ARUP AECOM

WP 1-085(PPRO 4/45/12) - Geotechnical Resilience Enhancement Measures

Workstream A: Understanding Highways England's Severe Weather Management Processes

06 April 2017

Version 0.3

Document Control

Document Title	WP 1-085(PPRO 4/45/12) - Geotechnical Resilience Enhancement Measures
Owner	Work Package Manager
Distribution	David Patterson
Document Status	FINAL

Revision History

Version	Date	Description	Author
0.1	05 Dec 2016	Initial Draft	Oliver Pritchard
0.2	23 Dec 2016	Draft incorporating stakeholder meeting comments	Oliver Pritchard
0.3	06 Apr 2017	Final incorporating client comments	Oliver Pritchard

Reviewer List

Name	Role
Chris Merrylees	Project Manager
Juliet Mian	Project Director

Signoff List

Name	Role
David Patterson	Client Package Sponsor

Table of Contents

1. Introduction

1.1. Purpose of Document

This report presents the findings from the initial phase of work within Work Package 1-085. This ‘Discovery Phase’ seeks to:

- Benchmark the approach developed for assessing geotechnical resilience to severe weather events in Task 634 (Arup, 2016).
- Understand existing approaches within Highways England for categorising vulnerable locations in a severe weather context.
- Provide recommendations as to how geotechnical asset vulnerable locations and the potential impacts of severe weather events can be better categorised.

1.2. Background

The Strategic Road Network’s (SRN) geotechnical assets have to date been very resilient to severe weather impacts. However, without timely maintenance, specific geotechnical assets may be prone to increased rates of deterioration and potential failure. The projected increase in the frequency and magnitude of severe weather events will potentially exacerbate the deterioration of geotechnical assets (Jenkins et al. 2009; Vardon, 2015). Without a more resilient approach in terms of anticipating, planning for, and responding to geotechnical failures, the overall resilience of the SRN may decrease.

Geotechnical incidents predominantly represent *low frequency, high impact events* which on the SRN have included the opening of dissolution holes and mineshafts, and slope performance failures. Such incidents can potentially result in loss of life as well as significant road closures and maintenance costs.

This task represents a follow-on from Task 634 (04/45/12) ‘*Resilience of geotechnical assets on the SRN to severe weather’* which was undertaken under Lot 2 of T-TEAR by the Arup Aecom Consortium. This task also represents a part of Highways England’s contribution to the National Adaptation Programme for Climate Change.

This report is part of the Highways England’s Geotechnical Knowledge Development Programme (Figure 1-1). This task will bring together a framework that incorporates SPaTS Task 1-062 ground-related hazard mapping task to help service providers understand the vulnerability of their respective networks’ geotechnical assets. In future tasks, this will also see the inclusion of knowledge gained from TTEAR Task 594 on special geotechnical measures (SGMs). This will allow them to anticipate potential events, be prepared for specific identified triggers, and develop the appropriate procedures for either pre-event adaptation, or post-event response and recovery, in line with the Department for Transport (DfT) recommendations outlined in the Transport Resilience Review (DfT, 2014).

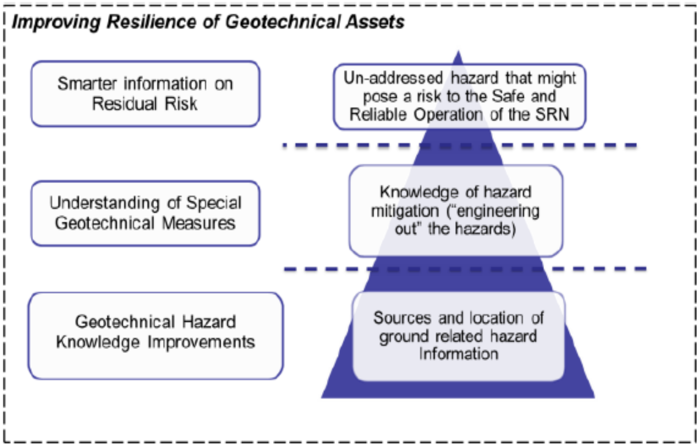


Figure 1-1: Geotechnical Knowledge Development Programme

1.3. Scope

The task has been split into two Workstreams (A & B). This report presents the findings of Workstream A, which has included the following activities:

- Benchmarking of current approach developed in Task 634.
- Review of terminology and their definitions used within Task 634.
- Understanding of key external and internal developments since publication of Task 634 (Arup, 2016).
- A review of vulnerable locations within Area Severe Weather Plans, which has specifically involved:
  - Consultation with Highways England's Severe Weather Group.
  - Review of Severe Weather Plan template (2016/17) and vulnerable location criteria.
  - Review of current Severe Weather Plans for respective Service Providers.
- Review of the frequency and impact of severe weather events on geotechnical assets.
- Conclusions and recommendations are then presented for Workstream B as well as those identified for further work beyond the scope of this task.

Further context and the line of sight for this Task is provided in Figure 1-2 below.

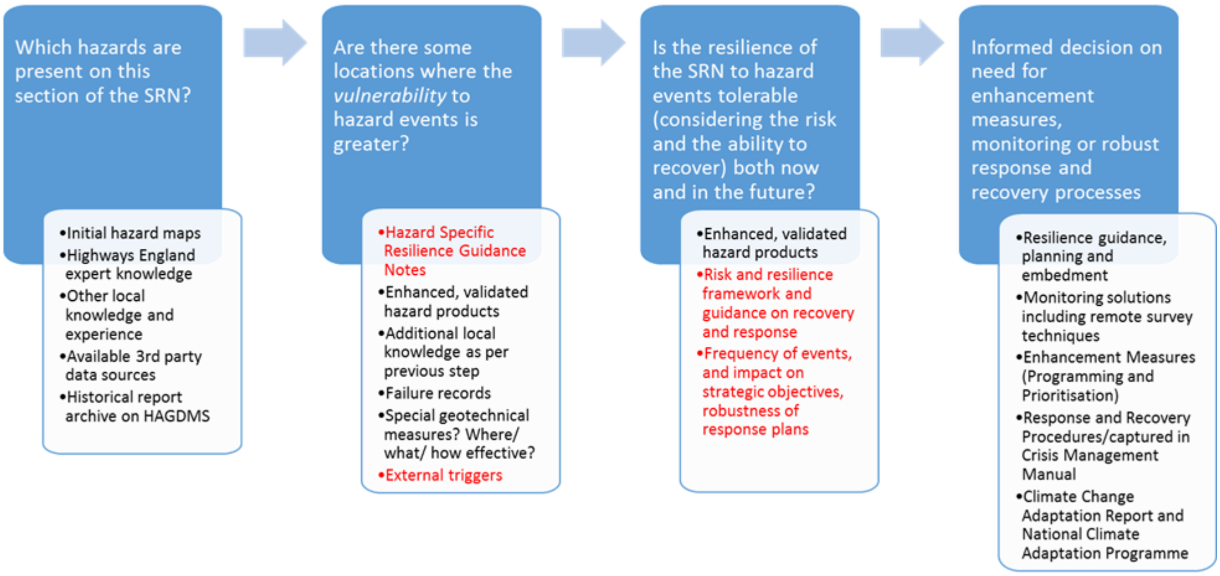


Figure 1-2: Line of sight for improving Highways England's geotechnical resilience (words in red represent activities specific to this Task)

1.4. Potential benefits

Ultimately, this task is helping to increase the resilience of geotechnical assets to severe weather events and help meet Highways England Strategic Objectives (Highways England, 2015).

Specifically, the envisaged benefits of this task are to:

- Contribute to an improved reliability during severe weather events which in turn contributes to 'A more free-flowing network'.
- Improve operational safety, through increased preparedness for geotechnical events that could have a safety impact, contributing to 'A safe and serviceable network'.
- Create an improved customer experience, through better planning for 'shocks' that may occur during severe weather events, which again contributes to 'A safe and serviceable network'.

2. Benchmarking

This section provides a summary of the benchmarking exercise undertaken to understand how the outputs of Task 634 (Arup, 2016), which produced a geotechnical asset resilience framework (Figure 2-1), is placed against other similar initiatives both within the UK and internationally. A more detailed assessment is provided in Appendix 1.

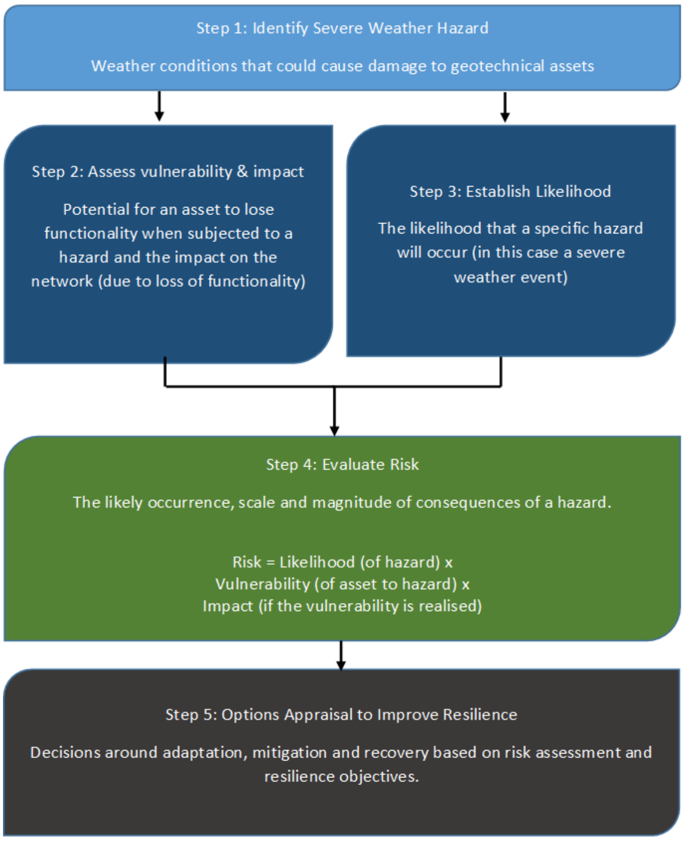


Figure 2-1: Resilience framework for Highways England geotechnical assets (after Arup, 2016, with minor alterations to terminology for clarity)

2.1. Application of the framework

This resilience framework provides a structured approach to assess and understand firstly the risks posed by the presence of geotechnical assets that are vulnerable to loss of functionality, and secondly the overall resilience of the SRN should the risk event occur.

To mitigate the overall impact of a ground-related event on the SRN, a range of options are available, from pre-event mitigation for significant risks, to operational responses immediately prior to, during, and after an event. These responses will depend on a number of factors including the likely severity of the event, and the criticality of the part of the SRN which is affected. A categorisation of resilience to a range of ground-related events would require a consistent understanding of the likelihood and impact of these events, considering local factors such as built-in resistance. Resilience categories would apply to the SRN as a system rather than the geotechnical assets. Tolerance to disruption, or the 'level' of required resilience, could then be defined to inform selection of options.

At this stage, there is insufficient data to develop anything other than a theoretical categorisation, which can't be tested and therefore does not add value. Resilience guidance notes, developed for Workstream #2 will present qualitative considerations, to be made at a local level, around the level of risk, the ability to recover from an event and hence pre- or post-event measures to introduce.

2.2. Model complexity

Task 634 (Arup, 2016) states that 'the overall maturity of the proposed framework will be governed by the minimum level of sophistication of any one part'. The resilience framework has been developed to incorporate a range of data complexities, governed by available data within Highways England. This follows the method developed by Thomas et al. (2010) in RIMAROCC (Risk Management for Roads in a Changing Climate).

