the likelihood of impact loading, of blocked drains, or of human actions such as excavating at the toe of slopes.

  Epistemic uncertainty is analogous to a pack of cards, whereby the next card in the pack is fixed, but we do not have the information to know what it will be. We can, however, use our experience and judgement and prior knowledge of cards that have gone before to reduce the uncertainty.

- **Natural variability** (also known as *aleatory* uncertainty)

  Stratigraphy, soil properties and ground water levels all vary naturally within the geological environment, and additional knowledge or investigation will not reduce these variabilities.

  Certain loading conditions have an inherent randomness, such as heavy rainfall, and the coincidence of heavy rainfall with other destabilising factors.

  Aleatory uncertainty is analogous to throwing a dice, which is random and cannot be predicted, or reduced.

Uncertainties in both internal and external factors are allowed for in design by using a factor of safety approach. An alternative approach uses reliability theory to explicitly quantify and allow for the affects of uncertainties. A reliability approach has the advantage that it directly communicates the risk of failure, rather than hiding it within a factor of safety approach. In practice, whether they are epistemic or aleatory does not affect the design decision, it is just a useful way to define reasons for uncertain future behaviour.

These sources of uncertain future behaviour of geotechnical assets are the reason that a risk-based approach is required, and that using a probability is the only appropriate means of describing future behaviour.

DETR (2000) also note that a **sensitivity analysis** is an essential tool to understand the impact of these uncertainties.

2.3 Risk-based asset management

Risk management is recognised as an important foundation for asset management.

Risk management is discussed within an asset management in key references and standards on the subject:

1. International Infrastructure Management Manual (IIMM, 2006)
2. PAS-55: 2008 *Asset Management*
3. CIRIA C677 *Whole-life infrastructure asset management: good practice guide for civil infrastructure* (Hooper *et al*., 2009)

PAS 55-1 also recognises that there are both asset related risks and asset-management related risks.

PAS 55-2 Section 4.3.2.1

Risk identification, assessment and control are important foundations for asset management. Their overall purpose is to understand the cause, effect, and likelihood of adverse events occurring, to optimally manage such risks to an acceptable level, and to provide an audit trail for the management of risks.

This is achieved by:

- **Identifying potential risks associated with the assets, and making an estimate of the associated risk levels, on the basis of existing or proposed risk controls.**
- **Determining whether these risks are tolerable; or**
- **Determining whether further analysis is required to establish whether the risks are, or are not, tolerable;**
- **Devising improved risk controls where these are found to be necessary or desirable.**

2.4 Arup (2007) QRA Study

Arup undertook research work for the Highways Agency in 2007 to investigate how Quantitative Risk Analysis (QRA) techniques could be applied to decision-making regarding earthworks maintenance.

This study derived probability distributions of theoretical future costs of maintenance and remedial works for an example earthwork. Uncertainty in both the asset behaviour and consequences was modelled using Monte Carlo simulation techniques.

Figure 2 shows an example of the results obtained for this study.

The conclusion from this study was that such curves derived for real situations and based on more extensive reliability and consequence data could be used to inform decision making processes.

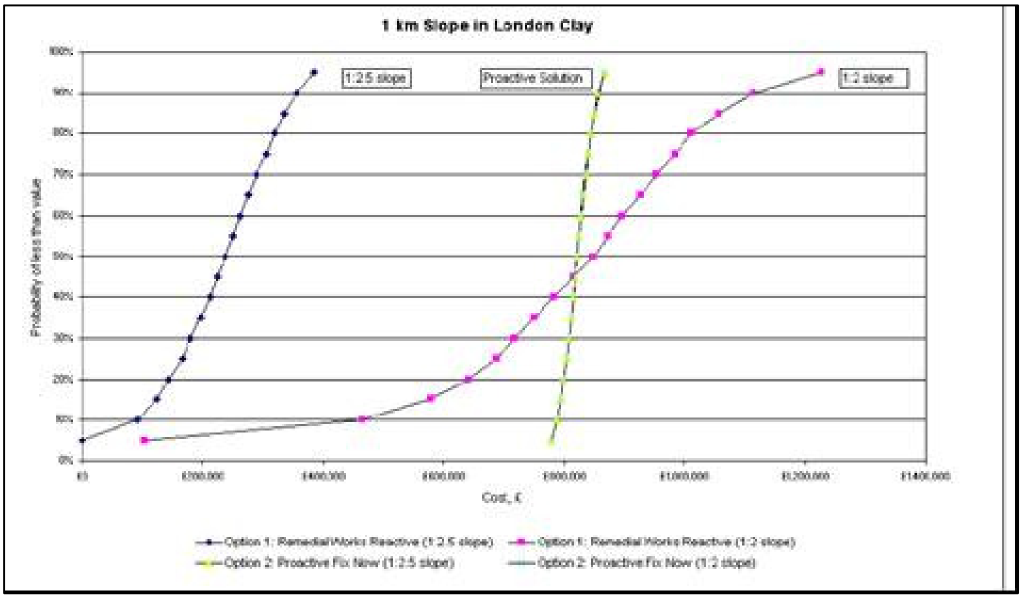


Figure 2: QRA-based comparison of maintenance work and proactive intervention

2.5 Scanning Study Report (Arup, June 2009)

The objective of the first phase of this task was to review current asset management practice within the Agency and in the wider asset management domain in order to define further work required to develop a risk-based approach to geotechnical asset management. The outcome was a recommended framework for managing geotechnical assets, as discussed further in Section 4. Some components of this framework are currently more advanced than others, and some are being developed within other tasks.

2.6 Performance and levels of service

Within the Asset Management programme, the Agency is developing clear, outcome-focused, customer-facing levels of service for asset management to drive tactical and operational asset management planning and delivery.

A risk-based framework for managing geotechnical assets must be integrated with the defined levels of service for asset management plans in order to define the impact of geotechnical asset condition on levels of service.

The following six core themes have been identified for Levels of Service:

1.	Asset Capability	A strategic road network which meets customer needs
2.	Sustainability	Responsible stewards of the strategic road network
3.	Customer Service	
4.	Value	Demonstrate value for money managing the network
5.	Safe Roads	
6.	Reliable Journeys	

All decisions regarding maintenance of geotechnical assets, as well as definitions of the *consequences* of maintenance practice or lack of asset performance should ultimately relate to these core levels of service.

Figure 3 shows the sub-indicators of the core levels of service. By inspection it can be seen that there are a number of areas of the level of service framework that will not be influenced by the performance of the geotechnical assets, or where the contribution of the geotechnical assets will be negligible compared to say the pavement asset.

An exercise should be carried out to develop the links between the technical measures used to report on performance of the geotechnical asset and the service areas described in Figure 3.

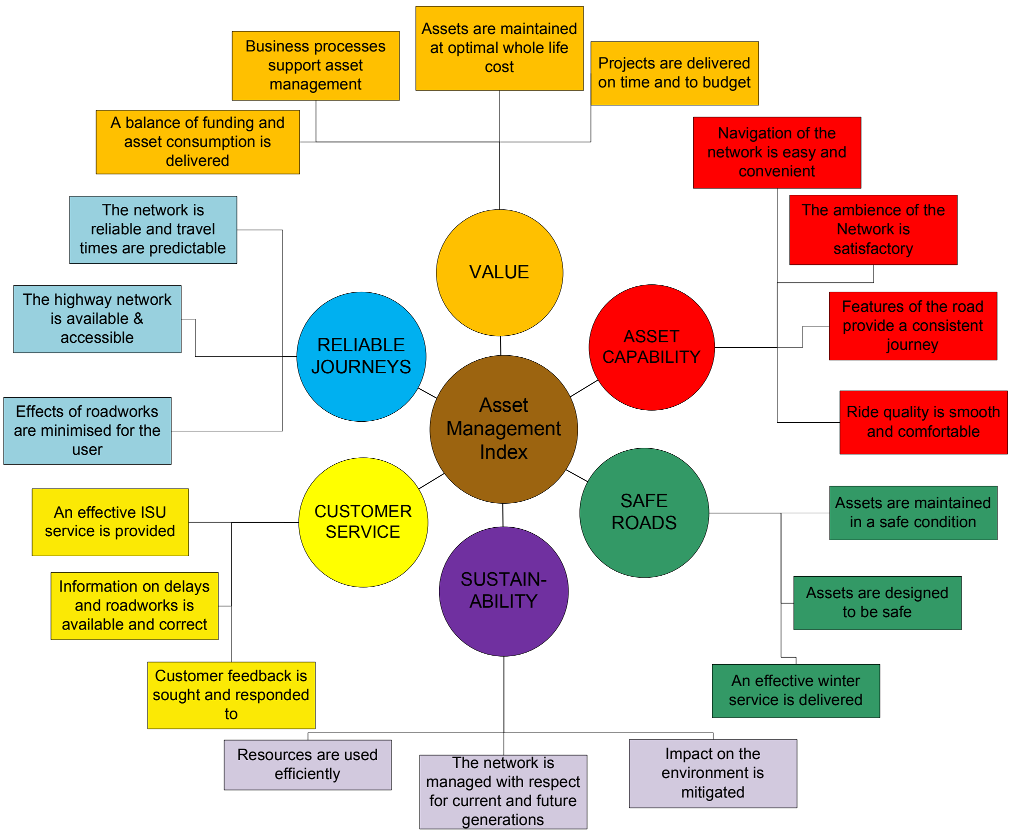


Figure 3: Asset Management Level of Service Framework

The intention of the Levels of Service is that they provide a single set of high level objectives which encompass the multiple goals, performance indicators, objectives etc. used by the Agency.

Within Task 191/1308, a mapping exercise was carried out to ensure that the Levels of Service not only mapped across to best practice Levels of Service used by other infrastructure operators, but also to existing DfT and Highways Agency plans and programmes from strategic through to an operational level.

2.7 Highways Agency Asset Management

The Highways Agency is responsible for the management and operation of the Strategic Road Network (SRN) in England. The SRN comprises multiple assets including, for example, pavements, structures and technology, and is currently valued at £89billion. The Agency's annual budget to support maintenance and enhancement of the SRN includes £840m devoted to network maintenance and £969m assigned for major project work in FY07/08.

To improve the management of these important assets, the Network Delivery Directorate (NDD) has developed an Integrated Asset Management (IAM) strategy, which outlines a clear vision for the future of asset management within the Highways Agency.

"*To optimise the operation of the network by taking a long term strategic approach to the management and monitoring of its asset performance.*"

This will be achieved through:

a) A single repository for asset information with unified standards and common measurements for condition, degradation and geographical location

b) A set of performance tools to monitor and drive delivery of operational outputs and outcomes.

c) The capability to optimise maintenance scheduling and works to ensure best value.

d) The creation of robust modelling tools to plan and justify strategic investment.

The strategy is described in the Asset Management Strategy, 2008 – 2018 (HA 2008a).

Initial development of the strategy was delivered through the IAM Programme. This has now evolved to the formation of an Asset Management Office (AMO) within NDD Central Team with responsibility for highway asset information, asset strategy, planning and performance monitoring.

The core assets of importance to the Agency have been identified as Pavement, Structures, Drainage and Geotechnical assets. The management of information relating to these assets has been transferred to the AMO.

The focus has been on evaluating current condition and determining initial estimates of future expenditure related to the 2010 Comprehensive Spending Review (CSR). Future planned developments include the implementation of a formalised renewal planning process supported by an Asset Management Strategy and AM Plans and a robust, data-based decision mechanism to develop work programmes and inform budget allocations.

Asset risk is incorporated within the current processes, however, it is neither explicit nor quantified in a standardised manner between assets. Cross-asset planning problems are raising this to be a significant future issue.

2.8 Decision Support Tools

Optimised Decision Making (ODM) is the method described by the International Infrastructure Management Manual (2006) to balance the trade-offs that are inherent in planning asset maintenance and renewal. 'Decision support tools' is the collective term for methods and techniques that are used to assist decision making.

As part of the Agency's asset management approach, a decision support tool WiLCO (SEAMS Ltd) has been used to explore the technology available to optimise decisions on asset renewal. WiLCO is a tool developed specifically for asset management decision making and uses a genetic optimisation method to determine the best asset management strategies for an asset populations and set of business rules. At its core this software is able to optimise mathematically the costs and performance trade-offs represented by expressions of business value, business constraints, technical performance and levels of service.