Arup (2016) proposed a 'simple model' which utilises a combination of qualitative and semi-quantitative data to inform the framework. This can then be updated to a 'developed model' which will see incorporation of a variety of complex and integrated datasets. This is presented graphically in Figure 2-2.

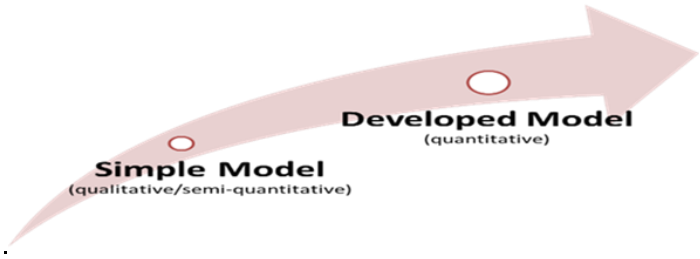


Figure 2-2: Framework data complexity

To ensure that a consistent approach across other infrastructure operators has been applied during the benchmarking exercise, information is presented on these two levels of data complexity.

2.3. Simple Model Benchmarking

Analysis showed that within the industry, simple risk-based frameworks for understanding weather and climate risks are broadly consistent. However, differences are found in the use of terminology and their definitions. This provoked a review of the terminology and definitions used, and results are presented in Appendix 2; these have since been agreed with the Task's Stakeholder Group for specific future use within this Task.

For benchmarking the simple model approach, two key sources were reviewed and are described below along with particular findings and recommendations:

- **Transport Scotland's Climate Change and Resilience Exposure and Risk Assessment approach (Aecom, ongoing)** – see Appendix 1 for framework outline.
    - Designed to assess vulnerability at trunk road asset level and network specific section level.
    - Allows the estimation of severity resulting from a weather-related event to be identified and ranked (e.g. number of lanes closed following an

incident). However, this requires accurate and comprehensive incident data.
    - Provides assessment of how present level of exposure will change in medium and longer term (i.e. up to 2050s).
    - Thresholds are applied against future climate change projections to assess and highlight which parts of the network will be subject to the highest vulnerabilities.
    - Proposes separate assessments for each specific weather type.

- **Highways England (2016) Climate Adaptation Risk Assessment: Update, January 2016**.
    - Provides necessary evidence to inform Highways England actions taken to reduce their risks to climate change.
    - Aligns with other corporate documents.
    - Vulnerabilities of geotechnical assets identified as currently being 'low' (further comments are made in Section 6.4).
    - Overall the resilience framework and the Climate Adaptation Risk Assessment remain aligned.
- **Highways England Flood Severity Index**
    - Flood Severity Index (FSI) coded into HADDMS for all flood events.
    - Assigns a score of 0 to 10 based upon the extent and duration of impact, and the type of road and traffic volumes impacted.
    - Similar or same scoring could be used for the impact component of Step 2a, if a semi-quantitative score is useful.
    - Provides a means of scoring impact, and has the advantage of being consistent with an existing Highways England measure.
    - It does not consider all impacts to Highways England such as safety, environmental impact

2.4. Developed Model Benchmarking

The developed model approach is dependent on more complex datasets. Four key areas of development are proposed, which include:

1. *Enhance intelligence for future climate change and transport projections;*
2. *Establish and quantify values and cost benefit of resilience measures;*
3. *Identify and integrate interdependencies; and*
4. *Consider implementation during initial design and upgrades.*

These four areas require more complex analytical solutions and more detailed datasets, which aren't easily implemented at present, but Highways England should consider and understand these going forward. This benchmarking exercise recognises that a number of ongoing parallel tasks will address development in some of these areas. Therefore, it is critical for Highways England and its suppliers to be aware of research to date and any future recommendations to ensure a consistent approach is achieved.

2.5. Terminology

As part of the benchmarking review and subsequent stakeholder discussions, the terminology put forward in Task 634 has been reviewed and simplified. The following are the key terms used to present the resilience framework, and further detail is presented in Appendix 2.

Criticality	The function and importance of an asset, route or particular location in delivering Highways England's strategic objectives – focusing on the themes of safety, environment, customers and economic growth.
Frequency	The number of occurrences of a hazard within a given unit of time.
Hazard	Accidental or naturally occurring event or situation with the potential to cause harm, damage or losses to people or property, and/or disruption to the environment and/or to economic, social and political structures.
Impact/Consequence	These terms are interchangeable and define the extent of the adverse effects or benefits arising from the realisation of a **hazard**. This may include harm, damage or losses to people, systems or property, and/or disruption to the environment and/or to economic, social and political structures. The impact of an asset loss of function is a function of the **criticality** of the affected location, and how badly the asset is affected (its **vulnerability**).
Likelihood	The possibility that a specific event will occur. Often measured quantitatively; as probability (out of 1), as chance (as a percentage) or as a frequency (per set period of time). May also be expressed using qualitative terms.
Resilience	The ability of assets, networks and systems to anticipate, absorb, adapt to and/or rapidly recover from a disruptive event. Resilience is secured through the four principal strategic components of: Resistance, Reliability, Redundancy and Response & Recovery.
Risk	Risk represents the likely occurrence, scale and magnitude of impact arising from the occurrence of a **hazard**. Risk is a function of the **impact** (or consequence) and the **likelihood** of that impact occurring.
Vulnerability	Vulnerability describes how severely a receptor (or set of receptors) is affected by a hazard. **Asset vulnerability** refers to the effect a hazard can have on a specific asset; **network vulnerability** refers to the effect a damaged asset can have on the wider network, which considers the criticality of the affected location.

3. Developments since Task 634

This section presents the key developments both within and external to Highways England with respect to recognising, preparing for and mitigating the impacts of severe weather and climate change impacts on transport infrastructure networks since the publication of Task 634 (Arup, 2016).

3.1. ResilienceDirect

The Civil Contingencies Act (2004) requires emergency responders to co-operate and share information to efficiently and effectively prepare for, and respond to, emergencies and ensure any resultant action is coordinated[1].

To facilitate this, the Cabinet Office have recently developed 'a new, fully accredited and secure information-sharing service called ResilienceDirect™'[2]. This platform is chaired by the ResilienceDirect Team from the Civil Contingencies Secretariat, Cabinet Office[3].

3.1.1. Highways England Response

Highways England have the role of Category 2 responder as defined in the Civil Contingencies Act (2004)[4]. Suggested material and data which Highways England will contribute to ResilienceDirect is currently in discussion. 'Vulnerable location maps' are one potential data product. Any other dataset which helps contribute to the strategic resilience of the SRN may be considered for inclusion in the system, such as spatial network location and sections of the SRN identified as Critical National Infrastructure (CNI).

Highways England are currently developing their Standard Operating Procedure for the system. Potential users within Highways England would be:

- National Resilience and Security Team (who also act as organisational sponsors)
- Regional Emergency Planning Teams
- Operations Managers
- Service Providers

The findings and outputs of this Task could be used to further develop the categorisation of Highways England's vulnerable geotechnical asset locations on the SRN. As such, continuing coordination will be required between this task and its outputs, and Highways England's Security and Resilience Team.

Recommendation: Including spatial information identifying geotechnical asset locations vulnerable to problems due to various trigger events (e.g. heavy rainfall or flooding) would be valuable to resilience planning, for example in being able to anticipate secondary or 'cascading' failures that may occur during event responses.

---

1 https://www.gov.uk/guidance/resilient-communications#resiliencedirect
2 https://www.ordnancesurvey.co.uk/business-and-government/case-studies/resilience-direct.html
3 http://www.emcouncils.gov.uk/write/Resilience_Direct_Presentation.pdf
4 http://www.legislation.gov.uk/ukpga/2004/36/pdfs/ukpga_20040036_en.pdf

3.2. Key publications update

This section presents a brief review of key documents which have either been published since the publication of Task 634 or which are thought to have significant bearing on the task development and were not considered in the previous Task 634 Scoping Study (Arup, December 2015).

3.2.1. Sector Security and Resilience Plans

The Cabinet Office have prepared a series of Sector Security and Resilience Plans for each of the critical infrastructure sectors, inclusive of transport. These plans are summarised in 'Summary of the 2016 Sector Security and Resilience Plans' (Cabinet Office, 2016).

Their role is to bring government, regulators and infrastructure owners together in order to help increase the resilience of the UK's infrastructure networks, paying particular emphasis on the risks identified in the National Risk Assessment (NRA). The NRA is a classified document, but a publically available version is available through the 'National Risk Register' document (Cabinet Office, 2015).

> *"The scale and exposed nature of the transport network makes it vulnerable to some significant risks, such as severe weather. However, multi-agency emergency planning, investment in engineering and technological solutions, and the interconnected nature of transport networks all lend resilience to the sector"*
>
> National Risk Register (Cabinet Office, 2015)

Moreover, the DfT is focusing on risks which have the biggest impact to the network. Climate change and severe weather are identified as a key focus for DfT. Specifically, identifying those sections of road network that are vulnerable to flooding and the impact of loss of those sections and/or bridges during an event on local communities and the wider society is of particular importance.

3.2.2. National flood resilience review

The National Flood Resilience Review, published in September 2016 by HM Government, focuses on the resilience of local infrastructure (i.e. local authority level) rather than at Highways England level. It does reinforce the statement that Highways England have pledged an investment of £78 million for the next five years as part of their flood risk management plan.

Importantly, referral to ResilienceDirect is made in terms of specific organisations providing a register of flood response assets that could be visible to others (i.e. organisations and emergency responders). However, there was no indication whether this would include Highways England assets (e.g. geotechnical embankments that are designated as flood defences).

3.2.3. CCRA Evidence Report

The Climate Change Risk Assessment (CCRA) evidence report was published by the Committee on Climate Change in July 2016. Unlike previous iterations, this document includes a specific section on infrastructure (Chapter 4) (Dawson et al. 2016). Infrastructure interdependencies in terms of perpetuating climate risk were highlighted as the most significant hazard facing UK infrastructure networks.

Specific weather events and their potential impacts on infrastructure networks were also detailed. In respect of geotechnical assets, particularly note was given to the impact of rainfall on the instability of slopes and the potential increased risk under current UK climate projections.

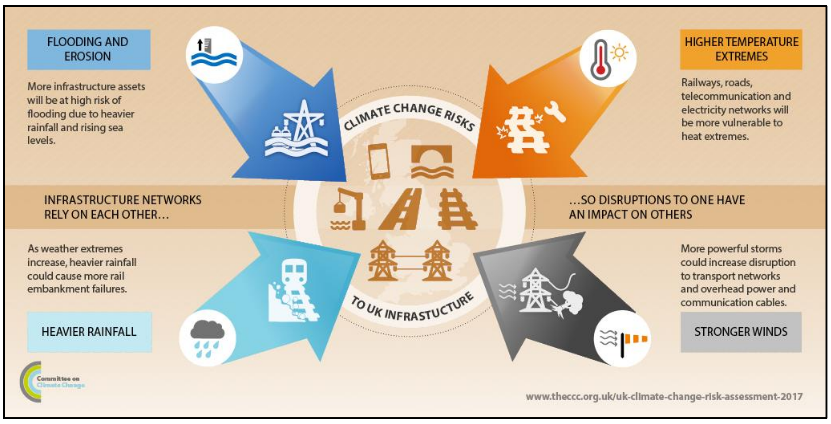


Figure 3-1: Climate change risks to UK infrastructure (Source: Dawson et al. 2016)

3.2.4. TRaCCA

The TRaCCA (Tomorrow's Railway and Climate Change Adaptation) executive summary report was published in May 2016 (RSSB, 2016). This programme of research has identified the weather and climate risks facing the UK rail network.

In particular the report notes "*Assessments of adaptation and resilience projects often find it difficult to estimate the economic and social costs of disruptions due to extreme weather, and therefore fail to appreciate the long term benefits of adaptation and resilience investments*".

Other relevant recommendations include:

- Identifying assets most at risk (i.e. vulnerable)
- Further understanding of asset interdependencies required
- Development of registers of assets affected by a particular weather impact.
- Improved monitoring and recording of weather conditions
- Use of smart technologies, telemetry and remote sensing technology
- Use of GIS-based alert systems and weather susceptibility maps

3.2.5. InTact

InTact is an EU-funded project which is developing and demonstrating best practices in a number of engineering disciplines as well as crisis response and recovery capabilities. An aspect of the project is considering the 'Vulnerability and Resilience of European Critical Infrastructures'.

The project is considering vulnerability and resilience through understanding of:

- Recent incidents of critical infrastructure failures caused by extreme weather hazards.
- Factors contributing to vulnerability and resilience of critical infrastructure to extreme weather hazards.

- The impact of global climate change on future critical infrastructure vulnerability and resilience.
- Generic measures and gaps to protect critical infrastructure and to mitigate emergencies.

A number of impact variables have been detailed, which have particular potential and include:

- Down-time
- Number of people losing critical infrastructure service
- Repair cost (normalised by cost of full reconstruction)
- Degree of service loss of the critical infrastructure (reduced road capacity).

3.2.6. Well-managed highway infrastructure

The UK Roads Liaison Group recently published *'Well-Managed Highway Infrastructure: A code of practice'* (UKRLG, October, 2016). A number of its recommendations are particularly pertinent to this task, and include:

- Recommendation 7: *"A risk-based approach should be adopted for all aspects of highway infrastructure maintenance, including…. Inspections, responses, resilience priorities".*
- Recommendation 20: *"Within the highway network hierarchy a 'Resilient Network' should be identified to which priority is given through maintenance and other measures to maintain economic activity and access to key services during extreme weather".*
- Recommendation 21: *"The effects of extreme weather events on highway infrastructure assets should be risk assessed and ways to mitigate the impacts of the highest risks identified".*

A 'Resilient Network' is likely to include:

- Those routes crucial to the economic and social life of the local or wider area.
- Take account of repeat events (e.g. flooding).
- Local factors (no specific examples are provided).

Climate change and adaptation are also considered, with the report identifying the relevant climate change projections and policy surrounding the adaptation of UK highway infrastructure to severe weather and climate change impacts.

The code states that highway authorities should consider various climate change variables which include, intense or prolonged rainfall, hotter temperatures, higher wind speed and how they will potentially impact on the highway asset. Of the greatest generic risks to the highway network, flooding, landslips and bridge scour are highlighted.

3.2.7. CIRIA Infrastructure Resilience Series

CIRIA have recently embarked on a series of events which will focus on infrastructure resilience. The series aim is to discuss common issues and challenges around the issue of infrastructure resilience and in particular will aim to highlight the particular focus of infrastructure operators, government, and academia around this issue.

4. Severe weather information service (SWIS)

Highways England recently replaced their weather service platform, HAWIS (Highways Agency Weather Information Service), with a new system called the *Severe Weather Information Service* (SWIS). SWIS was launched on 12th September 2016.

SWIS Provides:

- Severe weather alerts through the Met Office
- Environment Agency flood alerts.
- '*Alarms/Alerts*' tab for locations identified by users as vulnerable which are set at particular weather thresholds or when a severe weather alert is raised
    - For example, the Severn Road Bridge Crossing between England and Wales is often highlighted as being vulnerable during periods of high winds, which then prompts speed restrictions or road closure to heavy goods vehicles.
- '*Weather Summary*' tab which provides forecast information for a selected Area. Site specific forecasts can also be selected where required within each Area.
    - Currently, respective areas are able to procure their own weather service provider. However, the Severe Weather Group state that to ensure weather forecasting consistency, the Met Office will represent the sole service provider in the near future.
- Forecast images which are provided by the Met Office.
- *Environmental Sensor Stations* (ESS) (there are 255 locations nationally) provide live weather information as well as historic data which can be viewed in the system for a specific date/time.
- Active Severe Weather Plans for the majority of the respective Areas.

In addition to the SWIS system, Highways England have an embedded meteorologist, who is based within the National Traffic Operations Centre (NTOC) between the months of October-April which covers the period of winter service.

SWIS is predominantly tailored for the impacts of high winds and flooding as well as snow and ice. In terms of the latter, for example, there is increased functionality regarding the location, efficiency and maintenance of gritting vehicles and the total salt stock supply for the SRN.

4.1. Rainfall reporting in SWIS

Rainfall is reported in SWIS through Precipitation Satellite for both observed and forecast images, which are sourced from the Met Office.

Forecast images comprise both precipitation rate in millimetres per hour (mm/hr) providing forecasts for the next six hours in one hour intervals and precipitation type which have the same temporal forecasting period. Precipitation types include the following: Dry, Drizzle, Freezing Drizzle, Rain, Freezing Rain, Mixed Snow/Rain, Snow, Powder Snow, Soft Hail, Small Hail and Large Hail.

In terms of Weather Summary, rainfall is reported as the likelihood of ‘Heavy Rain’ and is classified as High, Medium and Low. Examples of screenshots from SWIS visualising precipitation rate and type are provided in Appendix 3.

Historical data are not directly available on SWIS, which is used primarily as a forecasting tool.

5. Vulnerable locations review

5.1. Highways England Severe Weather Group

Highways England Severe Weather Group are responsible for developing the Severe Weather Plan templates alongside managing the network of Environmental Sensor Stations (ESS). This section provides an overview of consultation with the group regarding the categorisation and identification of vulnerable locations and ongoing developments.

5.1.1. Severe weather impact tool

A recently commissioned project has been tasked with creating a '*Severe Weather Impact Tool'* which will be a GIS-based system. Ultimately, the information from the tool would feed into both SWIS and ResilienceDirect. At the time of writing, the development of the project is in its infancy. It is recommended to follow key developments as the task proceeds.

5.1.2. Stakeholder consultation report

A Stakeholder Consultation Report was published in October 2015 by TRL/Halcrow on Vulnerable Locations.

The report aimed to:

- Identify key stakeholders with an interest in vulnerable locations
- Clarify the approach regarding the identification of vulnerable locations undertaken by stakeholders (i.e. service providers)
- Clarify the needs of the stakeholders with regards to vulnerable location information; and
- Develop of a series of next steps for progressing the work beyond the current task

The report states that vulnerable locations across the SRN have been identified historically based upon service providers' experiences and knowledge developed whilst monitoring and managing the network during severe weather events. However, even this can vary between areas. For example, Area 1 use the historical knowledge of past severe weather incidents in the Area over a 20 year period, whereas Area 4 uses local knowledge that considers impact and its regularity.

A questionnaire which formed the basis of the report argued that the whole network requires assessment in terms of its vulnerability to severe weather. Furthermore, current annual reporting methods do not allow the addition of new vulnerable locations that potentially could be identified during/after severe weather incidents. This is particularly pertinent considering the increasingly higher magnitude weather events experienced in the UK (Met Office, 2014).

Recommendations from this report were:

- Vulnerable locations should be selected based upon a particular weather scenario.
- Increased use of the vulnerable location data would be made if a particular weather type was chosen which then only selected particular assets susceptible to that particular weather variable.

- A solution that could provide alerts when certain weather conditions are forecast is required.
- Consideration would have to be given to multiple weather scenarios (e.g. combined rain and high wind).
- Designated vulnerable locations need to be classified in terms of their risk to the SRN. A risk assessment should be prepared as a guidance note and issued by Highways England to service providers. A RAG (Red, Amber, Green) status is proposed as a clear identifier for vulnerable location risk during severe weather events.

The primary source of vulnerable location information is recorded within the Severe Weather Plans. Knowledge of these locations helps area teams and service providers to develop a suitable severe weather strategy. A number of stakeholders have an interest in the vulnerable locations list, ranging from service providers to emergency planners as well as Highways England Press and Communications.

5.2. Severe Weather Plan template

The current operational Severe Weather Plan template for the 2016/17 winter period was provided by the Severe Weather team. Within the Severe Weather Plan template, section 1.6.1 ‘Vulnerable locations’ provides the available guidance to service providers about the recording of vulnerable locations within their respective Areas.

> “*Areas known to be prone to the impacts of severe weather as well as those areas where although incidents may not have occurred, asset properties may make them* vulnerable”.
>
> Vulnerable location definition (Highways England, Severe Weather Plan Template 2016/17)

This definition suggests that vulnerable locations should not be based solely on historic experience of disruption during previous severe weather events.

Vulnerable locations are reviewed annually, with each iteration of the Severe Weather Plan template that comes into force at the beginning of each winter period (i.e. October). It is apparent that this current approach does not allow new vulnerable locations to be added between the annual publications of Severe Weather Plans.

A vulnerable location table template, extracted from the severe weather template (2016/17), is provided in Appendix 4.

5.2.1. Required weather information

The Severe Weather Plan template includes an Appendix on the required level of detail that is required in terms of weather forecasting for all Areas.

Particular service providers may use their own forecast provider. For example, Area 12 use Meteogroup and Area 14 use MetDesk. However, movement to the Asset Delivery Model (ADM) will see the Met Office being the sole source of weather information to Highways England.

The outlines of the level of detail of weather information required in the Severe Weather Plan are presented in Appendix 5 and 6.

5.3. Service Provider Severe Weather Plans review

Severe Weather Plans were reviewed for Network Management Areas defined in Table 5-1. For the majority, these plans were related to the 2015/16 winter period, with 2016/17 plans only available for Areas 5, 7 and 13. It is thought that these Severe Weather Plans will not have altered considerably since 2015/16. The Severe Weather Plans were downloaded direct from the SWIS platform.

Table 5-1: Severe Weather Plans reviewed

Area	Service Provider	Winter period
1	EM Highway Services Limited	2016/17
2	Skanska	2016/17
3	Kier Strategic Highways	2016/17
4	Balfour Beatty Mott MacDonald	2015/16
5	DBFO Co (M25 DBFO)	2016/17
6	Amey	2016/17
7	A-one+	2016/17
8	Amey	2016/17
9	Kier	2016/17
10	Balfour Beatty Mott MacDonald	2016/17
12	A-one+	2016/17
13	Kier	2016/17
14	A-one+	2016/17
29	Roads Management Services (Peterborough) Ltd.	2016/17
30	Carillion Highway Maintenance on behalf of UK Highways (M40) Ltd.	2016/17
31	Road Management Service (Gloucester) Ltd.	2016/17

5.3.1. Definition of a severe weather event

During times of severe weather, a severe weather desk will be established to deal with the response and recovery to the particular event. The severe weather escalation process is shown in Figure 5-1.

Not all service providers categorise a ‘severe weather event’ consistently.

For example, Area 7 defines the activation criteria as:

- Forecast severe weather on 2 to 5 day forecast
- Met Office Weather alert issued

Whereas Area 10 define activation criteria as:

- Prior to the forecasted commencement of severe weather

- As soon as possible in the event of un-forecasted severe weather

Reasons for different categorisations are likely a factor of a particular Area's weather data supplier having different levels for severe weather alerts. It would be more appropriate to have a single approach, in terms of severe weather alerts, for establishing a severe weather desk within the Severe Weather Plans.