A model of geotechnical asset future performance was developed and implemented within WiLCO by the NDD AMO. Separate models were also established for the pavement, structures and drainage assets. The geotechnical asset model predicted the deterioration of the earthwork asset as a change in *failed length*. Indicative costs of intervention & repair were used to determine the required future budgets for geotechnical renewal based on managing the predicted failed length. No uncertainty or variability was included in this model and as such it does not present a risk-based approach to predicting future performance and only evaluates the balance between costs of maintenance against performance.

The outputs were presented as likely expenditure or *deterioration* of the asset. The models were used to inform the Spend Review activities undertaken by the Agency in 2010.

2.9 Current Practice and Methods

An extensive literature review around the area of risk-based asset management, geotechnical asset management, and managing geotechnical risks has been undertaken, both within the first phase of this task, and in greater depth within Phase 2. The Bibliography at the end of this report presents a comprehensive list of relevant published information.

There are a number of relevant publications in the field of *landslide risk assessment* (e.g. Lee & Jones, 2004; AGS, 2007, shown in Appendix B; Glade *et al*., 2005; Hungr *et al*., 2005). This field of research is close to the subject of this task, with the key difference that landslides tend to occur in natural slopes, rather than engineered slopes, and have the potential to cause significant damage and destruction, including widespread loss of life.

Publications that deal specifically with the risk-based management of geotechnical assets within infrastructure systems are less common, it does not appear to be an area of particular research at present. There are related publications by Bernhardt *et al* (2003) and Loehr *et al.* (2004) referred to subsequently.

HD41/03 describes the process by which inspections lead to the categorisation of observations, which lead to a risk ranking. This is based on identification of defects in the geotechnical assets as part of inspections. Field based assessments of the observation and proximity to the highway (or other significant assets) result in a qualitative statement of the risk posed by the condition of the asset.

A five point-scale of Negligible to Severe is used to describe the risk. Assets categorised as **Severe** or **High** risk are passed forward into the development of works programmes as described in Table 1.

HD41/03 Section 3.1

A risk assessment is carried out on all geotechnical features identified during a Principal Inspection:

(i) to classify the nature of the feature

(ii) to determine the level of risk to the network

(iii) and hence to determine any actions that may be required.

The methodology is summarised as:

What + Where + When => Risk Level => Action

Risk Level	Description	Recommended Geotechnical Action
S	Severe	Remedial action must be undertaken with highest priority and H&S/Traffic Management requirements considered and kept under constant review. Consider VFM of Preventative works on adjacent Class 2 assets and potential impact on other Routine or Capital maintenance activities.
H	High	Remedial action required, timescale to be determined by the Overseeing Organisation Geotechnical Advisor and Overseeing Organisation Area Manager, but within 5 years. Interim monitoring/inspection may be called for and H&S/Traffic Management requirements considered. Consider VFM of Preventative works on adjacent Class 2 assets and potential impact on other Routine or Capital maintenance activities.
M	Medium	Remedial action may not be required but preventative action advisable within 5 years. Review inspection and/or monitoring regime and potential impact on other Routine or Capital maintenance activities.
L	Low	No immediate action required. Review inspection and/or monitoring regime. Consider VFM of Preventative works. Review potential impact on other Routine or Capital maintenance activities.
N	Negligible	No immediate action required. Re-inspect in five years.

Table 1: Recommended Geotechnical Action by Risk Level (Table 3.6 in HD41/03)

Asset risk / reliability is not explicitly included in the Highways Agency Value Management (VM) process (Highways Agency, 2010). Discussion of risk in a VM context tends to focus on project delivery (cost and time) risks and safety risks rather than asset–related reliability.

3 Scope and Methodology

3.1 Scope

The objective of moving towards a risk-based approach to managing assets is primarily that it should provide *a practical aid to decision making*.

This report describes a pragmatic strategy that can be used to manage the Highways Agency's geotechnical assets with a rigorous and objective approach to risk. The output of the report is a series of short- and long-term goals to achieve this.

The recommendations are developed within the context of what the Agency does at present.

Geotechnical asset refers to all earthworks and at grade-sections. The details of this framework do not cover retaining walls, foundations, or pavement sub-grade, although the principles described are generally applicable to all infrastructure assets.

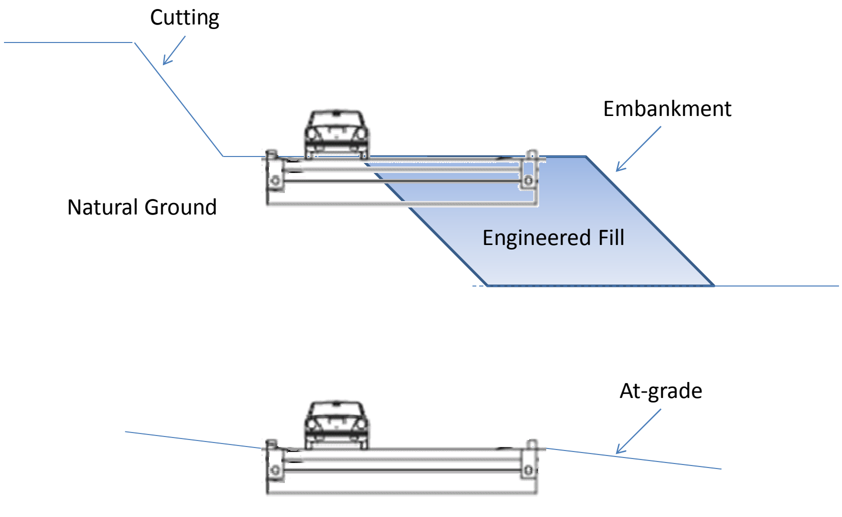


Figure 4: Definition of a "Geotechnical Asset"

3.2 Methodology

The main activities undertaken to develop the recommendations have been:

- Literature review of best-practice, research and recent developments in various fields including risk management, asset management, landslide hazard mapping and slope engineering.
- Analysis of historical data recording frequency and consequence of defects on the Highways Agency's geotechnical assets.
- Development of a *test bed* to understand the practical implications of the recommendations.

- Informal consultation with Highways Agency geotechnical advisors (David Patterson, Andrew Jukes, David Gwede), other geotechnical advisors (Mott MacDonald), and Arup staff with experience of Highways Agency projects and maintenance activities.

3.3 Interfaces

3.3.1 Task 651(666) Future performance of geotechnical assets

The objective of Task 651(666)ARPS is to:

Task 651(666)ARPS:

Derive models / algorithms for geotechnical asset deterioration (embankments and cuttings) for use in asset performance modelling.

This task, reported by Arup (2010b), provides an enhanced understanding of the *frequency* of loss of performance of geotechnical assets. This is essential for the assessment of risk. Conversely, for the definition of the performance requirements of the geotechnical assets presented in this report (Section 5.2) it is essential to ensure that the frequencies refer to the relevant event. The two tasks are therefore closely linked.

3.3.2 Task 191(1308) Asset Management Levels of Service

The outcome of Task 191(1308)ARPS, see also Section 2.6, will be clear, outcome-focused, customer-facing levels of service for asset management that will be used to define tactical and operational asset management planning and delivery.

These levels of service should form the basis of the performance requirements of the geotechnical assets. They will also drive the criteria by which decisions are made and options optimised.

3.3.3 HD 41/03 update

Mott MacDonald are undertaking Task 090(1308)MOTT, which comprises an Interim Guidance Note to provide guidance and update to aspects of the current inspection and maintenance standard, followed by a full revision. The timescale for the full revision is to be defined. The recommendations in this report are to inform future revisions of HD41 and associated changes to the data management system HAGDMS. The proposed update also provides an opportunity to introduce changes in terms of how data are collected, reported and stored.

3.3.4 Task 376(387) Transfer of desk study information

This task, reported by Arup (2010c) relates to the use of geohazards information and the effective transfer of knowledge about geohazards from preliminary design stage through to maintenance. Hazard information is a necessary input to the first step within a risk assessment, and knowledge of hazards informs subsequent asset management decisions.

3.3.5 NDD Asset Management Office

The Asset Management Office (NDD Central Team) is tasked with developing and evolving an asset management approach within the Agency (Section 2.7).

Asset related risk is an integral part of the asset management process and increasingly needs to be included in the approach applied by the Agency.

The AMO is considered the approach and how risks are incorporated in a standardised manner through AM Planning and included in decision support tools to support the development of works programmes.

The output of this task, related to an approach to managing risks within a specific asset type will inform this process.

4 The proposed framework

Based on the literature review, and the conclusions of the Scanning Study (Arup, 2009), a framework is proposed for the risk-based management of *any* assets. The central column of Figure 4 shows the framework, which is sufficiently broad to be applicable to all asset groups, and the *input* and *outcomes* are specific to geotechnical asset management.

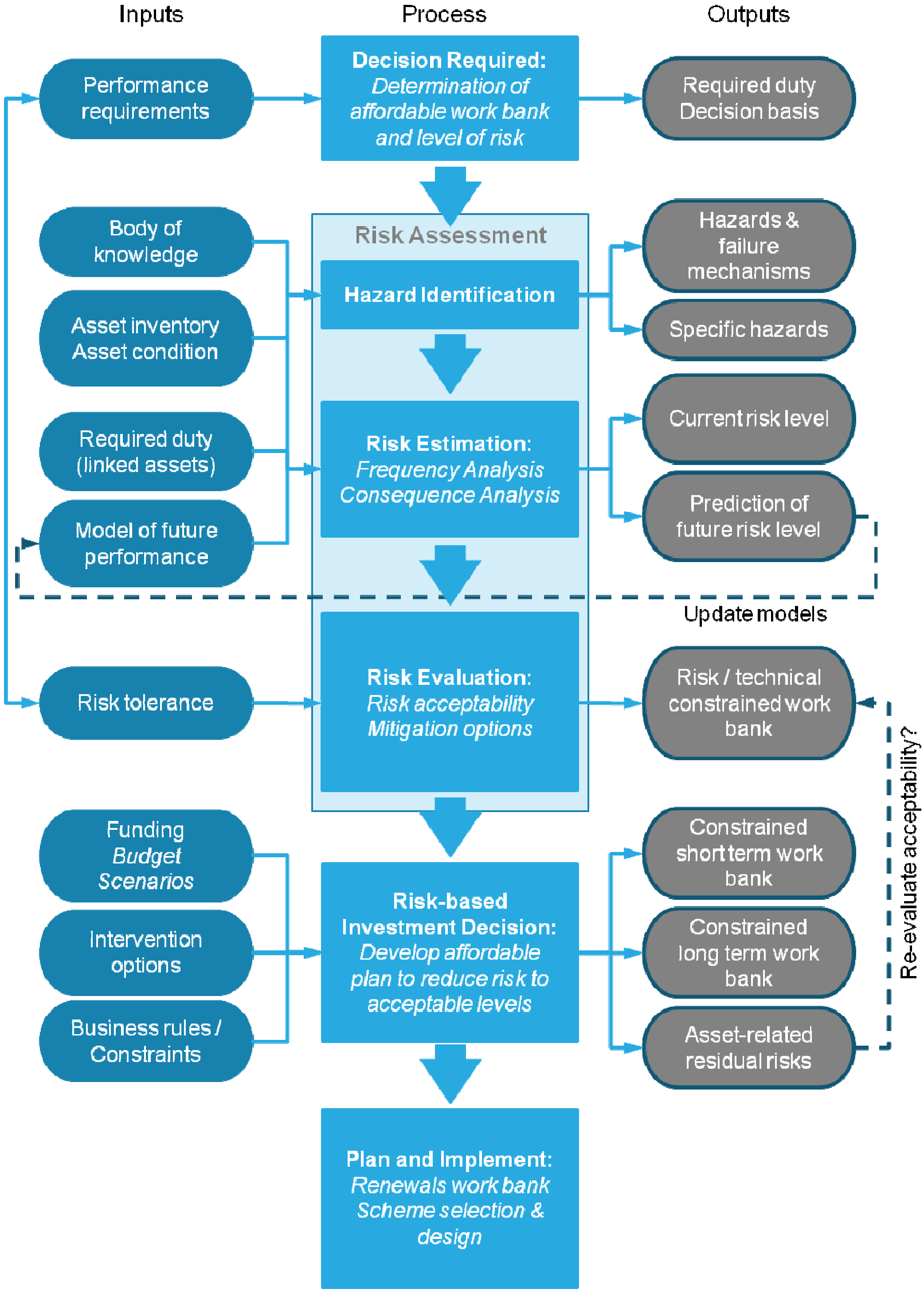


Figure 5: Framework for risk-based asset management

Subsequent sections of this report follow the process flow outlined in Figure 5.