Alert Level	Forecast Conditions	Strategy	Actions
1	Frost or sub-zero conditions	***Business as usual***	• Plan pre-salt or required treatment as required in Severe Weather Plan treatment matrix. • Notify stake-holders of planned treatment.
2	Snow and/or ice	***Consult with RCC about warning motorists***	• Plan treatments as required in conjunction with SWP • Look to suspend any non-critical activities • Liaise with RCC and adjacent authorities • Ensure shift numbers are adequate to carry out all planned operations • Consider mobilisation of Severe Weather Desk
3	Prolonged severe weather event effecting most domains	***Reduce network activities and liaise with all stake-holders***	• Suspend all proposed works and remove Traffic Management from the network where possible • Ensure the shift numbers are enhanced to deploy all extra effort clearance equipment • Look to move resources from other depots to deal with potential event • Establish Severe Weather Desk and inform Silver Command Officer of forecast conditions • Liaise with all stake-holders and advise of likely effects to road-users • Relay the message to local media of potential weather event
4	Extreme severe weather conditions effecting all domains for prolonged period	***Look at all resource levels and request mutual aid if required***	• Severe Weather Desk fully operational • Silver Command Officer in /NCC • Staff and Operative levels enhanced to maximum capacity • All non-critical activities suspended • All adjacent authorities notified of current and proposed treatments and actions • Continuous monitoring of plant, labour and material levels • Liaise with adjacent areas with regard to the possible supply of Mutual Aid • Continuous liaison with MET Office • Prioritisation of treatments depending on hierarchy of carriageway • Liaison with RCC/NTCC to notify road users of likely conditions in Area 13

Figure 5-1: Severe weather escalation process (from Area 13 SWP)

5.3.2. Vulnerable locations

The number of vulnerable locations in the Severe Weather Plans for the Areas reviewed are provided in Table A-1 in Appendix 7. The number of vulnerable locations vary considerably between one and 66.

Analysis was undertaken to understand what particular vulnerabilities are associated with the respective Areas; this is provided in detail in Appendix 5 and is summarised in Figure 5-2. This shows that snow/ice/hail is the primary cause for an area being designated as a vulnerable location. With heavy rain, flooding and gradient being other major causes for designation. These types of severe weather events and/or network properties presenting a reasonably frequent operational risk to the SRN.

Importantly, interdependencies with other networks are also identified for a number of Areas. SRN links with major ports and airports have been identified as being particularly vulnerable to severe weather events.

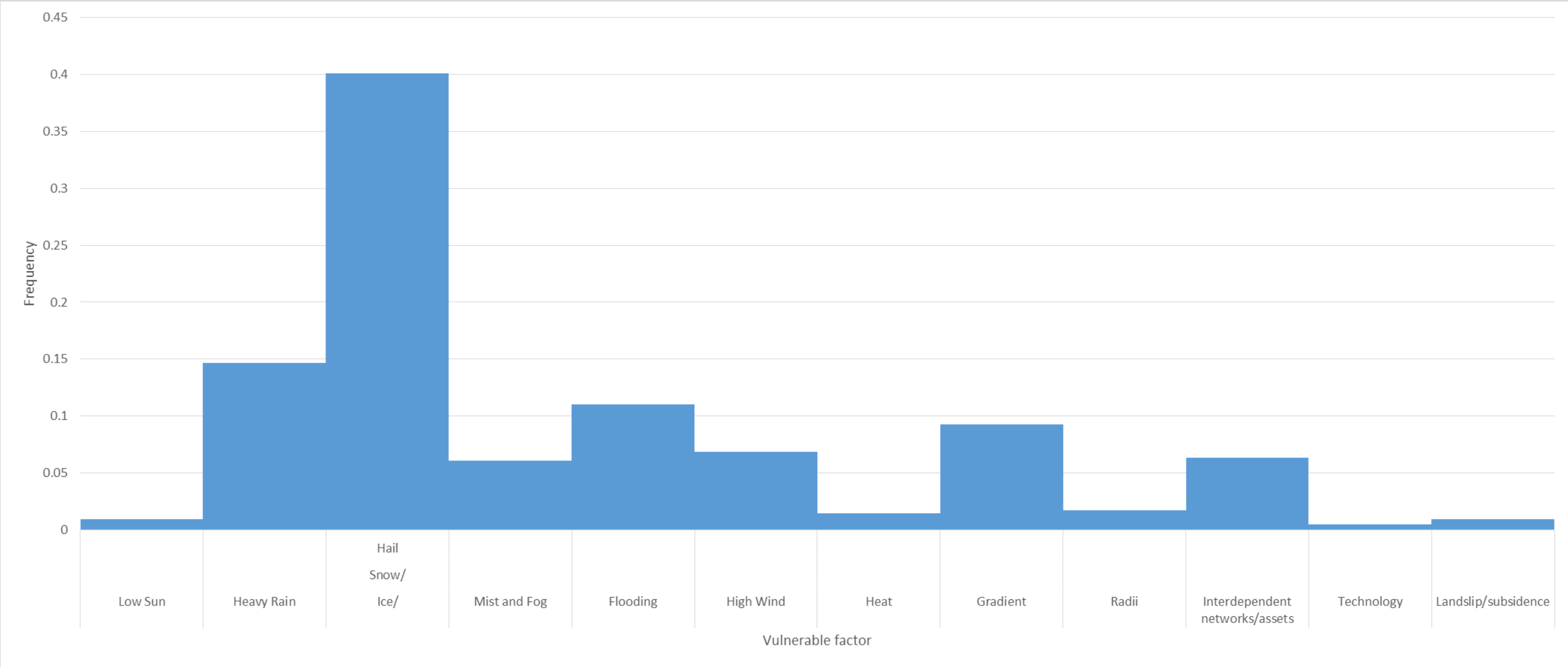


Figure 5-2: Frequency of vulnerable factors (weather and non-weather related) identified in the Severe Weather Plans reviewed (frequency normalised against total occurrences)

5.3.3. Geotechnical asset vulnerable locations

Only a limited number of the Severe Weather Plans reviewed identified particular geotechnical assets as vulnerable locations.

Geotechnical assets included in the vulnerable location lists for each respective area are detailed in Table 5-2. The majority of areas don't have a single geotechnical asset identified as a vulnerable location. Moreover, the relatively few locations included appear to be based upon where previous incidents have occurred.

As an example, Area 4 highlights the M2 between junctions 5 and 6 as 'susceptible to ground subsidence'; the schedule for this vulnerable location is presented in Appendix 8. This inclusion as a vulnerable location likely results from the dissolution hole that opened up in the central reservation in February 2015. Figure 5-3 shows the soluble rock hazard for the M2 corridor, which indicates that the risk of soluble rock hazard is equal across much of the M2 and therefore much more of the network could potentially be vulnerable to this particular ground-related hazard.

Table 5-2: Vulnerable geotechnical locations identified from Area Severe Weather Plans

Area	Number of geotechnical vulnerable locations	Notes
1	1	A38 Glyn Valley – 'prone to flooding/landslips/fallen trees'
2	0	N/A
3	1	A3 Liphook and Petersfield Bypass – 'Sand subsoil with increased risk of low temperature'
4	1	M2 Junctions 5-6 – susceptible to ground surface subsidence
5	0	N/A
6	0	N/A
7	0	N/A
8	0	N/A
9	0	N/A
10	1	A56 southbound Woodcliffe Cutting – 'Area known landslip site'
12	0	N/A
13	0	N/A
14	0	N/A
29	0	N/A
30	0	N/A
31	0	N/A

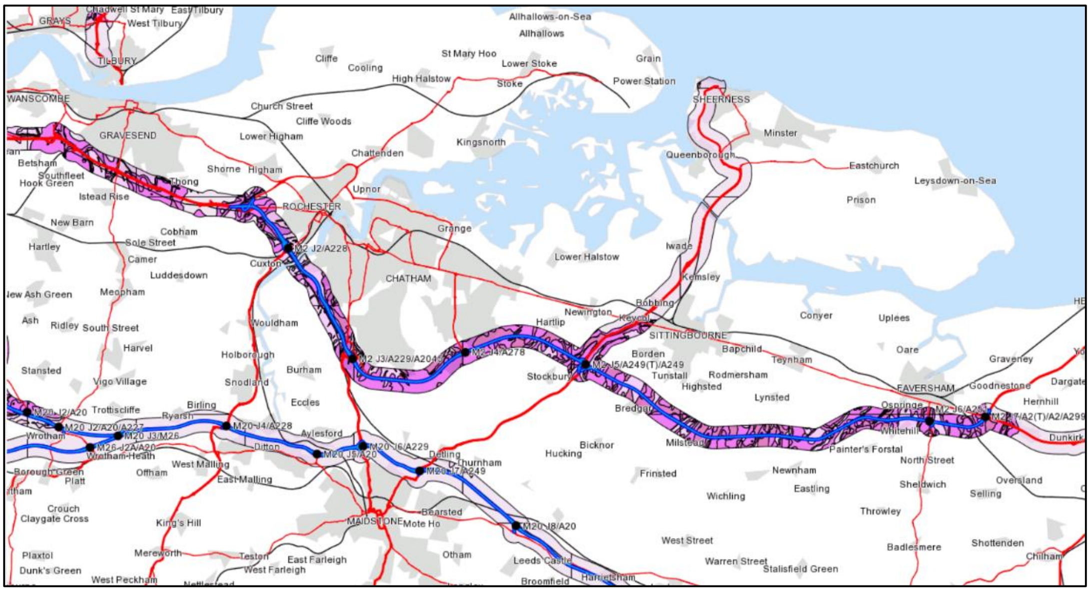


Figure 5-3: Soluble rock hazard along M2 corridor (Data source: HA GDMS, BGS Geosure Data)

5.4. Area 13 approach to severe weather management

Consultation[5] with Area 13 (Cumbria) established the current practices employed during periods of severe weather. Area 13 is particularly prominent as it is subject to high levels of rainfall, and showed a number of vulnerabilities during the recent Storm Desmond event during December 2015.

Area 13 uses the following methodological approach to assess vulnerable locations when severe weather is forecast:

- Following warning for heavy rainfall event, asset inspectors check flooding hotspots.
- Any action required to maintain drainage assets at these locations will then be undertaken.
- Following a flood event and after receding of the water, drainage assets and geotechnical assets in the vicinity will be inspected for any potential defects as a result.
- Any defects recognised during a geotechnical asset inspection will then be reported onto HA GDMS.

Further information is provided in the Area's *Asset Inspections & Maintenance Frequency Exceptions Report* (Kier, January 2016). A risk-based approach to asset inspections was introduced from April 2016, whereby inspection frequencies will be determined by a number of factors, including: asset age, flooding hotspot, traffic flows, and Category 1 defects.

[5] Phone conversation (17/10/2016) between Kevin Clague, Kier, Area 13 Needs Manager and Oliver Pritchard, Arup

5.4.1. Area 13 GeoAMP

Area 13's Geotechnical Asset Management Plan (GeoAMP) for 2015-2020 (Kier, August 2016) stresses that the majority of the network, despite several severe weather events, has remained extremely resilient.

Despite this, section 3.2 titled '*Geotechnical Events*' contains a significant amount of information relating to the impacts of severe weather on geotechnical assets. In particular, the impacts of Storms Desmond, Eva and Frank during the winter of 2015/2016 are highlighted which resulted in significant damage and disruption to the network. However, this information was not reflected in the 2016/17 Severe Weather Plan for the area, which does not identify any geotechnical assets as being vulnerable.

Furthermore, the GeoAMP has identified significant secondary risks to the SRN, which are reflected in this extract:

"It is noted that significant erosion/scour took place around the western pier of the River Eden Bridge on the Temple Sowerby Bypass and of the slope adjacent to the River Greta to the north of A66 east of Keswick as a result of the storm events. Whilst these are not considered to be geotechnical events (and therefore not recorded as such on HAGDMS) they have had, or the potential to have, a significant impact on the network."

5.1. Summary

In summary, the following points can be made about Highways England's current approach to vulnerable location categorisation:

- Vulnerable locations identified in the Severe Weather Plans are primarily focused on 'snow, ice and hail', 'heavy rain' and 'flooding' impacts.
- Criticality of a particular location is not considered in the Severe Weather Plan definition of a vulnerable location. Therefore, it appears that only the location that is vulnerable and not necessarily the SRN as a system.
    - However, understanding of network interdependencies is incorporated into the vulnerable locations schedule in some Areas (e.g. links with major ports, airports, major shopping centres etc.).
- There is no consistent classification of vulnerable locations in terms of their frequency or their impact. Therefore, it is difficult to currently understand whether it's correct that geotechnical assets are simply not included due to lower frequency and/or impact.

Recommendation: It would be considered prudent, when improving the categorisation of vulnerable geotechnical asset locations, to review GeoAMPs across the entirety of Highways England Areas. This report has shown, for Area 13 that qualitative information is available within the GeoAMP highlighting geotechnical assets vulnerable to severe weather and which is not available through the severe weather plans. Other Areas were not investigated further in this report. Reporting of vulnerable locations in GeoAMPs may however be susceptible to consideration of events which occurred in the recent past, rather than considering all events over the assets lifecycle, which has also been seen in the severe weather plans. However, Section 6 (frequency and impact) attempts to understand asset defects across all areas which result from severe weather events.

6. Frequency and impact of severe weather events on Highways England's geotechnical assets

The frequency and impact of severe weather events on geotechnical assets are of interest because they could be used to contrast and compare between the different types of vulnerable locations usually considered in the SWPs.

Analysis in Section 5.3 identified that geotechnical assets are not widely considered as vulnerable locations in respective Severe Weather Plans. This is likely because of the low frequency of geotechnical incidents that have occurred to date.

Despite this, severe weather events will exert a number of impacts on Highways England's geotechnical assets, mainly accelerated deterioration which can ultimately result in asset 'failure'. Failure can be interpreted as something that leads to a Serviceability Limit State (SLS) failure or one that more rarely leads to the Ultimate Limit State (ULS) failure of an asset (CIRIA, 2003a and 2003b).

For consistent data recording within HA GDMS (Geotechnical Database Management System), the definition of an earthworks failure has taken from Mott Macdonald, Task 434 report, (April 2016):

- An observation of Feature Class 3 that has no previous record of another Feature Class (e.g. an historical repair).
- A Geotechnical Event Form (GEF) describing a failure, irrespective of the type or severity of surveyed defect.

The remainder of this section undertakes an analysis of these particular data sources to assess the impact and frequency of severe weather events on geotechnical assets.

6.1. Observation reporting

Observations are defined in HD41/15 'Maintenance of Highway Geotechnical Assets' as *'group of characteristics located on a geotechnical asset'.* Observations are recorded as defects only if it is assigned Class 1 in accordance with HD41/15.

Observations are contained within the Geotechnical Asset Database (GAD). In a data output from 4th April 2016, there were 3,642 observations recorded which included such items as: slip, tension cracks, subsidence, slope bulge etc. These observations are associated with the time period between 26/7/2002 and 01/4/2016.

The following summary of observation data is provided:

- 42 records were attributed to '*exceptional rainfall*'.
- Additional 33 records (75 in total) associated with '*Erosion of slope*' – which is in most cases attributed to water movement (either through flooding or direct rainfall).
    - There is an additional trigger of '*utility failure*' which should exclude those failures caused for example, by a burst water main.
- These 75 records were only representative of 2% total Observation records.
    - The severity of the weather events cannot be quantitatively assessed at present in relation to these observations. This results from the temporal recording of the observation, which may not necessarily

represent the date of defect manifestation. However, prevailing weather conditions are recorded at time of inspection.

6.2. Geotechnical event reporting

A geotechnical event is defined by HD41/15 as *"a geotechnical defect that poses a threat to the safety of users, workers or other parties such that immediate action is to be taken".*

6.2.1. Geotechnical Event Forms

Geotechnical events are reported on Geotechnical Event Forms (GEF) and were reviewed to understand the potential impact of severe weather on the frequency of geotechnical 'failures'. The overall process of recording a geotechnical event is shown in Figure 6-1.

GEFs, which are recorded according to the standard defined in HD41/15, have only been recorded within Highways England since 2015. Before this time such events were not recorded within HA GDMS.

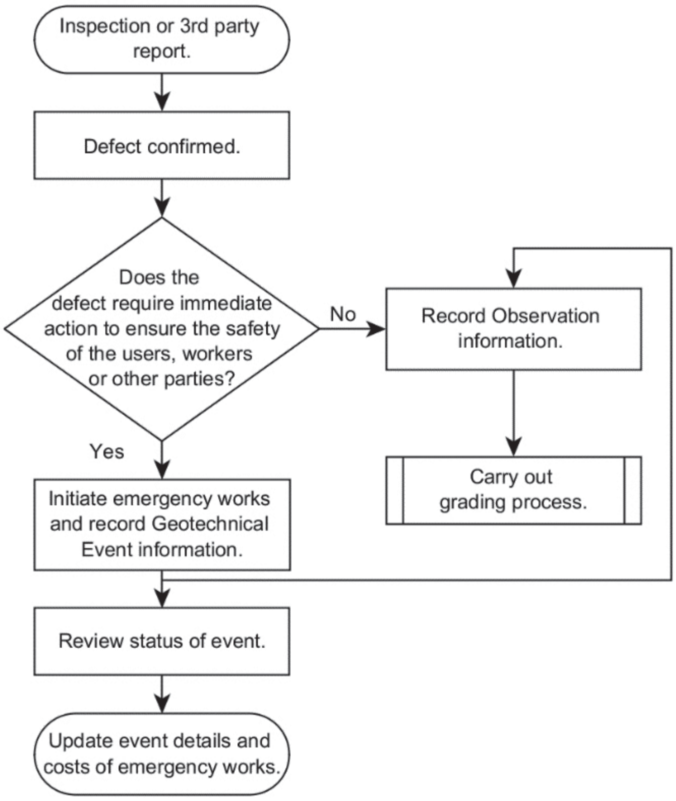


Figure 6-1: Geotechnical event process (HD41/15)

The following summary of GEFs are provided:

- Only 19 GEF records are contained within HA GDMS, due to their short existence since 2015.
  - Furthermore, two of these are 'test' events and so should be discounted.
- Only four of the 17 GEFs can be qualitatively associated with a weather event.

- A number were related to significant slope movements, which have likely manifested over a longer period of time and therefore have not been related to any particular triggering event.
- Similarly to Observations, the temporal reporting may not correspond to the time of the geotechnical event. Therefore, it is potentially difficult to associate a particular weather event as a trigger for the event.
- Costs (in terms of renewal and traffic management) of geotechnical events are reported within a GEF.

6.2.2. Geotechnical Maintenance Forms

Geotechnical Maintenance Forms (GMFs) have been superseded and expanded upon by GEFs in terms of recording failure events on the SRN's geotechnical assets (HD41/15). GMFs are defined in HD41/03, specifically Form A which we are considering here, as a notification of a Class 1 defect requiring investigation and/or remedial works.

GMFs potentially contain additional information which is of use for further understanding the impacts of severe weather events. GMF Form A data was downloaded from HA GDMS on 24/02/2017 and analysed to understand particular relationships between identified defects and severe weather events.

The following summary of GMFs is provided:

- There are 1,664 GMF Form A records provided on HA GDMS (Figure 6-2).
- Through a textual analysis, the following terms associated with weather and/or severe weather were identified:
    - 79 records attributed to 'erosion' (which could be a result of flowing water from rainfall and flooding)
    - 57 records attributed to 'desiccation'. (related to periods of prolonged high temperatures and low rainfall)
    - 25 records attributed to 'flooding' (related to periods of high and/or intense rainfall)
    - 13 records attributed to 'weathering' (related to prevailing weather, but maybe triggered by a severe weather event)
    - 5 records attributed to 'rainfall'.
- The impact of the class 1 defect on the network is not defined.

This analysis suggests that there are a number of GMF's that can be qualitatively associated with severe weather events. However, similarly to GEFs it is difficult to accurately associate these with actual weather conditions due to the temporal recording of the GMF.

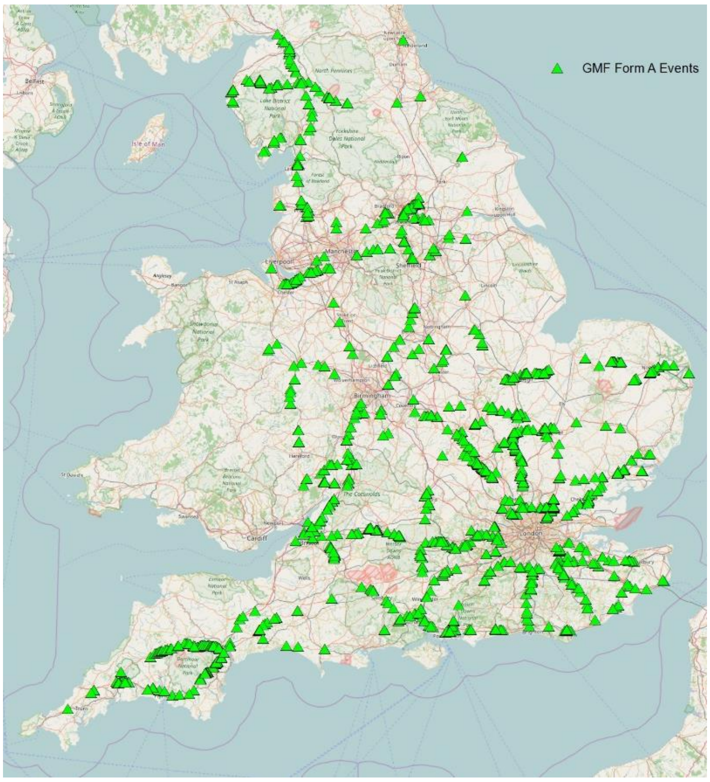


Figure 6-2: Locations of Geotechnical Maintenance Forms (Form A) Events (based on HA GDMS download of 24/02/2017)

6.3. Relative impacts on other assets

A severe weather event resulting in a particular defect and/or geotechnical event is a relatively low frequency occurrence. However, an SLS or ULS failure of a geotechnical asset has the potential to result in a significant cascading impact causing damage and disruption to a number of other asset groups which may be founded in that particular geotechnical asset.

GEFs document third-party impacts and potential third-party assets that could be affected are shown in Figure 6-3. Of the 17 GEFs currently available on HA GDMS, all were recorded as having impacted on other assets.