Within the existing framework for managing geotechnical assets, comprising HD41/03 and HAGDMS, HD22/08, plus the Value Management procedures, SAS Geo etc., a number of the components defined in Figure 5 already exist, to some extent.

Figure 4 provides a clear link between each component and consistent terms of reference.

5 Decision Context

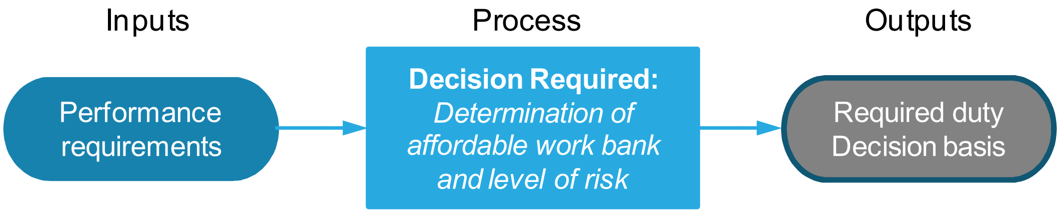


Figure 6: Step 0 of risk-based asset management framework – Define the decision

The objective of this step is to define the maintenance or renewal activity that is required to be decided on, based on defined performance requirements. The spatial and temporal limits of the decision should also be defined (e.g. 1 year, 5 year or 30 year time horizon; network wide or area wide).

5.1 Decision elements

The general context for making renewal and intervention decisions on the basis of assessed risk is as follows:

- Slope instabilities and other geotechnical defects are still a regular occurrence on the HA network and the cost of repairing these is estimated to be > £20m per annum.
- Earthworks that form the boundary to the highways are engineered to be stable. Defects in any geotechnical assets, such as settlement, tension cracks and soil slippage, are indicative of the onset of failure to perform the required duty. At present defects are used as the basis of decision making on asset maintenance and renewal. The current approach to managing geotechnical assets is defined in HD41/03.
- In the future, with more equipment sited on geotechnical assets (e.g. cabling, signs, noise barriers) and the use of hard shoulders as running lanes, there will be increased likelihood of small frequent events disrupting network operation or leading to higher consequential loss that seen to date.
- Pro-active maintenance is predicated on the fact that spending money now on repairs can save money in the future – either in the cost of the repair itself or the consequences of unplanned events (network budget certainty, network reliability etc.).
- Conversely, adopting a reactive maintenance strategy has an associated risk due to the uncertainty of future behaviour, which should be understood.

5.2 Performance Requirements

"*Goals and objectives must be tied to clear measures of performance. Targets established for these performance measures will guide decisions through the analysis of options, setting of priorities, and program budgeting and implementation*." (NCHRP Report 551, 2006).

The Highways Agency, in common with most other infrastructure operators, does not define specific Agency goals or KPIs about the performance of geotechnical assets. Nonetheless, the role of geotechnical assets in delivering levels of service across the network is significant.

Section 2.6 defines the Level of Service framework. At present the link between this high level statement of performance requirements and the actual performance of individual asset groups is not defined. Furthermore how risk fits in with the level of service framework is not clearly defined. There is some additional work required to link what is known about the duty and performance of geotechnical assets to the Level of Service framework.

The primary duty of geotechnical assets can be summarised as to provide satisfactory support for roadways, to be stable, and to allow the required vertical alignment to be met.

5.3 "Failure" of a geotechnical asset

A risk-based framework for managing geotechnical assets requires explicit assessment of *consequence*. There are a number of variables that contribute to the assessment of consequence, discussed in greater detail in Section 0.

Failure of a geotechnical asset is a relative term dependent upon consequences. *Failure to meet performance requirements* is a more precise term. There is a need to manage the safety of geotechnical assets themselves to prevent them failing in terms of exceeding their serviceability or ultimate limit states, but this is only one particular adverse outcome of the geotechnical asset system. From circumstantial data both in the UK and elsewhere, it is reasonable to assume that safety consequences are very low.

An important and somewhat unique aspect of geotechnical assets, as compared to say bridges or pavements, is their role in supporting other critical assets.

> Ground movements that can be small in size and benign in appearance can cause damage to or loss of pavement sections, loss or reduced effectiveness of guardrails and other safety measures, blocking of drainage channels, and potential damage to bridges and other structures due to loss of ground support or additional loads imposed by sliding soil and rock (Bernhardt *et al.,* 2003).

Figure 7: Hard-shoulder pavement affected by embankment instability (Kidd, 2009)

In these cases failure of the asset to perform its duty has occurred even though ultimate limit state failure has not.

The term *failure* should be avoided within this framework, unless its meaning is clearly defined. Defect occurrence is a more appropriate generic term.

5.4 Current procedure for reporting performance of geotechnical assets

Currently, in accordance with HD41/03, performance of the geotechnical assets is observed and reported in terms of the length of the network at *severe, high* or *moderate* risk.

The risk category is determined during Principal Inspection whereby a "severity" class is assigned to an observed defect and consequence determined by assigning a Location Index (A to D) to the feature, where A has the most severe consequence.

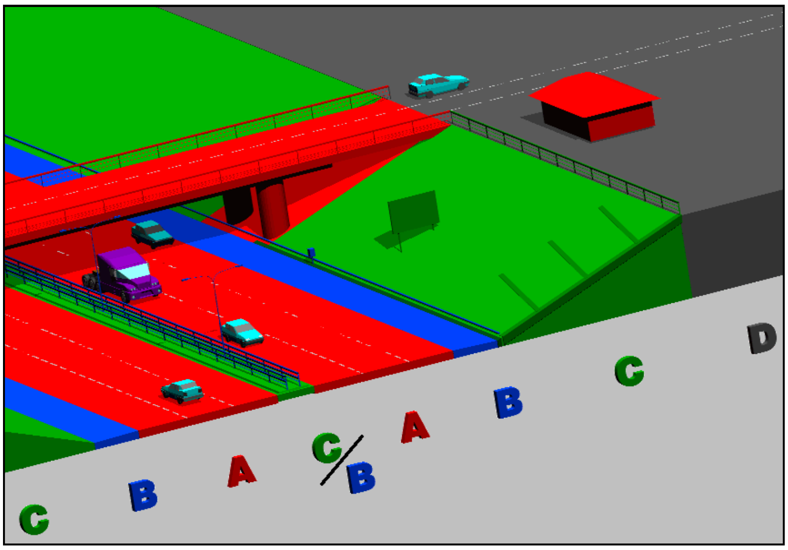


Figure 8: Location Index used in Principal Inspections

To estimate future levels of "risk", *a subjective assessment is also made of how the feature may deteriorate over the next 5 years, and what Class it may have at the end of that period* (HD41/03). No variation in duty (or consequence) is assumed over this intervening period.

From HD41/03:

The process is summarised as:

Class + Location Index + Timeframe => Risk matrix by timeframe

Although risk terminology is used for the inspection and current reporting, it has the following limitations:

1. As the risk assessment is based on observed defects, it could be argued that these, having occurred, are no longer risks. This depends on the type of defect, and whether a defect is an *indicator* of the potential for a problem (e.g. a tension crack, classed as a 1A defect), or whether the defect itself is the problem (e.g. a rockfall, classed as a 1B defect). Inspected condition should be one component of the likelihood of future loss of performance, but not the sole contributory factor.

2. No specific definition of *consequence* is included. This means that a *high* risk in the next 5 years cannot be compared with other assets, nor can a value be assigned in order to make more informed strategic maintenance decisions.

In order to rigorously determine the consequence of a particular event, in terms of a change in the level of service delivered, there needs to be an improved classification of defects and condition, and consequence. [1] A good example of this is in HA DDMS for drainage assets, where the link between flood events and drain conditions is directly reported.

Within the WiLCO whole life costing work, the presence of *features* is also reported in terms of *failed length* - Class 1 (A to C), *risk length* (Class 1D and 2B), *repaired length* - Class 3 (A and B), and *other*. There is the confusion between a 'failed length', which then creates a length at 'severe' or 'high-risk', and a 'risk length', which would actually be classified as a 'moderate' or 'low risk'.

5.5 Performance measurements for other Highway Agency assets

The Highways Agency approach is summarised by Jandu (2005 and 2008). Jandu (2005) describes a recommended approach, whereas Jandu (2008) describes the current practice in terms of project prioritisation through Value Management. Particular areas that could be transferable to a geotechnical management system include:

[1] TRL (2010) have proposed a number of new performance indicators including a closures indicator to represent lane availability, and a 'service' indicator to represent quality of service. Whilst these represent a move towards reporting into a Levels of Service framework, they do not complete the linkage by reporting on the asset that has caused lane closure or poor quality of service.

- Condition classified with respect to structure type and dimensions and *element importance* and *element condition*.
- Condition is reported in terms of both *severity* and *extent* using four point scales.
- Structure condition is derived from a weighted average of condition and importance of the individual elements, and then weighted according to size and type of stucture and asset value.
- Availability due to restrictions on highway structures should be reported, including details of type and duration of the restriction, increased journey length, environmental impact etc.
- A *reliability indicator* is proposed to represent the ability of the structure stock to support traffic and other appropriate loading taking into account the consequence of failure. This should be a function of *probability* of failure and *consequence* of failure.

5.6 Summary

A decision to be made must be defined in the context of performance of the geotechnical asset. For cross-asset decisions, the performance measures for geotechnical assets should be better aligned with other highway assets, and this should be done through the Level of Service framework.

The decision must also be informed by the **risk** of a **loss of performance** and its consequences.

The other dimension to decision making is the **time period**. The likelihood or probability of failure is dependent on the age of a geotechnical asset at the beginning of the decision period, and the length of the decision period.

6 Hazards

Figure 9: Step 1 of risk-based asset management framework – Hazard Identification

In any risk assessment framework, a *hazard* is any event that should it occur; will lead to a change in performance of the system under consideration. The existence of a hazard is not time dependent; it is likelihood, and possibly consequence that may change with time. Full definition of the hazard should cover both the type of event and its magnitude/amplitude. The purpose of this stage is to identify any possible problems affecting the performance of the assets.

Hazard: An uncertain event, leading to loss of performance ideally with magnitude direction etc.

In the broadest geotechnical context, the hazard presented by geotechnical assets is *ground movement*. As discussed in the report for Task 651 (Arup, 2010b) ground movements can occur by a number of mechanisms and be instigated by a variety of triggers (Figure 9).

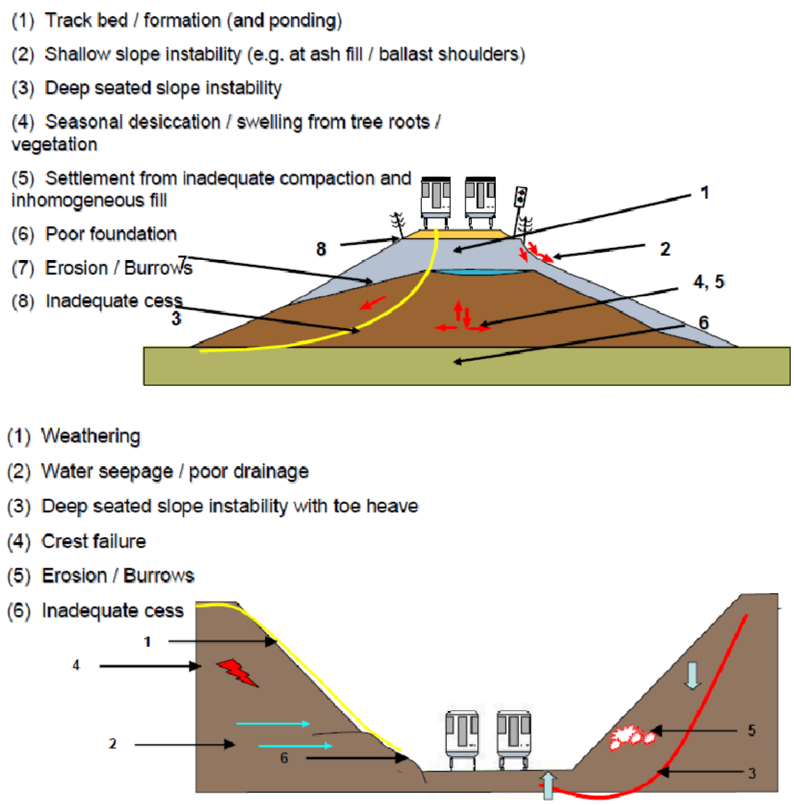


Figure 10: Summary of issues affecting performance of (a) embankments and (b) cuttings (Butcher, 2009)

6.1 Inputs

Data collected during an asset inspection will be of use in a risk analysis only if it can help to identify either the probability or consequence of a hazard (Perry *et al.*, 2003a).

The data stored in HAGDMS and reported in accordance with HD41/03 is an essential component of the risk-based asset management framework.

Individual components of data collection for risk-based management of geotechnical assets are discussed in the following sections.

6.1.1 Static asset inventory data

The inventory of 'static' features of the Agency's geotechnical assets is comprehensive. It provides information on the following questions: what, where, how big, type, age? The data includes location, extent, height, soil properties etc. These variables are the basis for determining both the likelihood and consequence of earthwork failure.

Presently data are defined for each individual geotechnical asset, the key variability being the length of earthwork or at-grade section, which, from start to finish, varies from a maximum length of nearly 6 km to numerous earthworks with less than 10 m length.

In considering current and future performance and consequences, there are a number of advantages to discretising the entire network into uniform cells of 100m length, rather than considering the entire earthwork length as is presently done (see Arup 2010b).

6.1.2 Observed condition

Performance data, based upon the inspected condition of assets is the 'dynamic' component of the data, in that it changes with time.

The Principal Inspections record "observations" on the geotechnical assets including defects. These defects provide detailed information on the condition of the assets and provide the following:

1. A 'snapshot' of condition at a point in time, which can be used to inform the likelihood of failure in the future (Section 7.1, and Arup, 2010b)
2. A summary of the condition of all geotechnical assets, which provides the link to the performance indicators and levels of service (Section 7.1)

In terms of the likelihood of failure of geotechnical assets in the future there is a lot of useful data stored in HAGDMS that is being used to improve our understanding of the distribution, causes, and nature of failures in the past. There are also some aspects that the data does not help with, either because the relevant records do not exist, or because there are some things that can't be shown through historical data. These issues are discussed in the Report on Task 651 (Arup, 2010b).

As discussed in Section 5.4, a Class 1A/B/C defect can be a failure that has *already occurred* or an indicator of a significant failure that could happen although its timing is not certain.

6.2 Hazard identification

6.2.1 HD41/03 hazard classification

Hazards that occur on the Highways Agency's network are described in Table 3.1 of HD41/03 (with some suggested clarifications in HA Guidance note on geotechnical asset management, HA 2010). These hazards may be *major* or *minor*, and some are also classified as *localised* rather than representative of the wider behaviour of the geological unit.

The main hazard types specifically mentioned in HD41/03 are:

- Soil slope slips (major or minor)
- Tension cracks (major or minor)
- Rockfalls
- Settlement (major or minor)
- Seepage of contaminated water
- Desiccation, ravelling, erosion etc.

An ideal definition of a hazard includes the *type*, as listed above, its *magnitude*, which could be major or minor, where some definition is provided for these terms, and its *cause*, since this influences its frequency.

As discussed in more detail within Task 651 (Arup, 2010b), the *likelihood of occurrence* of a hazard can only be derived from existing inspection data, and therefore the hazards must be defined in terms of the available information, i.e. *defect class*. The other variable that is relevant to defining hazard is the *length of the defect*.

6.2.2 Geohazards

As well as observed defects on the network, future risk may be affected by the presence of *geohazards* (a ground related condition with the potential to affect the performance of the highway system). Typical geohazards include:

- Presence of compressible ground
- Presence of collapsible deposits
- Pre-existing landslides
- Soluble rocks
- Abandoned mines
- Shrink/swell behaviour
- Presence of landfill gases

- Presence of contaminated soil and/r groundwater

A series of recommendations regarding the incorporation of known geohazards information within HAGDMS was made by Arup (2010a) within Task 376(666) *Electronic Transfer of Desk Study information*, and the implementation of these steps would create an additional layer of useful and relevant information within HAGDMS that informs the assessment of risk. Coal Authority data and detailed BGS maps have already been incorporated into HAGDMS.

6.3 Outputs

The output from this component of the framework is a definition of general hazards and failure mechanisms, and specific hazards, which will then inform the asset management strategy (Figure 11).

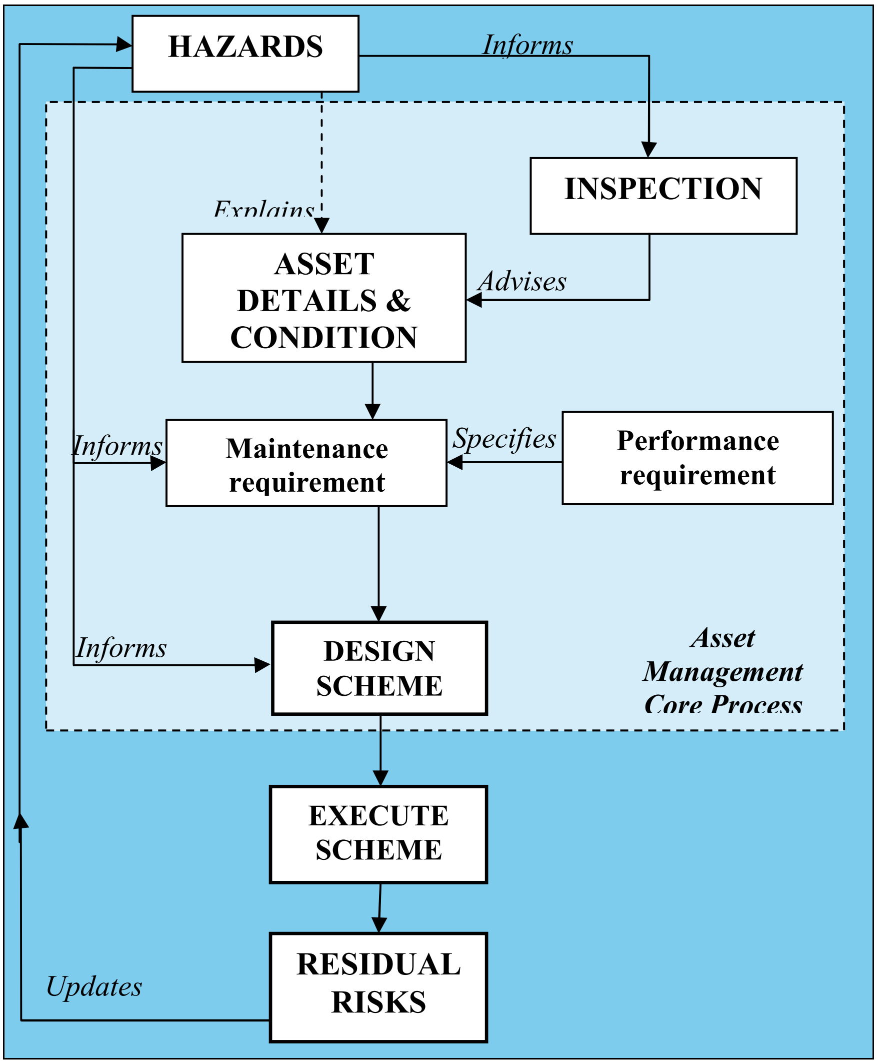


Figure 11: How hazards inform the asset management process (Arup, 2010a)

7 Risk Estimation

Figure 12: Step 2 of risk-based asset management framework – Risk Estimation

Risk estimation represents a sub-stage of the risk assessment process wherein values are assigned to the likelihood and consequences of a risk (BSI, 2002).

7.1 Model of future performance

The report *Future Performance of the Geotechnical Asset* (Arup, 2010b), for Task 651(666) discusses estimation of *likelihood* of failure.

Key issues include:

- *Likelihood* is a qualitative term, typically reported using terms such as *almost certain, highly likely, rare, very rare,* etc.
- Where historical data are used, the data will enable us to evaluate *frequency* of failure. *Frequency* is not the same as a theoretical probability, although the larger the sample set, the closer the two will be.
- Likelihood should ideally be expressed as probability of occurrence, within a reference period, of an event with a given magnitude/intensity (Van Westen *et al.,* 2006).
- In order to assess risk and make a risk informed maintenance decision for geotechnical assets, the probability of failure against time is required.
- As discussed in Section 5.3, *failure* is a relative term. The existing definition of "failure" as a Class 1A/B/C defect is used, although there is potential for an improved definition. Significant defects are indicators that a geotechnical asset is not performing the required duty – *to provide satisfactory support for the highway*.
- If qualitative terminology is used to describe likelihood of failure then this is by definition uncertain, as the bands associated with descriptive definitions are fuzzy. Where a more rigorous quantitative approach is adopted it is essential that uncertainty is reported, in the form of confidence levels for different performance curves. To fail to report

uncertainty is misleading and negates the usefulness of a risk-based approach, by implying an accuracy of prediction that is not really there.

7.2 Consequence based on model of required duty

Perry *et al.* (2003a) list the following performance requirements for geotechnical assets in CIRIA 592:

1. Ensure safety of road users and construction workers.
2. Satisfy the statutory, regulatory and operational requirements of the owner.
3. Maintain dimensions (including line and level) within specified tolerances.
4. Support their own weight and reasonably foreseeable loads during their design lives, subject to routine maintenance.
5. Wherever possible enhance the local environment and avoid negative impact on it.

The converse of the above requirements represents the *risk objectives* and can serve as the reference point for defining *consequence.*

These requirements present a useful summary of the role of the geotechnical assets; it is suggested that items 3 and 4 are most likely to govern intervention and renewal decisions. There is presently a gap between these definitions of the required performance, and the reported performance data (Section 5.4).

Specific components of required duty, that inform *consequence,* are discussed in the following sub-sections. Ideally different consequence components would all be described in comparable units, for example a monetary unit assigned to all consequence, although in practice, this is hard to achieve because of the wide range of consequences (Lee & Jones, 2004). A fully quantitative analysis of risk can only be achieved if all consequences are expressed in monetary units. This is not currently possible due to insufficient data and considered not fully appropriate for the geotechnical asset.

7.2.1 Direct and indirect consequences

Direct consequences refer to the direct impacts of the loss of performance of a geotechnical asset, and include:

- Repair costs
- Costs to clear roadway for *reactive* works.
- Emergency or planned traffic management cost.
- Investigation and survey costs associated with design of remedial works.
- Costs associated with injury or death.

Indirect consequences include user delay costs, socio-economic impact and damage to reputation. Their assessment and quantification is complex. Ultimately these consequences should be part of a cross-asset approach.

It is worth considering what we know about consequence from existing data. Compared to condition data from inspections, data on repair costs for geotechnical assets are presently somewhat sporadic and inconsistent. They are reported within the Geotechnical Management Forms (GMF) Parts A to C (HD41/03) and recorded within the HAGDMS data system. Less than 10% of the earthwork failures reported in the GMF Part A's required emergency works, which gives some indication that consequence resulting from Class 1A, B or C defects was generally minor.

The general lack of detailed cost information covering direct and indirect consequences precludes the development of fully quantified risk estimation at present. The following describes a semi-quantitative approach, using indices to define the consequence.

7.2.2 Other affected highways assets

A fundamental function of highway earthworks, and at-grade sections is to support other highway assets (Section 5); therefore the asset inventory should include definition of all assets that interact with geotechnical assets.

Typical consequences mentioned in GMF Part A's include:

- Alignment changes (vertical or horizontal) affecting cables, fences, safety barriers, signs etc to lean, tilt, topple or deform.
- Road surface changes such as settlement, subsidence or cracks

The above list, although not comprehensive, is a useful indicator of the type of indirect consequence resulting from observed defects in practice.

Asset Criticality (PAS 55-2, 2008)

The concept of asset criticality is a particular manifestation of risk management - this is the recognition that assets and asset systems have differing importance (value), or represent different vulnerabilities, to the organisation.