Impacts

Impacts	☑ Affecting carriageway ☑ Affecting HA estate (within boundary) ☑ Affecting 3rd party land/property ☐ Affecting communications ☐ Affecting signage	☑ Affecting drainage ☐ Affecting structures ☐ Affecting safety barrier/equipment ☐ Other impact
Description of other impact		

Figure 6-3: Example from GMF form regarding geotechnical event impacts on other asset types

6.4. Climate change impact

UK climate change projections (Jenkins et al. 2009) suggest that the UK will generally experience hotter, drier summers and warmer, wetter winters through to the end of the 21st Century. Moreover, it is likely that the frequency and severity of severe weather events will increase.

Most geotechnical assets have long design lives (i.e. greater than 60 years) and service lives that can extend beyond this, which can make them particularly susceptible to longer-term climate change impacts compared to other asset groups (e.g. pavements).

The likelihood of climate change causing geotechnical assets to lose function will be influenced by their original design. Design specifications and standards and the environmental loads they would have considered are dependent on the age of the asset. Modern design specifications and standards have improved significantly since the original phases of motorway construction (i.e. 1960's).

The impact of climate change will also be dependent on the presence of and condition of the special geotechnical measures that have been put in place; these are being investigated as part of T-TEAR Task 594.

Highways England's CCRA update (Highways England, 2016) states geotechnical assets are at a 'low vulnerability' to climate change and that current action is to 'do minimum' (Figure 6-4). A 'do minimum' approach means that the thresholds and tolerances involved are considered already suitable to cope with the current climate change projections (Highways England, 2016). The following example is provided in the 2016 CCRA:

- *"An increased frequency of soils and sub soils drying out, followed by increases in extreme precipitation, could destabilise material and lead to erosion. This is not considered a significant risk in the design and construction of new and replacement geotechnics assets, because erosion at present is limited to a few isolated areas. Existing specifications allow for the use of topsoil retention systems where deemed relevant and any risks are already addressed on a project specific basis."*

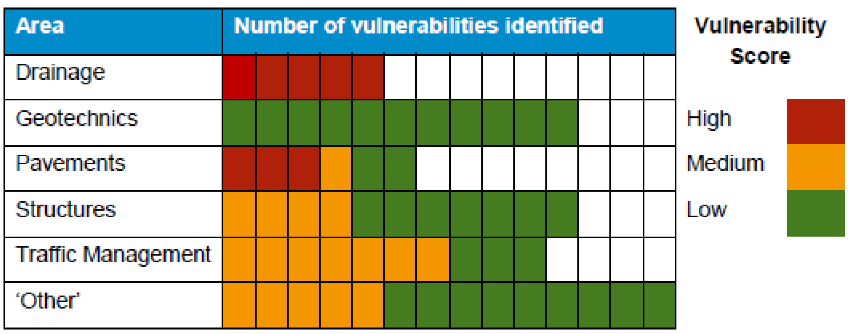


Figure 6-4: Vulnerabilities identified across each business area (Source: Highways England, 2016)

However, it should be considered that the climate change impacts potentially facing the SRN (Figure 6-5), could lead to increased asset deterioration, or act as a trigger for ground-related hazards across the network. Contrastingly, some impacts may reduce asset vulnerability. For example, increases in the average temperature will likely reduce the number of icy days in winter; repeated freeze-thaw events on rock cuttings can lead to accelerated deterioration and potential failure.

There is some uncertainty over slope stability in future climates especially as they age. Highways England are actively looking to establish links with academic research, mainly through providing data on the condition of its earthworks to allow suitable analysis to be undertaken. For example, Highways England are an active stakeholder in a research project entitled iSMART. Specifically, this project is considering the impact of future climate projections on clay slopes in the UK. This includes long-term in-situ monitoring of a Highways England embankment on the A34 near Newbury. This research was reviewed in the previous Task 634 report (Arup, 2016). It will be prudent to incorporate information resulting from this project as it develops.

Climate change hazards – Significance to Highways England		
Primary climatic changes	Secondary climatic change impacts	Importance for users
Increase in average temperature	Longer growing season Reduction in fog days in winter Reduction of icy days in winter	Low
Increase in maximum temperature	Extreme summer temperatures	High
Increase in winter rainfall	Flooding Increase in snowfall	High
Reduction in summer rainfall	Reduction in soil moisture	Low
More extreme rainfall events	Flooding	High
Increased wind speed for worst gales	Wind speed more frequently exceeding operational limits	High
Sea level rise	Higher frequency of extreme storm surges	Low

Figure 6-5: Climate change hazards on Highways England's SRN (Source: Highways England, 2016)

7. Conclusions – vulnerable locations review

The following conclusions have been drawn from this review:

Severe weather management within Highways England

- This is currently focused on mitigating the impacts of snow and ice, flooding and high winds due to the higher frequency of impacts on the SRN.
- This is subsequently reflected in SWIS, which is principally targeted at winter maintenance as a result of cold/icy weather.
- Highways England are developing a severe weather impact tool, which could have potential benefit for visualising vulnerable locations.

Vulnerable location categorisation and recording

- Vulnerable locations are not consistently identified.
  - There are no specific criteria in the Severe Weather Plan for establishing vulnerable locations on the SRN in terms of the risk these locations present to the SRN (in terms of likelihood and impact).
  - It is therefore difficult to consider whether geotechnical asset locations should be included in Severe Weather Plans.
- Vulnerable locations are primarily based upon the location of past events, rather than consideration of the potential hazards which may exist, even though the definition of a vulnerable location includes previously un-recorded future events.
- Vulnerable locations could be defined and classified in terms of the risk they present to the network. With a consistent risk framework, it would then be possible to categorise geotechnical assets as either:
  (a) 'Vulnerable geotechnical locations' which should be included in Severe Weather Plans, recognising that failures are infrequent, but their potential impact is significant; or
  (b) Not vulnerable when compared to other severe weather impacts due to their relatively low level of risk, and therefore requiring different processes to ensure their resilience.
- Annual review of vulnerable locations doesn't allow for additions following severe weather events.
- Work is ongoing within Highways England Severe Weather Group to better categorise vulnerable locations.
- Capability should be made within SWIS to add those high-risk vulnerable geotechnical locations if deemed appropriate. This would allow them to be more fully represented in the severe weather management process.

Frequency and impact of severe weather events on geotechnical assets:

- A limited number of geotechnical 'events' (four since 2015) and 'observations' (75 since 2002) have been recorded that are associated with severe weather events.
  - A number of these incidents have occurred during or shortly after widespread flood events.

    - However, temporal reporting of an event or observation may prove problematic in terms of quantitative association with a particular severe weather event.
    - Details of the impact on the SRN (in terms of extent of delay or disruption) are not consistently recorded.
- Geotechnical Maintenance Forms (GMFs) are a potential source of information to identify vulnerable geotechnical asset locations.
- A potentially significant amount of information regarding the location of vulnerable geotechnical assets exists within GeoAMPs and HA GDMS.
    - However, neither of these sources at the moment presents a frequency of failure for a vulnerable location, which makes it difficult to compare to against other vulnerable locations.
- Although there are a number of systems for response and recovery, currently these systems act independently in terms of severe weather management. As such, further linkages are required between SWIS, HA GDMS, GeoAMPs and SWPs.
- Climate change will potentially have a significant impact on the deterioration of assets and hence the frequency of weather-related failures in the future unless appropriate interventions are undertaken.

8. Developing the resilience assessment framework

Resilience is defined in this context as "*the ability of assets, networks and systems to anticipate, absorb, adapt to and/or rapidly recover from a disruptive event*" (Arup, 2016); a *disruptive event* being representative of a severe weather event.

Francis and Bekera (2014) argue that the resilience approach emphasises an assessment of the system's ability to:

I. Anticipate and absorb potential disruptions;

II. Develop adaptive means to accommodate changes within or around the system;

III. Establish response behaviours aimed at either building the capacity to withstand or recover as quickly as possible after an impact.

The resilience framework (Arup, 2016) includes steps of vulnerability and risk assessment by considering known and identifiable hazards (Park et al. 2013). The resilience aspect is introduced by considering and incorporating recognition of adaptation and mitigation measures which can be applied to help geotechnical assets absorb, adapt to and recover from severe weather events.

8.1. Improving resilience assessment

As defined in the Task 634 report, of the steps presented in the resilience framework (Figure 2-1), not enough information is available to fully assess the risks presented by severe weather. However, a high level simple assessment can be done for all steps apart from Step 3 – likelihood of a severe weather event.

Currently, there is a lack of available longer-term historic weather data, understanding of future return periods of severe weather events and the recognition of particular weather thresholds that can and have triggered geotechnical asset serviceability '*failure*'. All of these are required to be able to adequately define the likelihood of a severe weather event with the potential to lead to a loss of functionality.

The conclusions presented in Section 7 argue that a more consistent approach is required for identifying and categorising a vulnerable location on the SRN. As such, the following recommendations are presented going forward to help develop the categorisation of vulnerability:

- A vulnerable location should be based on both the occurrence of past events and the inherent and external susceptibilities of the particular asset(s).

  Smarter use of information available within the GeoAMPs and HA GDMS to further understand the location of potentially vulnerable geotechnical assets.

- Geotechnical Event Forms should be reviewed say annually, as the number and hence the potential for analysis increases.
- The frequency and impact of geotechnical asset incidents should be measured against other severe weather impacts.
- A risk-based approach should then be used to prioritise vulnerable geotechnical assets on the SRN which require attention preceding a severe weather event.

- Ability for Service Providers to be able to update vulnerable asset locations following a severe weather event, where significant impacts may have affected the SRN. In contrast to the current annual reporting frequency.
- Improving knowledge of ground-related hazards that may impact on the SRN. This is related to the outputs of Task 1-062 (Geotechnical Hazard Knowledge).
    - This will be supported by the production of a series of hazard guidance notes to provide Service Providers with a qualitative assessment of the likelihood and potential impact of ground-related hazards to impact on the SRN (particularly during severe weather events).
    - As these hazard maps are developed, they can be more fully implemented in the resilience framework.

8.2. Developing resilience categorisation

Resilience categorisation to a range of ground-related events requires a consistent understanding of the likelihood and impact of triggering events, considering local factors such as built-in resistance. Resilience categories would apply to the SRN as a system rather than the geotechnical assets and should be consistent with other potential disruptive events, for example the vulnerable locations described earlier in this report. Tolerance to disruption, or the 'level' of required resilience, could then be defined to inform selection of options.

Currently a more qualitative approach, providing guidance to Area teams in terms of the information and other factors they should consider when assessing the risks that particular ground related hazards present to the SRN is advised.

A related task – Risk-based asset serviceability (Task 694, Arup, March 2017) presents a candidate framework for assessing the criticality of each HAPMS Section across the network, in terms of Safety, Users, Strategic Importance and Environmental impact. These scores, which are based on location not the asset, could be used to consistently define the impact of a loss of function at a given location.

REFERENCES

Arup (2010) *A risk-based framework for geotechnical asset management: Phase 2 report*. November 2010.

Arup (2015) *Resilience of geotechnical assets on the Strategic Road Network to severe weather events: Phase 1 – Scoping Study*. Task 634 (4/45/12), Issue 1.

Arup (2016) *Resilience of geotechnical assets on the Strategic Road Network to severe weather events: Phase 2 – Final report*. Issue 3.

Cabinet Office (2015) *National Risk Register of Civil Emergencies: 2015 Edition*. March, 2015, London

Cabinet Office (2016) *Summary of the 2016 Sector Security and Resilience Plans*. November 2016, London.

Ciria (2003a) *Infrastructure cuttings – condition appraisal and remedial treatment*. Ciria Report C591. Ciria, London.

Ciria (2003b) *Infrastructure embankments – condition appraisal and remedial treatment*. Ciria Report C592. Ciria, London.