Table 2, below, shows a schedule of assets that may interact with geotechnical assets on the Highways Agency network. The consequence of these assets being affected by ground movements is a combination of their *criticality, vulnerability* and their *proximity* to the slope. Where multiple assets interact with a slope, the one with the highest potential consequence is likely to govern the risk assessment.

This information should be assembled by fusing data from other highways asset data systems and using the toolset provided by Geographical information Systems (GIS) to undertake a spatial analysis that determines the interrelationships between assets.

Table 2: Assets that may interact with highway geotechnical assets

PAVEMENTS	Carriageway – surface, Carriageway – structure, Hard Shoulders
FOOTWAYS & CYCLE TRACKS	
ROADS MISCELLANEOUS	Centre Islands, Centre Reserve, Crossovers, Kerbs, Pedestrian crossings, Ox-Bow Laybys

STRUCTURES	Bridges, large culverts, small span structures, retaining walls, walls <1.5m, service crossings, underbridge, overbridge, gantries, tunnels
STREET LIGHTING	Lighting Point, Lit signs, Lit bollards, Gantry lighting, street lighting cabling, power supply cabling, Feeder Pillars, Switchroom, Distribution Point
DRAINAGE	Gullies, catchpits, channels, culverts, piped grips, manholes, balancing ponds, filter drain, grips, interceptors, ditches, counterfort drain
SAFETY FENCES & BARRIERS	Safety Fence, pedestrian guardrails
FENCES, WALLS, SCREENS & BARRIERS	Boundary fencing, noise barriers, anti-dazzle screens, security fencing Environmental fencing (e.g. newt fencing, rabbit fencing), Emergency access gates, boundary walls
LINES & STUDS	
SIGNS AND SAFETY BOLLARDS	
TRAFFIC SIGNALS	
COMMUNICATIONS	Cabling for overhead gantries, managed motorways, 3rd party structures, CCTVs

Asset criticality

Table 3 shows a proposed *CRITICALITY* scale. This tells us – if the asset is affected by a geotechnical failure, how much would it matter? Scores have not been assigned to the assets listed in Table 3, as this would require cross-discipline agreement.

Table 3: Proposed Criticality scale

Score	**Impact on operation of the network and delivery of levels of service**
1	Low. The asset is nice to have but has no impact on delivery.
2	Moderate
3	High
4	Essential

Asset vulnerability

Table 4 shows a proposed *VULNERABILITY* scale, designed to reflect the sensitivity of an asset to ground movements. This answers the question, if there is ground movement, how much damage is likely to result?

To be fully representative of actual behaviour, this scale should have two components:

1. To represent the expected degree of ground movement, and
2. To represent the response of an asset to that movement.

However, this cannot be achieved with the level of detail available at present, and a simplified approach that considered the generic vulnerability of an asset in response to a major defect.

The assumption in assigning a vulnerability rating to an asset, using the scale shown in Table 4, is that the behaviour is a response to a major defect (Class 1A/B/C).

It should be noted that vulnerability is typically scored between (0 and 1) where 0 represents no damage, and 1 represents complete loss of function. However, for consistency with *criticality* and to allow combination of criteria, a 1 to 4 scale is proposed in this case.

Table 4: Proposed vulnerability scale

Score	Description of response to major defect
1	Not affected (no loss of function)
2	Minor (slight loss of function)
3	Moderate (some loss of function)
4	Complete (complete loss of functionality)

It is proposed that engineering judgement is used to populate a database of asset criticality and vulnerability.

Proximity

Proximity is an attribute used to express the likelihood of an asset being affected, should a geotechnical failure occur. In reality, this is a function of the mode and magnitude of the failure (for example, rock fall versus localised shallow slip). However, mode and magnitude can only be properly assessed at a detailed design level; therefore a proximity rating is proposed. Proximity factors could be evaluated using a geometric analysis of the base data and relationships between assets.

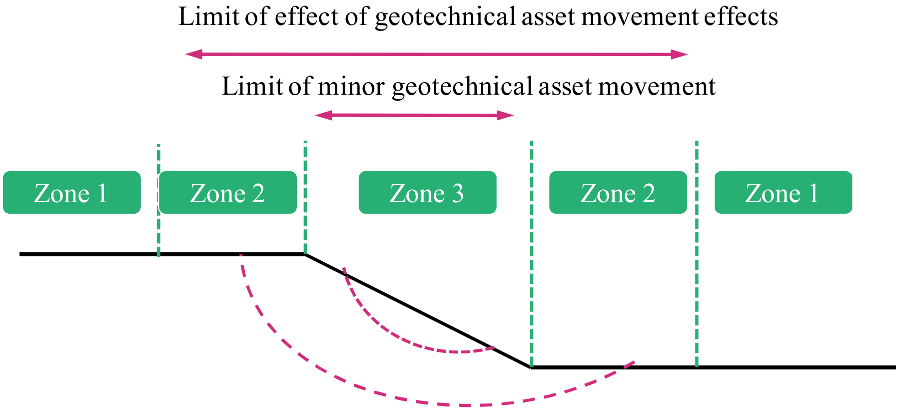


Figure 13: Indicative proximity rating for assets that may interact with earthworks or at-grade sections.

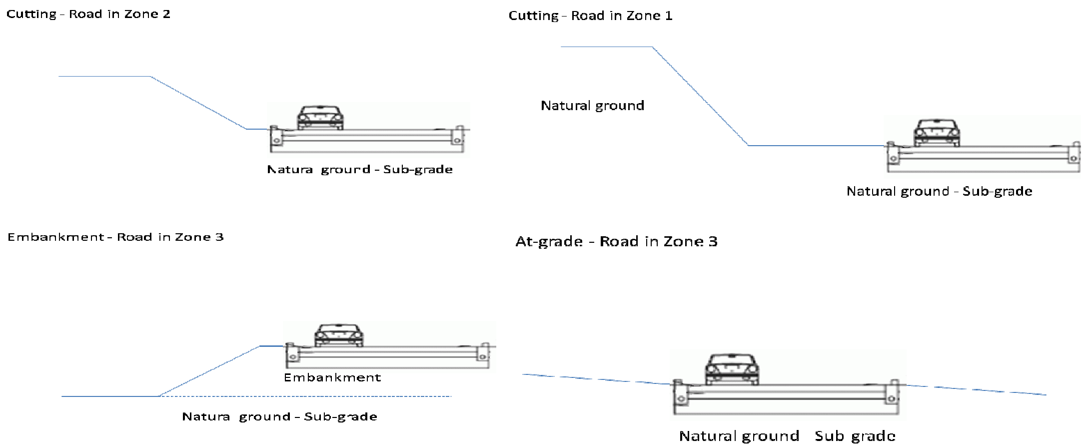


Figure 14: Example proximity ratings for different configurations.

7.2.3 Route Priority Rating

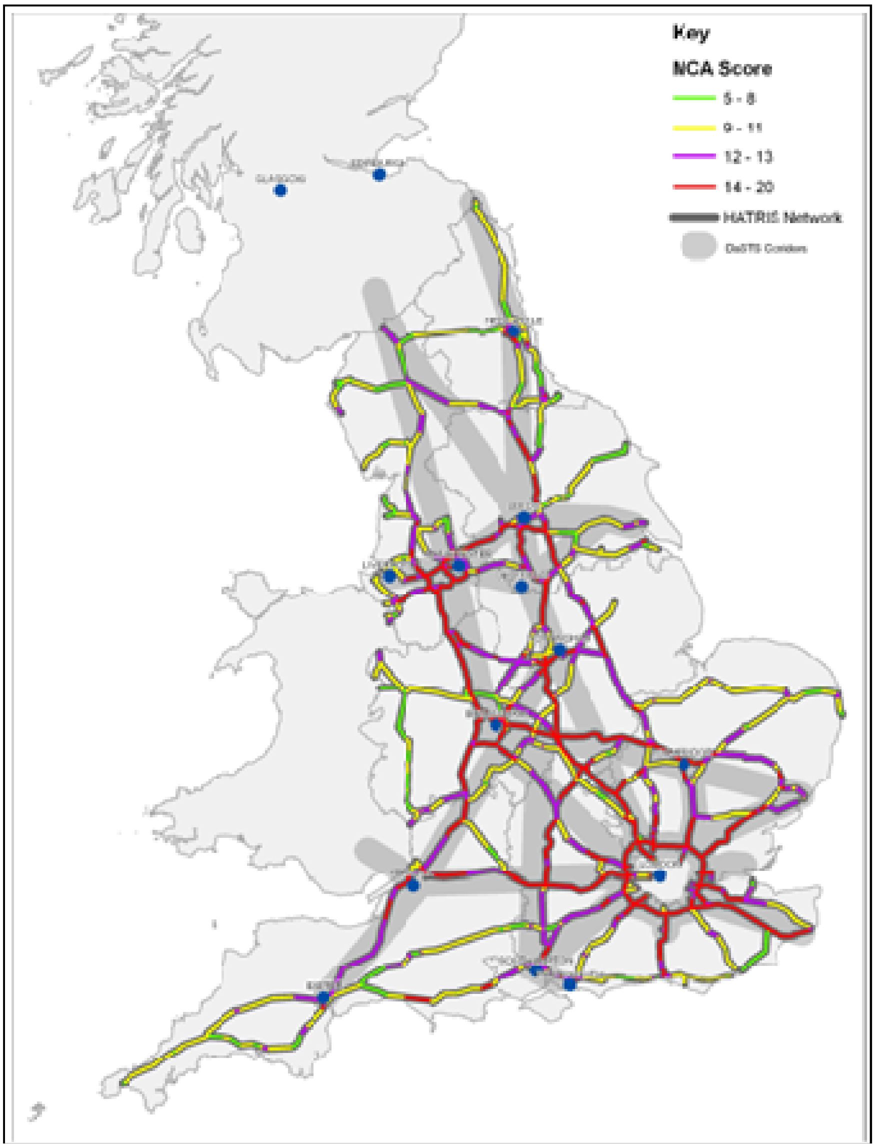


Figure 15: Proposed route prioritisation for the network (Arup, 2010c)

The importance of the route that the geotechnical asset is required to support affects both direct and indirect consequences. Factors affecting the importance of the route include:

- Traffic flow (represented by the AADT, Annual Average daily Traffic).
- Stress levels (a descriptor of how congested a route or link is).
- Journey Time Reliability (JTR).
- Proportion of traffic Heavy Goods Vehicles.
- Percentage of day time to night time traffic – this influences when maintenance activities can be done.
- Strategic importance of the route (according to the DfT DASTS routes).

Arup (2010c) have prepared a report for the AMO entitled *Asset Management Service Levels – Route Prioritisation Final Report* which proposes a high level ranking criteria (1 to 4, with 1 being highest priority) for each link on the Agency's network, based on the variables listed above (Figure 15). This information should be included in the analysis of consequence related to geotechnical asset performance failure.

7.3 Risk Estimation

7.3.1 Likelihood of failure

Likelihood of failure has been investigated within Task 651/666 (Arup, 2010b), and a suite of frequency values from observational data have been derived, including confidence levels on the mean values.

Typical curves representing change in likelihood of failure are shown in Figure 16 (Task 651/666 Arup, 2010b).

As information on frequency of failure is more comprehensive than available information about consequences, there is a dichotomy here that the frequency of failure side of the model is considerably more developed than the consequence, and frequency can actually be expressed quantitatively with uncertainty bands at any level of granularity on the network.

However, there is no benefit to using a more sophisticated rating on only one side of the risk equation; therefore a qualitative grading of likelihood is also of value, based on ranges of likelihood of failure, over a specified time period from *Very Unlikely* to *Very likely*. Ideally such a rating system should be consistent across all assets.

Based upon condition data, it is recommended that a likelihood rating of *certain* should also be used, where defects have been reported. Without this additional level, the approach doesn't adequately take account of the current inspection data.

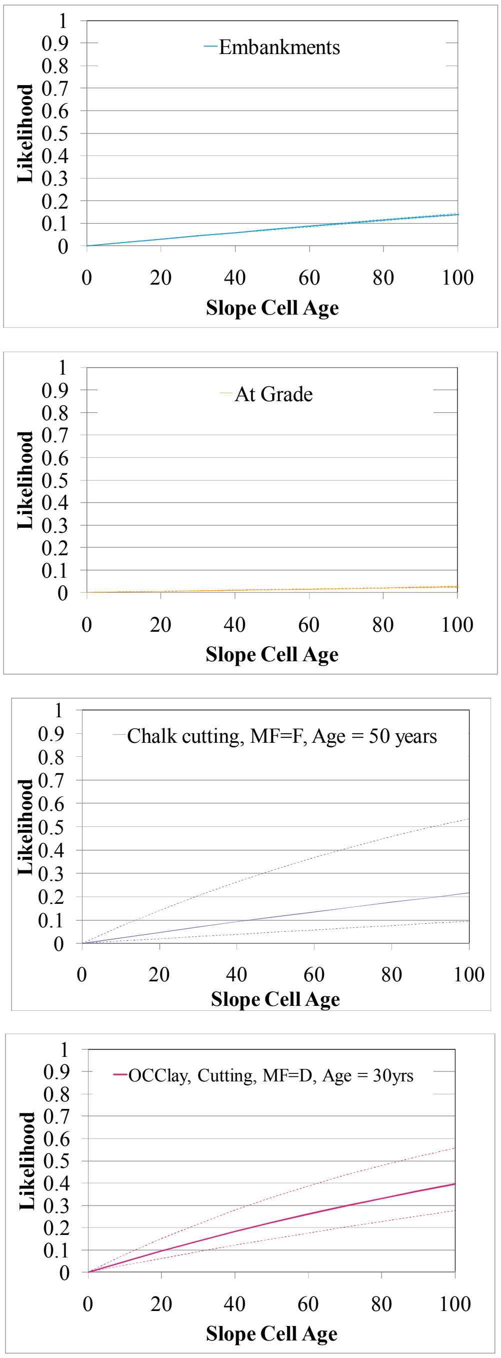


Figure 16: Curves of probability of defect occurrence versus time passed for selected geotechnical asset types. Dashed lines show the 5 to 95% confidence intervals.

7.3.2 Consequence of failure

Consequences should relate as closely as possible to the Levels of Service framework in Section 2.6, but consequence should also be reported at the direct and indirect level in terms of the impact of an event.

The contributory factors to an assessment of consequence have been discussed in Section 7.2 and are summarised below:

The key consequence components are as follows:

1. Geotechnical asset
2. Affected assets (defined by proximity, vulnerability and criticality)
3. Route Priority
4. Intangibles losses

Different assets could be 'binned' in terms of their consequence attributes – e.g. high safety impact, high repair costs etc.

As noted previously the historical data on consequence is of much poorer quality that the data on frequency of failure (see Task 651 report, Arup, 2010b). Therefore a qualitative ranking scale is more appropriate. This is often the case. Lee & Jones (2004) note that "except in the cases of small and clearly defined problems, (consequences will) inevitably have to be broad-brush..."

An interim qualitative measure for consequence is proposed whereby each component of consequence, as shown in Table 5 is individually rated. Risk can then be considered in terms of either an individual consequence or a combined rating, depending on the requirements of the risk decision. Multi-criteria analysis (MCA) simple method uses a method of weightings to combine the multiple criteria into a single value.

A long term objective of estimating probability distributions of consequence uncertainties should be set. These would only be required where high level risk assessments indicate significant risks. Quantitative consequence estimates would include analysis of the uncertain vulnerability of asset response to uncertain ground movements.

Table 5: Consequence classification for an indicative 100m cell

Affected Assets				**Route Priority No**
Asset Type	**Vulnerability**	**Criticality**	**Proximity**	
Street Lighting cabling	4	1	3	3
Safety Barrier	2	2	2	3
Etc.				

On the basis of an assessment of the separate components of consequence, a *consequence rating* can be defined which would use an aggregated score from the separate components. Weighting factors may be appropriate for specific components.

7.3.3 Risk estimation methods

Risk estimation is a generic term for the tools used to assess a risk on the basis of the *probability* or *likelihood* of an event occurring (Section 7.1), and the *consequences* if the event does occur (Section 7.3.2).

Risk = Likelihood (of event) x Consequence (if event occurs)

The available tools and techniques range in detail and complexity from qualitative risk matrices, to complex Monte Carlo analyses requiring definition of the ranges and distributions of all the uncertain variables.

For certain asset types or asset groups and decisions, there may be an advantage to undertaking an FMEA[2] analysis. This approach is still qualitative, but provides more detail in terms of defining the effects and describing causes, controls, actions etc. It also provides a management tool – in terms of recording decisions and actions, and can be applied across assets (See Appendix C).

However, the focus in the Section is on the use of high level risk matrices. Section 9.2discusses application of quantitative approaches.

A risk matrix is a standard tool for considering pairs of likelihood and consequence, usually qualitatively ranked, such as those described in the previous sections, and assigning a risk level to these pairs. Typically high consequences, high likelihood pairs will have a high risk ranking. Figure 15 shows a typical risk matrix that can be used to assign risk scores on the basis of consequence and likelihood ratings.

			Consequence			
			Catastrophic	Serious	Moderate	Negligible
			4	3	2	1
Likelihood	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

* A **certain** rating of likelihood can only be made if inspections have identified major defects

Figure 17: Example of a general strategic level risk matrix to categorise level of risk and prioritise actions

7.4 Outputs

The result of the risk estimation stage is an estimate of the current level of risk associated with the geotechnical asset and an understanding of future risk levels.

The consequence score input to the risk estimation can either be individual or aggregated depending on decision to be made.

This provides an understanding of levels of risk across the network within the time period, which can be used both for high-level decision making, and for rapid

2 Failure Mode and Effect Analysis, see Appendix C

illustrations of the impact of a decision, in terms of risk levels increasing or decreasing.

This fulfils the same purpose as the current risk procedure in HD41/03, in that those assets with the highest risk rating are those which must be prioritised for urgent action. However, this framework represents the following improvements:

- *Likelihood* is based on observational data for all asset types and all locations, in uniform 100m cells. Probabilities are also available for all cells.
- *Consequence* now makes separate consideration of each component that can contribute to the overall consequence.

A risk rating has been derived, whereby a risk score between 1 and 20 is calculated based on likelihood and an aggregated consequence score.

Using the risk ratings, the assets within any 100m cell can be ranked in risk order. Risk can then be evaluated by considering the acceptability or otherwise of the indicated rating. This occurs in the risk evaluation stage (Section 8).

8 Risk Evaluation

Figure 18: Step 3 of risk-based asset management framework – Risk Evaluation

8.1 Inputs

The outputs of the Risk Estimation step of the process (Section 7) are *risk ratings* for all geotechnical assets under consideration, discretised into 100m cell lengths (see Figure 17).

Decision-making based on the on the risks requires an understanding of risk tolerance which in turn defines what risk (*risk rating*) is acceptable.

An approach to this would be for the decision-maker needs to ascertain the risk rating level that indicates either (a) immediate action is required or (b) no intervention in necessary. Intuitively there is probably an upper and lower bound to the acceptable risk as these issues are rarely that precise. Upper and lower thresholds for risk would work as follows:

- Above the upper threshold, urgent and immediate action is required.
- Below a lower threshold no action is required other than perhaps continued monitoring.
- Between the thresholds the risk mitigation is less clear. Works could be carried out but this requires more evaluation and inclusion of costs and timescales.

In terms of *risk acceptability* this *risk ratings* provide an initial identification of assets that present *critical risks* and which MUST be repaired, as well as those that represent *low priority* where no action is required.

Using the risk scoring system proposed in Figure 17, the following risk ranking is proposed (see Figure 19):

Risk rating = > 15	Essential
Risk rating = 8 – 14	High Priority
Risk rating = 4 – 7	Moderate Priority
Risk rating = < 4	Low priority

			Consequence			
Likelihood			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

Essential

Priority

A matter of choice?

Not required

Figure 19 : Risk matrix with indicative rankings given to risk scores.

In the above, a risk rating of above 14 represents work that is *critical*. Ratings of below 4 indicate no work is necessary in the time period under consideration.

The decisions that need to be put forward in to an Optimised Decision Making Process (Section 9) are those in-between the two extremes. These represent assets that *should* or *could* be repaired, but in the context of constrained budgets, a decision *not to repair* might be taken. The residual risk associated with this decision should be evaluated, and it may be appropriate to undertake more detailed analyses for these assets.

8.2 Mitigation

The decisions that are made by this process for managing the risks will depend upon this determination of risk acceptability:

Table 6: Typical risk actions

Risk Evaluation	Risk Action	Examples
Acceptable	Accept	Continue with current monitoring regime.
Not Acceptable	Remove / Prevent	Re-grade slope, pile sensitive assets on slopes. Timeframe: immediate
Between thresholds	Reduce	Carry out preventative maintenance Reduce likelihood by considering cause (e.g. potential for blocked drains) and scheduling improvements Reduce consequence by re-locating affected assets if possible. Timeframe: a matter of choice?
	Contingency	Set aside emergency budget
	Transfer	Not applicable

8.3 “Technically constrained” workbank

The output of the risk evaluation stage is the development of an *unconstrained workbank* (in terms of budget) or a*’Technically constrained*’ *workbank*:

- Assets[3] that require immediate intervention and the required scale of intervention.
- Assets that could be worked on to reduce risks and the range of options including timing of works.

This is defined in terms of an indicated level of risk, the risk rating and a definition of the acceptability of that risk. The reason the workbank is not fully constrained is that cost and budget have not yet been introduced. These constraints are introduced in the next section.

[3] In this case ‘assets’ refers to 100m cells

9 Make decision

Figure 20: Step 4 of risk-based asset management framework – Risk-based decision making

Inevitably the unconstrained workbank provided from the process of risk evaluation has to be considered against the business constraints of resources and budgets.

As noted in Section 8, the difficult decisions are around those assets that do not present *critical* risks, but do nonetheless have a non-negligible degree of risk associated with them. In these cases there is a risk associated with the decision not to intervene that must be communicated and accepted.

Decisions can be made on the basis only of risk, for example using QRA results that provide probability distributions of the expected costs to prioritise particular asset groups, or alternatively they may be optimised. As all asset management decisions represent a trade-off of many competing assets, an optimised approach is intuitively appropriate.

Optimised Decision Making (ODM) compares intervention options and timing in a cost function together with level of risk or reliability that results. This requires an objective function where:

Outcome = *f* (cost of any option, reliability/residual risk)

9.1 Inputs

Decision rules, or constraints should be set, these are typically based around the options of doing nothing, doing minimum or doing maximum at different points in an asset life cycle.

Intervention and mitigation options will also influence the decision. These generally include no repair, minimum repair, or full repair.

For ease of calculation only, it is generally assumed that any repair carried out to a geotechnical asset represents a full repair.

Where an optimised decision making scenario is used, the indicative consequence scales proposed in Section 7.3.2 are inadequate. Costs associated with the different intervention options must be used.

The unconstrained workbank developed from the Risk Evaluation stage is used in the process. Work items that are required may represent fixed activities that are not optimised but are included in the evaluation. These items, for instance may have such a large impact on the evaluation that no other work can be scheduled, or the decision–maker may be forced to re-evaluate the acceptable level of risk; i.e. return to the previous stage of the process.

9.2 Make risk-based decision

The decision making method that is selected must reflect the degree of data and nature of the decision.

If the decision is made on a *risk-only* basis then the process may be no more than a cost-based prioritisation. This could be made on a network, regional or single asset basis.

Optimisation tools could be configured to optimise functions of cost and risk rating.

9.2.1 Quantitative Risk Analysis

Where sufficient information is available, and the decision to be made warrants this level of detail, a Quantitative Risk Analysis (QRA) tool using @Risk™ or similar can be implemented within the optimisation process.

More specialist software such as RISKOptimizer (Pallisade: http://www.palisade.com/riskoptimizer/) could also be used to carry out risk-based optimisation that includes uncertainty.

The advantages and disadvantages of including quantitative risk analysis within the approach are summarised below.

Table 7: Advantages and disadvantages of QRA

Advantages of QRA	Disadvantages of QRA
Specific allowance of uncertainty associated with all components of a risk assessment	Requires specialist software
Graphical presentation of results	‘Rubbish-in, rubbish out’
Explicit plotting of confidence intervals	Implies a level of detail that may not exist
Rigorous	Time consuming
Produces a mathematical value to define risk.	