Dawson RJ, Thompson D, Johns D, Gosling S, Chapman L, Darch G, Watson G, Powrie W, Bell S, Paulson K, Hughes P, Wood R (2016) *UK Climate Change Risk Assessment Evidence Report: Chapter 4, Infrastructure*. Report prepared for the Adaptation Sub-Committee of the Committee on Climate Change, London.

Francis R, Bekera B (2014) A metric and frameworks for resilience analysis of engineered and infrastructure systems. *Reliability Engineering and System Safety*. 121: 90-103.

Halcrow (2015) *Vulnerable Locations: Stakeholder consultation report*. TTEAR435/13. Package Order 435/4/45/12, October 2015.

Highways England (2015) *Strategic Business Plan: 2015-2020*. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/396487/141209_Strategic_Business_Plan_Final.pdf

Highways England (2016) *Highways England: Climate Change Adaptation Risk Assessment, Progress Update 2016*. January 2016.

HM Government (2016) *National Flood Resilience Review*. September, 2016. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/551137/national-flood-resilience-review.pdf

Hosseini S, Barker K, Ramirez-Marquez JE (2016) A review of definitions and measures of system resilience. *Reliability Engineering and System Safety*. 145: 47-61.

Hughes JF, Healy K (2014) *Measuring the resilience of transport infrastructure*. February 2014. New Zealand Transport Agency research report 546.

Jenkins GJ, Murphy JM, Sexton DMH, Lowe JA, Jones P, Lisby CG. (2009) *UK Climate Projections: Briefing Report*. Met Office Hadley Centre, Exeter, UK.

Kier (January 2016) *Asset Inspections & Maintenance Frequency Exceptions Report 2016/17*. Area 13 MAC.

Kier (August 2016) *Area 13 MAC: GeoAMP 2015 to 2020, Part One*. HAGDMS Ref: 28817. Kier, Area 13 Penrith Highways Depot, Cumbria.

Kier (August 2016) *Area 13 MAC: GeoAMP 2015 to 2020, Part Two*. HAGDMS Ref: 28817. Kier, Area 13 Penrith Highways Depot, Cumbria.

Met Office (2014) The recent storms and floods in the UK. February 2014. http://www.metoffice.gov.uk/media/pdf/n/i/Recent_Storms_Briefing_Final_07023.pdf

Mott MacDonald (November 2016) *Geotechnical Hazard Knowledge (SPaTs 1-062): Work Package Quality Plan*. 9 November 2016. Mott MacDonald, WSP Parsons Brinckerhoff.

Park J, Seager TP, Rao PSC, Convertino M, Linkov I (2013) Integrating risk and resilience approaches to catastrophe management in engineering systems. *Risk Analysis*. 33(3): 356-367.

Perry J (1989) *A survey of slope condition on motorway earthworks in England and Wales*. Research report 199, Transport and Research Laboratory, Crowthorne, Berkshire.

RSSB (2016) *Tomorrow's Railway and Climate Change Adaptation: Executive Report*. Rail Safety and Standards Board, London.

Thomas B, Yves E, Jean-Jacques F, Stefan F, Bo L, Marjolein M, Michel R, Frode S. (2010) *Risk Management for Roads in a Changing Climate: A guidebook to the RIMAROCC method.* Project No. TR80A. http://kennisonline.deltares.nl/product/22249.

Vardon PJ (2015) Climatic influence on geotechnical infrastructure: a review. *Proceedings of the ICE: Environmental Geotechnics*. 2(3): 166-174.

Vessely M, Barrows R, DeMarco M (2012*) Incorporation of geotechnical elements as an asset class within transportation asset management and development of risk-based and life cycle cost performance strategies*. Shannon and Wilson Inc. http://onlinepubs.trb.org/onlinepubs/conferences/2012/assetmgmt/presentations/Geotechnical-Vessely-DeMarco-Barrows.pdf.

UK Roads Liaison Group (2016) *Well-managed Highway Infrastructure: A code of practice*. October, 2016. http://www.ukroadsliaisongroup.org/download.cfm/docid/4F93BA10-D3B0-4222-827A8C48401B26AC.

APPENDICES

APPENDIX 1 – Benchmarking Report

WP 1-085(PPRO 4/45/12) - Geotechnical Resilience Enhancement Measures

Benchmarking Report

07 March 2017

Version 0.03

Document Control

Document Title	WP 1-085(PPRO 4/45/12) - Geotechnical Resilience Enhancement Measures: Benchmarking Report
Owner	Work Package Manager
Distribution	
Document Status	Final

Revision History

Version	Date	Description	Author
0.01	26 10 2016	First Draft	Conor McGreevy
0.02	30 10 2016	Final Draft	Conor McGreevy
0.03	07 03 2017	Final	Caroline Toplis

Reviewer List

Name	Role
Caroline Toplis	Associate Director
Juliet Mian	Project Director

Signoff List

Name	Role
	Client Package Sponsor

This is a controlled document.

This document is only valid on the day it was printed. Please contact the Document owner for location details or printing problems.

On receipt of a new version, please destroy all previous versions.

Table of Contents

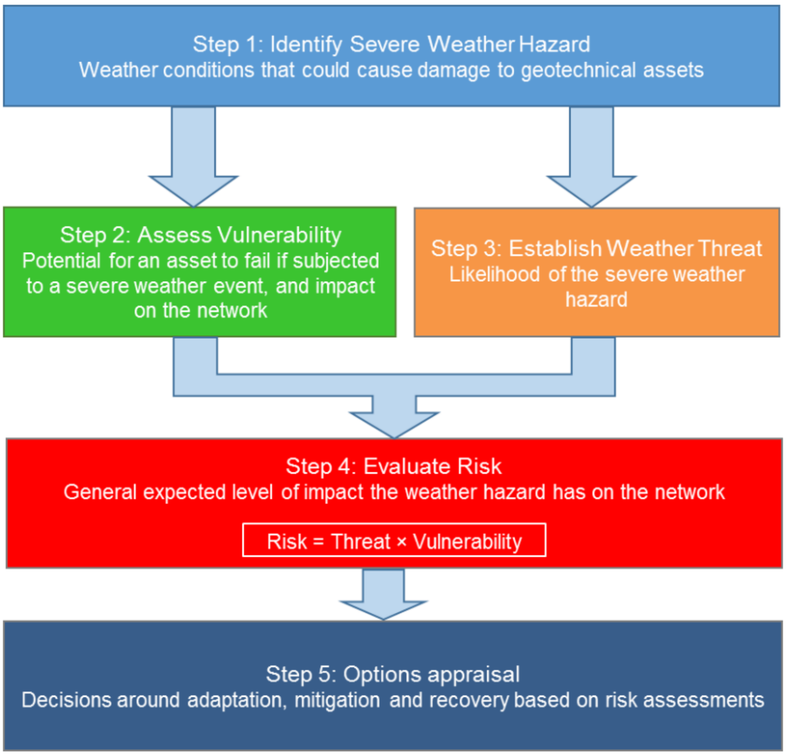
1. Introduction

This report documents the findings and recommendations of a benchmarking exercise of the Resilience Framework for Geotechnical Assets, developed during Task 634 (Arup, 2016).

2. Background

A geotechnical asset resilience risk framework was developed for Highways England (Figure 1).

Figure 1 – Resilience Framework for Geotechnical Assets



3. Resilience Framework for Geotechnical Asset Synopsis

The Resilience Framework for Geotechnical Assets consists of five distinct stages which must be observed and implemented within their methodical sequence. The five stages include;

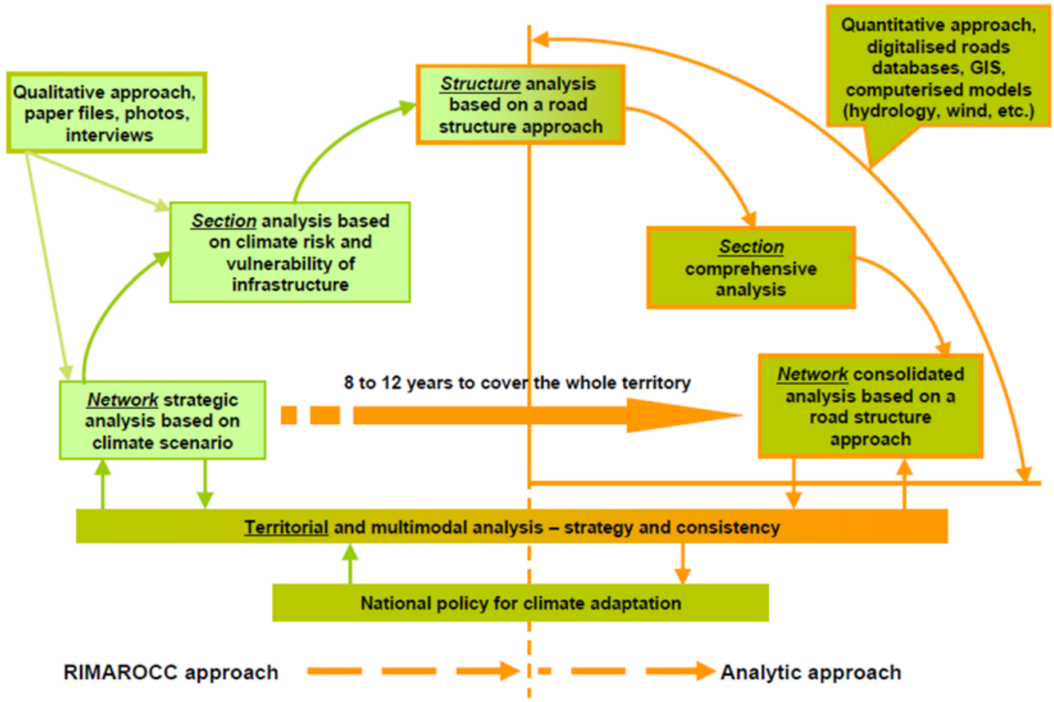
1. Identify Severe Weather Hazard;
2. Assess Vulnerability;
3. Establish Severe Weather Threat;
4. Evaluate Risk; and
5. Options Appraisal.

As documented within the Task 634 final report, 'the overall maturity of the proposed framework will be governed by the minimum level of sophistication of any one part', and has therefore been developed to consider two levels of data complexity.

The ‘Simple Model’ utilises a combination of qualitative and semi-quantitative data to inform the framework, whereas a variety of complex and integrated qualitative data sets will be integrated to the ‘Developed Model’. Due to the availability and accessibility of informed qualitative data to Highways England the framework is currently restricted to the ‘Simple Model’.

This approach is also adopted by the Risk Management for Roads in Changing Climate Programme (2010) with the development of the RIMMAROCC Framework (Figure 2). This is discussed in greater detail within the Task 634 scoping study (Arup, 2015), but is referenced again to provide clarity on this approach.