One of the key issues is that despite its quantitative output, a QRA is no more neutral or objective than a qualitative risk-based approach. Another key issue is that whilst a QRA approach provides valuable information for the decision making process, it relies on the input distributions of probability and consequence, and if consequence is not adequately understood to be defined quantitatively, then the QRA output will be of little relevance.

9.3 Outputs

The output from this assessment by whatever method is selected would be a constrained workbank for the time period of the decision.

Ideally a range of time periods would be selected to reflect the impact of short term work programmes on the longer term health of the asset.

9.4 Risk Communication

Risk communication is an essential component of any risk management strategy. A primary reason for adopting a risk-based approach is to recognise and manage uncertainty about future events. Failure to communicate this uncertainty represents a failure in the risk-based approach.

Communication of risks serves primarily to advise those involved from strategic down to operational levels about the consequences of decisions, and furthermore to encourage a collective approach to making decisions (DETR, 2000).

As with the assessment of risks (Section 7.3.3), communication of risks can vary in complexity from a simple red, amber, green type rating, to risk comparisons from FMEA type assessments, to full quantitative communication or risks in terms of probabilities of exceedance of different risk levels.

10 Discussion and Recommendations

Task 580(308)ARPS has developed a quantitative approach to risk-based decision making process to determine the maintenance and renewal activities for the geotechnical asset. The proposed process is based on best practice for estimating and evaluating risks and sets out a defined vocabulary for describing likelihood, consequences and risks which is aimed at enabling cross-asset assessments. The approach is not fully quantitative due to the difficulties in establishing the full costs of asset "failure" (failure to perform required duty), see Section 7.3.2.

The primary reason for proposing this risk-based framework for managing geotechnical assets is to improve budgeting decisions. The risks that are considered are focussed on unforeseen budget expenditures. Safety risks are included within the assessment but not explicitly stated.

Clear and consistent terminology is a fundamental part of the framework. Specifically, a *risk* can only be defined by the two components of *likelihood* and *consequence.* A common misuse of the term *risk* is to define a hazard.

The proposed process is also an evolution of the existing inspection and maintenance determination process described in HD41/03. The implementation of the approach, however, requires some additional work in specific areas as described in the following sections.

Neither this report nor the report for Task 651 (Arup, 2010b) included a thorough review of the asset data. The work has, however, identified sufficient shortcomings in the existing data to warrant a more rigorous data review, outside this task. Some recommendations for further work in this area are also therefore included in the following. As described in Section 3.3.3, work is ongoing in this area, and the recommendations below reflect the interface between this report and the HD41 update.

10.1 Further Work

10.1.1 Hazard identification

An ideal definition of a hazard should include:

- Type of hazard (slope instability, rockfall, settlement etc.).
- Magnitude of hazard, at a high level this could be *major* or *minor*, with some quantitative ranges provided to define these terms.
- The *trigger* that would cause the hazard to occur (e.g. human interaction, heavy rainfall, or no specific trigger where underlying ground conditions are the cause), since this influences its frequency.

10.1.2 Asset Condition Data

The data collected on asset condition and failure needs to be reviewed in the light of this report's recommendations.

It is proposed the categorisation of defects is adjusted to highlight the status of the geotechnical asset resultant from the defect.

The key recommendations regarding data collection and storage for a risk-based geotechnical asset management approach are:

1. Use of 100m discrete assets ("cells") for analysis and reporting on condition data. In the longer term there may be a benefit in using this as the basis for Principal Inspections. This, however, would require some reconsideration of the mechanism for determining asset segments in the field and a possible re-evaluation of minimum asset lengths.

2. Revise definitions of defects and introduce greater clarity to the relationship between defect and condition. This may require addition sub-categories especially of Class 1B (Section 10.1.6).

3. Create links to related asset data sets to provide an instant assessment of cross-asset interaction.

4. Form A – C data should be improved such that it provides greater input to the risk assessment process. In particular the use of free text and ability to leave responses blank should be reviewed. Particular areas where the Form A – C data should be regularly analysed include: cause of failure, cost and type of remedial work, length of remedial work as a ratio to length of defects.

There is also an opportunity to redefine the condition of the asset in terms of the 100 m slope cells and an assessment of the cells condition based on the defects observed within that discrete length. This approach could be progressed without any change to the current inspection and data capture process, but would improve the communication of asset status and provide a mechanism to inter-relate asset condition and criticality. This work could be carried out as a data modelling analysis within HAGDMS, however, some additional work is required to further define the appropriate approach. Output would need to be available for use in risk assessments or ODM.

10.1.3 Highway Asset Criticality and Sensitivity

As discussed in Section 7.2, the duty of geotechnical assets is to support the highway assets, be stable, and allow the required vertical alignment. Failure of geotechnical assets is therefore seldom critical in terms of the impact on the geotechnical assets themselves, but more likely to be important or critical to the assets they support (e.g. road pavement, structures, gantries, communication cables and signage).

All 'other assets' within a 100m cell need to be determined and categorised, to allow asset interaction to be considered. It is suggested that a spatial analysis of asset relationships is undertaken. GIS would provide a suitable tool to fuse data from other asset datasets and determine the connections to discrete sections of the geotechnical assets. A 100 m section length is proposed this assessment. This report provides initial categories for asset criticality and sensitivity. These may need some development to better represent the range of assets on the highway network.

10.1.4 Cost Consequence Data

To undertake the decision-making process described in Section 9, appropriate cost information is required for the direct and indirect costs.

Compared to condition data from inspections, data on repair costs for geotechnical assets are presently somewhat sporadic and inconsistent.

As part of the ongoing improvements to HD41 and HA GDMS, collection of consistent, quantitative consequence information should be a focus.

The cost information on Form A-C and Geotechnical Asset Management Plans (GAMPs) should be reviewed with this in mind.

Further work is required to determine the appropriate cost categories and collate information on these costs to provide suitable input including cost variation into the ODM process.

10.1.5 Revised DST Model

The model for assessment of the future performance of geotechnical assets and determination of maintenance requirements described in this report (and the report for Task 651) are different to the model used in the WiLCO decision support tool.

If the WiLCO model or similar is progressed then an updated decision algorithm is required for use in the ODM process within the Agency's selected DST.

In particular it is important to recognise that the optimisation process should be able to accommodate uncertainty into the predictions of cost and performance.

10.1.6 Performance requirements for geotechnical assets

Additional or revised technical measures are required that provide links between the performance of the geotechnical assets and the levels of service framework shown on Figure 3. *For example, a measure of lane closures due to geotechnical assets condition would inform 'available and accessible' within the Reliable Journeys theme.*

This can be achieved by either reclassifying defects, or using sub-classes, particularly for 1B type defects, which currently encompass multiple behavioural modes and multiple consequences.

The types of feature encompassed within Class 1B have potentially very different consequences in terms of performance; a rock fall may impact reliability or safety, differential settlement may influence ride quality, and presence of leachate may represent an environmental consequence. To enable these consequences to be assessed, sub-division of Class 1B (and hence 2B, 3B) is recommended. It is acknowledged that there would be a challenge in assuring the relevance of historical data that uses a superseded classification.

In the interim, current defect classes could be aligned with a condition classification (section 5.4) that will ultimately allow cross-asset comparisons.

Use a clear delineation in the inspection and reporting process between a failure that has already occurred, and a Class 1A/B/C defect as an indicator of *high likelihood* of failure if intervention is not carried out.

A more generic condition classification is suggested where:

SERVICEABLE	Repaired length + other
MARGINAL	1D
POOR	1A + 1B + 1C
FAILED	

An additional condition class of *FAILED* is suggested above, which leads to a clear performance target of minimising the *failed* length.

Vassie & Ricketts (1997) use the term ‘significant state’ to define the condition point where remedial measures can be carried out effectively, and the safety and serviceability of the asset are not affected. This is a useful definition, but under the current reporting regime it is not clear whether a 1A/B/C defect reflects such a state.

10.1.7 Risk-based Inspection frequency

An approach to managing risks that have been identified but not removed (Section 9.4) might be to use *risk-based inspection* as discussed in some detail in the HD41 Guidance Note (September 2010).

A risk-based approach to inspection frequency would enable more efficient use of resources whilst ensuring a reasonable distribution of risk across the network (e.g. McMahon & Woodward, 2006). A risk-based inspection (RBI) approach could be based on either the likelihood of deterioration, or the risks associated with failure, or a combination of these.

Two key factors that need to be considered are:

- Defects commonly associated with that type of asset
- The ability of an examination to detect a defect (this depends on defect type, asset type and examination type)

Risk-based inspection intervals must work backwards from an understanding of the time available to inspect, identify, and repair a defect once it has occurred.

Typically, risk-based inspection assumes a defect which deteriorates along an understood pathway over a number of years. In the case of geotechnical assets, neither the deterioration pathway, nor the time between observing a defect and the asset reaching a limit state condition are adequately understood.

However, there are some features from risk-based inspection procedures that could be introduced, for example, McMahon and Woodward (2006) describe a *critical* defect as one which deteriorates rapidly.

This option could be included in to the ODM process by including costs and an assessment of the reduced risk that it provides.

10.1.8 Trial of the Approach

A trial of the approach should be undertaken. This could comprise a network level assessment or validation within an Area against their current GAMP.

Either trial would need the assessment of related-asset criticality to be undertaken as a pre-requisite (Section 10.1.3).

10.2 Benefits

The following are considered to be the benefits of the proposed approach.

10.2.1 Risk Management

The risk-based approach described in this report requires that the likelihood of geotechnical asset *failure* is considered in conjunction with both the direct and indirect consequences to the asset and the highways assets as a whole. This reflects specifically on the variability in asset performance caused by natural materials and environmental factors, and the duty of the geotechnical assets in that their role to support the highway assets is perhaps more significant.

Failure is defined in this context as the assets do not perform their duty to support the highway and its associated infrastructure.

This approach is therefore a more complete assessment of the contribution of geotechnical assets to the Highways Agency Network and a full consideration of the cause, effect and likelihood of adverse effects occurring.

This meets best practice requirements as set out by standard texts including PAS 55 (2008) and the International Infrastructure Management Manual (2006).

10.2.2 Risk Communication

The process outlined uses defined terminology and a standard approach to estimating and evaluating risks. The use of a common vocabulary and standard scales/quantities for likelihoods and consequence will enable clear and transparent communication of uncertainties and risks across the organisation.

10.2.3 Cross-asset interaction

The approach described is inherently cross-asset. The assessment of consequence described herein includes for the affects of the assets affected by *failure* of the geotechnical asset.

The common expression of likelihoods and risks proposed will enable consideration of asset risks provided other assets are assessed using a similar framework.

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Appendix A

Glossary of Terms

A1 Glossary of terms

Acceptable risk	A risk that has been assessed and understood, and the risk owner has decided that no additional risk mitigation measures are needed
Consequence	Outcome of an event affecting objectives
DST	Decision support tool
Event	Occurrence or change of a particular set of circumstances
Extreme Events	Events that cause catastrophic risk but have a low likelihood of occurrence (Dicdican *et al*., 2004)
Failure	(1) Failure of an asset to fulfil its required duty (2) Reaching a Limit State
Frequency	a measure of likelihood expressed in terms of the number of occurrences within a given unit of time.
Hazard	the potential for an event or condition to occur with the potential to cause a change in performance. The description of hazard should include as much information as possible about location, size, classification etc.
Likelihood	Chance of something happening
Monitoring	Checking, supervising, critically observing etc.
Probability	A quantitative value representing the likelihood of something occurring, on a continuous scale between 0 and 100%.
QRA	Quantitative Risk Analysis
Residual risk	Remaining after risk treatment
Risk	A combination of the probability, or frequency, of occurrence of a defined hazard and the magnitude of the consequences of the occurrence (DETR, 2000)
Risk assessment	The overall process of risk analsyis and risk evaluation (IRM, 2002)
Risk analysis	Systematic use of information to identify sources and to estimate the risk
Risk estimation	Process used to assign values to the probability and consequences of a risk
Risk evaluation	Process of comparing the estimated risk against given risk criteria to determine the significance of the risk
Sensitivity analysis	An evaluation of how different sources of uncertainty contribute to the overall variability of the final risk estimates.
Uncertainty	The condition in which the number of possible outcomes is greater than the number of actual outcomes and it is impossible to attach probabilities to each possible outcome. (Green Book, HM Treasury, 2003)
Vulnerability	the degree of loss to a given element or set of elements (0 = no damage, 1 = total loss)

Appendix B

Australian Geomechanics Society (2007) Framework for landslide risk management

B1 AGS Landslide Risk Management

The framework proposed by the Australian Geomechanics Society (2007a, b, c) for landslide risk management is shown in Figure B1. A particular distinction is between the activities of *risk analysis* as being a sub-activity within *risk assessment* which in turn is a sub-activity of *risk management*.

A significant part of this framework is devoted to assessment of size, velocity and distance of travel of landslides, which is not applicable to this work on infrastructure earthworks. Nevertheless, both the framework and the individual components are very relevant to this study.

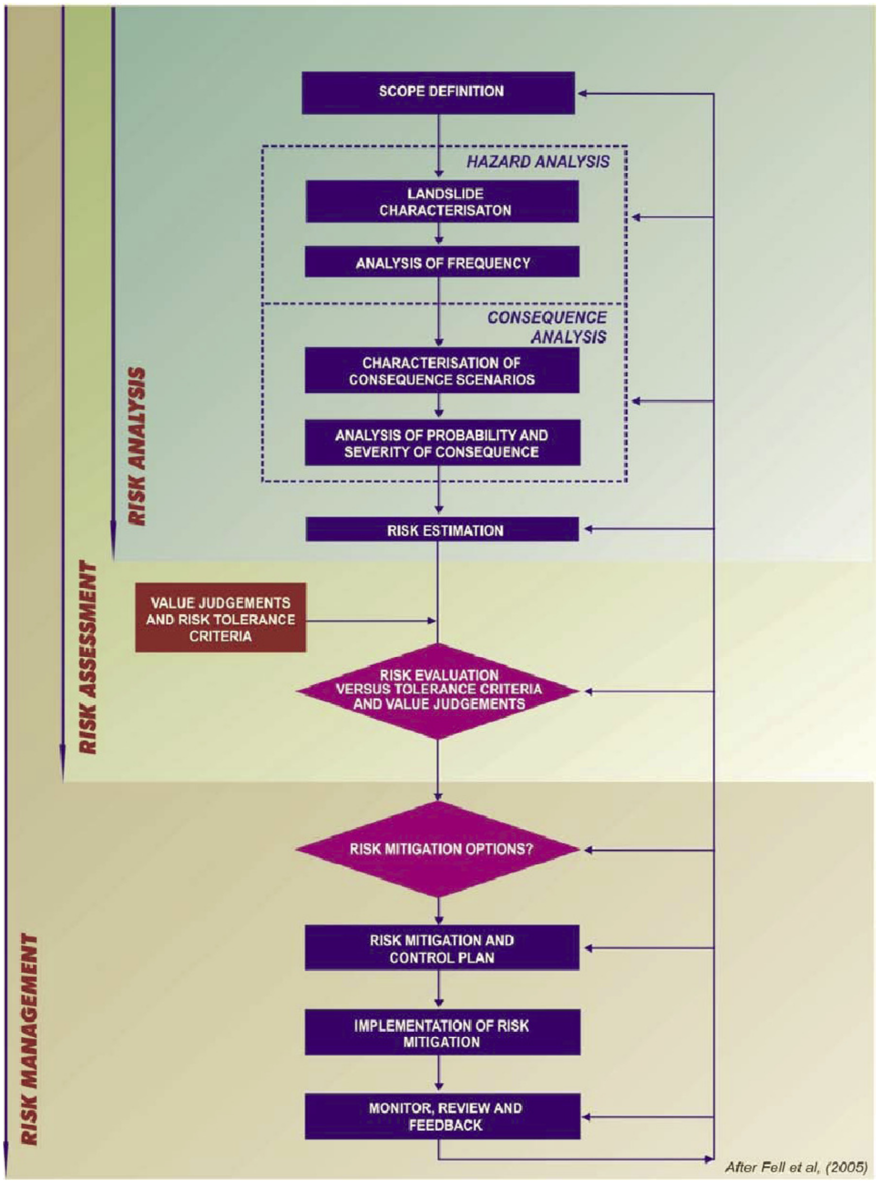

Figure B1 Framework for landslide risk management (AGS, 2007a)

Consequence classification after AGS (2007a)

QUALITATIVE MEASURES OF CONSEQUENCES TO PROPERTY

Approximate Cost of Damage		Description	Descriptor	Level
Indicative Value	**Notional Boundary**			
200%	100%	Structure(s) completely destroyed and/or large scale damage requiring major engineering works for stabilisation. Could cause at least one adjacent property major consequence damage.	CATASTROPHIC	1
60%	40%	Extensive damage to most of structure, and/or extending beyond site boundaries requiring significant stabilisation works. Could cause at least one adjacent property medium consequence damage.	MAJOR	2
20%	10%	Moderate damage to some of structure, and/or significant part of site requiring large stabilisation works. Could cause at least one adjacent property minor consequence damage.	MEDIUM	3
5%	1%	Limited damage to part of structure, and/or part of site requiring some reinstatement stabilisation works.	MINOR	4
0.5%		Little damage. (Note for high probability event (Almost Certain), this category may be subdivided at a notional boundary of 0.1%. See Risk Matrix.)	INSIGNIFICANT	5

Likelihood classification after AGS (2007a)

QUALITATIVE MEASURES OF LIKELIHOOD

Approximate Annual Probability		Implied Indicative Landslide Recurrence Interval		Description	Descriptor	Level
Indicative Value	**Notional Boundary**					
10^{-1}	$5x10^{-2}$	10 years	20 years	The event is expected to occur over the design life.	ALMOST CERTAIN	A
10^{-2}	$5x10^{-3}$	100 years	200 years	The event will probably occur under adverse conditions over the design life.	LIKELY	B
10^{-3}	$5x10^{-4}$	1000 years	2000 years	The event could occur under adverse conditions over the design life.	POSSIBLE	C
10^{-4}	$5x10^{-5}$	10,000 years	20,000 years	The event might occur under very adverse circumstances over the design life.	UNLIKELY	D
10^{-5}	$5x10^{-6}$	100,000 years	200,000 years	The event is conceivable but only under exceptional circumstances over the design life.	RARE	E
10^{-6}		1,000,000 years		The event is inconceivable or fanciful over the design life.	BARELY CREDIBLE	F

Note: (1) The table should be used from left to right; use Approximate Annual Probability or Description to assign Descriptor, not *vice versa*.

Appendix C

Risk estimation methods

C1 Fault trees and event trees

An event tree is a 'bottom up' approach for analysing the possible sequence of events following the first initiating event. A logical, graphical approach is used to show the sequence of events and outcomes.

An advantage of event trees is that they can deal with a large number of scenarios and different components of failure.

A fault tree is the opposite to an event tree in that it takes an event, such as system failure and analyses all the possible ways in this might occur (i.e. a top down analysis).

C2 Decision trees and influence diagrams

These tools structure the components of a decision, and allow quantification of the different outcomes based on uncertainties and consequences associated with each step (Loehr *et al*., 2004).

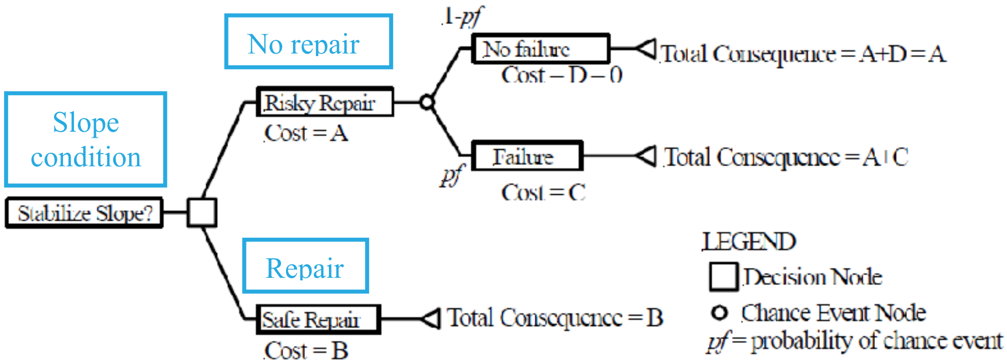

Figure C1 Decision tree proposed by Loehr *et al* (2004) with suggested modifications/simplifications.

Loehr *et al* (2004) present an approach based upon decision trees for making geotechnical decisions (Figure C1). These are based around the need for choosing between different stabilisation methods, with different levels of reliability and different costs. However, the approach works at a simpler level where the decision to be made remains at a lower level, i.e. to repair or not to repair, as shown in Figure C1.

Thus, in Figure C1, for our simplified case, where A and D = 0, the choice is between p_fC and B. This is a fairly straightforward decision; however, the process rapidly becomes complex when additional variables such as a time horizon are introduced. Loehr *et al.* note that the model itself is fairly straightforward if the required parameters of probability of failure and consequences are available.

It should be noted that decision trees actually combine an assessment of risk directly with the decision to be made.

C3 Failure Mode and Effect (and Criticality)Analysis

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

FMEA works best where the failure of a single component is the source of the system failure, rather than considering interaction of two or more components (Vassie & Rickets, 1997), so the assumption of independence between different components is required. An important part of FMEAs is the consideration of the 'ease of detection' of a particular failure, which contributes to the resulting risk.

FMEA is a 'bottom up' analysis, similar to an event tree, in that the occurrence of an event is extrapolated up to all possible consequences.

Failure Mode Effect and Criticality Analysis (FMECA) considers the severity of the effects as well as the probability of occurrence by adding a criticality analysis to the FMEA, FMEA analyses different failure modes and their effects on the system, while criticality analysis classifies or prioritises their level of importance based on failure rate and severity of effect of failure. Criticality is a function of seriousness and frequency.

Element	
Potential Failure Mode	In what ways can the element fail?
Potential Failure Effects	What is the impact on the system performance?
SEV	A rating of severity of failure (1 -10)
Potential Causes	What causes the failure?
OCC	Frequency or likelihood of failure or cause (1 – 10)
Current Controls	Existing **controls** and procedures that prevent either the Cause or the Failure
DET	Ease of detection of the cause or the failure? (1 – 10)
RPN	Risk Priority Number = SUM(SEV + OCC + DET) (+ criticality, optional)
Actions Recommended	What are the actions for reducing the occurrence of the cause, or improving detection?
Resp.	Who is responsible for the recommended action?
Actions Taken	Note the actions taken. Include dates of completion.

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

Step 1 System
Define the system and all its components
Define external effects that could cause 'failure' (e.g. rainfall)

Step 2 Consequence
Define types and levels of consequences as a result of component 'failure'
Capture the full range of component failure effects e.g. from catastrophic to trivial
Define a *rank ordered scale of consequence category to define Severity of Failure* (SEV) (typically 1 – 10

Step 3 Likelihood
Develop a *rank ordered scale of likelihood of failure mode occurrence* (OCC)

Step 4 Risk Priority Number
= likelihood + consequence

Step 5 Analysis process
Consider each component in turn and each failure mode, assign consequence and likelihood categories
On this basis assign a relative risk to each possible failure mode within the system

Step 6 (Optional) Detection and intervention
Means of detection and intervention and measures to mitigate the risk by reducing likelihood and/or consequence. E.g. high cost/low cost or long delays, short delays

Application

- **Risk tradeoffs** – e.g. look at highest ranked Severity and Occurrence scores and adopt a different solution that will cause different likelihood/consequences to be ranked highest.
- Without considering risk, components, or failure modes can be 'binned' in terms of consequence attributes: e.g. high life safety effect; critical pollution effects; long repair time; high repair costs.
- Different decisions and different types of analysis can then be used for different groups. E.g. very high consequence – remediate straight away. For others, use a probabilistic approach.

Advantages

- Can be applied to any set of criteria or objectives since ranking is purely in terms of risk.
- Can direct investigations to the greatest risk contributors.
- Good potential to be multi-disciplinary
- Explicitly demonstrates that *individual components that achieve optimal performance on their own do not necessarily yield optimal system performance*.

Disadvantages

- Failure mode effect can be taken to be consequence only, which is not risk – must incorporate likelihood.
- Cannot easily deal with complex failure modes.
- Can be used to sidestep complex probabilistic approaches