Figure 2 – RIMMAROCC Framework



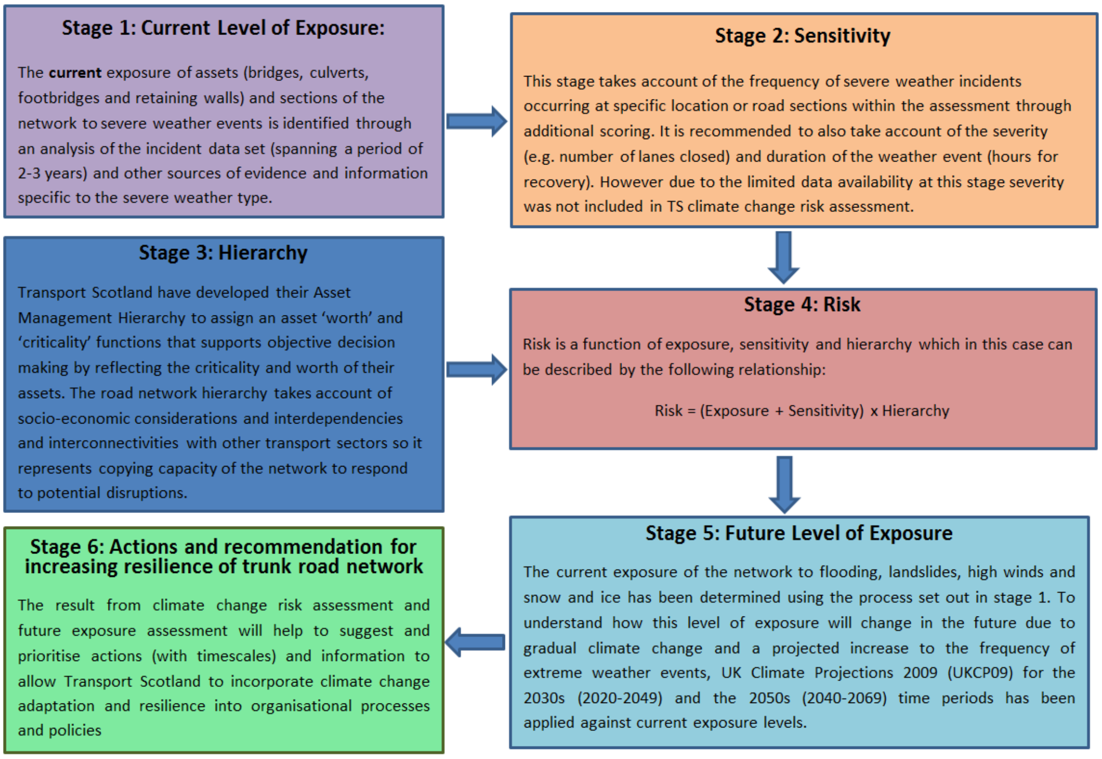
To ensure a consistent approach has been applied during the benchmarking exercise, the information is presented within two categories, which are reflective of the Simple and Developed models. The reviewed information and subsequent analysis is now presented within the next sections of this report.

4. Simple Model Benchmarking

4.1. Transport Scotland’s Climate Change Framework

A Transport Scotland climate change adaptation study is currently being undertaken by AECOM to comply with a variety of climate change legislation, identify methods of reducing the costs associated with climate related risks, and achieve cost and resource savings associated with emergency and reactive work following extreme weather events. The framework is presented in Figure 3. This framework is designed to assess vulnerability at a trunk road asset and network section specific level.

Figure 3 – Transport Scotland's Climate Change and Resilience Exposure and Risk Assessment



The frameworks are conceptually similar. The following key observations are made:

- The Transport Scotland approach considers previous events as an integral part of the vulnerability assessment process. The impact of these events is also included within Transport Scotland's wider assessment of event disruption, allowing for different levels of severity to be identified and ranked. This requires accurate and comprehensive incident data.
- The present level of exposure and risk to severe weather on the road network will change in medium and longer term (up to the 2050s). Within the Transport Scotland approach, thresholds are also applied against future climate change projections to assess and highlight which parts of the network are going to experience the greatest increase in vulnerability. This approach has proven effective and could be applied by Highways England.
- The Transport Scotland approach applies separate assessments for individual weather and impact types (i.e. flooding, snow and ice, high winds etc.), through the assessment of current levels of exposure.
- This approach allows for historical extreme weather events to be incorporated into the assessment, whilst integrating specific technical data and evidence, such as the use of Potentially Vulnerable Areas (PVAs)[1] as developed by the Scottish Environmental Protection Agency (SEPA).

1 PVAs are partly identified as areas at the greatest risk of being affected by flooding. They are also based on the following receptors: indicative number of inhabitants, types of economic activity (business and transport), designated protected areas and bodies of water, Integrated Pollution Prevention and Control installations (IPPC) and any protected area or body of water which could be affected by pollution from an IPPC.

4.2. World Road Association – International Climate Change Adaptation Framework for Road Infrastructure

The World Road Association's International Climate Change Adaptation Framework (WRA, 2015) for Road Infrastructure is an award winning framework developed by AECOM which guides road authorities through identifying relevant assets and climatic variables for assessment, identifying and prioritising risks, developing a robust adaptation response and integrating assessment findings into decision-making processes.

The framework was developed through extensive research and consultation with international road authorities. It synthesises best practice and knowledge available internationally to develop an effective and usable tool which can be used by any road authority irrespective of geographical, climatic, economic or environmental condition.

The framework includes the following four Stages:

- Stage One: Identifying scope, variables, risks and data;
- Stage Two: Assessing and prioritising risks;
- Stage Three: Developing and selecting adaptation responses and strategies; and,
- Stage Four: Integrating findings into decision making processes.

There are a number of examples of good practice from the World Road Association framework which could be incorporated in to the Highways England framework, for example:

- The World Road Association framework identifies that once vulnerability has been assessed, the existing adaptive capacity of a system should be evaluated. The assessment of adaptive capacity is qualitative and based upon a number of questions requiring professional judgement. From this high-level assessment, the varying levels of adaptive capacity can be categorised and incorporated into subsequent stages of climate change risk assessments.
- The World Road Association Framework also provides a more holistic and sustainable approach to prioritising climate change adaptation action, providing a framework for identifying, selecting and prioritising adaptation responses based upon resource availability, technical feasibility, economic viability, environmental responsibility and social acceptability. Methods including cost-benefit and multi-criteria analyses are also explored, with the development of an adaptation action plan being the final output of the process, allowing for ownership and a mechanism of measuring progress.

Finally, Stage Four of the World Road Association framework provides information on how the findings of such an assessment can be embedded within business-as-usual and how barriers can be overcome through training, education and development of business cases to promote buy-in. Such an approach ensures that the findings of an assessment are used in a proactive, strategic way to facilitate change and to enhance resilience.

4.3. 3CAP/ Midlands Highway Alliance Climate Change Adaptation Studies

The Midlands Highway Alliance (MHA) commissioned AECOM to undertake a study to identify, capture and share examples of how individual MHA authorities (and others across the UK) are taking action to understand and prepare their highway networks for the future impacts of climate change and an increased frequency and severity of severe weather events. This task followed a previous review of climate change impacts for the 3 Counties Alliance Partnership (3CAP – Derbyshire, Leicestershire and Nottinghamshire County Councils), which had the objective of identifying the 'Effects of Climate Change on 3CAP's Highways Network Policies and Standards'.

In the 3CAP study, a risk register was developed that ranked the level of climate change risk faced by seven policy areas (drainage, grass cutting, tree maintenance, winter service, resurfacing, materials, and bridges and other structures). This subsequently led to the development of a prioritised Adaptation Action Plan. In the study, risk was calculated as follows:

Risk Score = Impact x probability x influence

Where:

- **Impact:** The likely magnitude and severity of the impact, if it were to occur.
- **Probability:** The probability of an impact occurring based on climate change projections and evidence of recent impacts of this nature.
- **Influence:** Level of responsibility and influence that the organisation (local authority in this case) has over the risk and associated responses.

Assessing the influence and responsibility of an organisation on the potential impacts of climate change on networks or assets, adds an additional layer of complexity to an assessment, and allows for those risks where an organisation can most easily take action to reduce the risk to be prioritised above those where the organisation has little or no control or responsibility. This can facilitate 'quick wins', whereby resilience measures that are wholly introduced and managed by the organisation are more easily identified and prioritised for implementation. Adding this consideration into the Highways England assessment process would allow for Highways England's influence and level of responsibility to be better integrated in the risk scoring and resilience measure assessments.

Adaptation Scotland's '5 Steps to Managing Climate Risk' was assed as part of the development of this benchmarking report, and was also highlighted and applied in the MHA/ 3CAP study. Adaptation Scotland, in collaboration with public bodies from across Scotland, identified the 'Five Steps' as follows:

- Getting Started;
- Understand the impacts of climate change;
- Identify and prioritise actions;
- Tack action; and,
- Monitor, review and evaluate.

Whilst the framework is similar in its approach to measuring and managing climate risks to the other frameworks and mechanisms identified within this review, there is a strong focus on monitoring, reviewing and evaluating climate change adaptation responses, including the importance of lessons learnt. It will be essential for the Highways England framework to consider 'next steps' after comprehensive assessments have been undertaken to ascertain varying risk levels of assets and systems.

This study could be further reviewed to identify examples of good practice for specific climatic variables, as and when they are highlighted through the Highways England framework assessment.

4.4. Highways England Flood Severity Index

The Highways England Flood Severity Index is used to determine the severity of the impact of a flood upon a carriageway. The Index can be used for any network incident as the data inputs required are not tailored towards specific incident variables, as follows:

• Impact on Traffic (e.g. total road closure, only one lane closed, congestion only)	Factor A (0<A<1)
• Duration of Impact (less than 15 minutes not considered significant)	Factor B
• Road classification	Factor C
• AADT for one carriageway	Factor D
Flood Severity Index: A * B * C * D * 10	

Once a Flood Severity Index has been calculated, outputs can be input into the following table to derive overall flooding hotspot risk status. It should be noted that the use of the rule 'The hotspot is not within an EA flood risk zone' could be removed to facilitate the methodology being used with alternate weather and impact variables and/or incident types beyond that of flooding.

	Overall Flooding Hotspot Risk Scores (Defined by the most severe of that determined by the severity index or the third party impacts)		
	Number of flood events within the hotspot		
	>5	2 to 5	0 to 1
The hotspot is within an EA flood risk zone			
Severity index of most severe flood			
7 to 10	A (Very High)	A (Very High)	A (Very High)
3 to 6	A (Very High)	A (Very High)	B (High)
0 to 2	B (High)	C (Moderate)	D (Low)
No history of flooding	D (Low)	D (Low)	D (Low)
Most severe third party impact			
Residential or critical infrastructure	A (Very High)	A (Very High)	B (High)
Commercial	A (Very High)	B (High)	C (Moderate)
Agricultural	B (High)	C (Moderate)	D (Low)
None	D (Low)	D (Low)	D (Low)

The Flood Severity Index was developed to facilitate the following benefits to flood risk management (which could be replicated for other vulnerabilities and risk types):

- Established method for recording floods;
- Reporting on effects of individual floods;
- Regular reporting on all floods;
- Prioritisation of resources to worst affected locations; and,
- Established method for implementing mitigation.

It should be noted that the Flood Severity Index is slightly disadvantaged in that it offers a reactive approach yet this is offset by its suitability for application in areas of poor asset knowledge.

5. Developed Model Benchmarking

Although the Developed Model is dependent on more complex data sets, four key areas have been identified for further development, to ensure a comprehensive framework is applied. These are discussed in more detail in the following sections, and include;

1. Enhance intelligence for future climate change and transport projections;
2. Establish and quantify values and cost benefit of resilience measures;
3. Identify and integrate interdependencies; and
4. Consider implementation during initial design and upgrades.

5.1. Enhance intelligence for future climate change and transport projections

To improve the applicability to climate change hazard as well as severe weather hazard, consideration could be given to estimated traffic volume and climate change projections. Estimates indicate that there could be a 60% increase in traffic volumes on the Strategic Road Network (SRN) by 2040 (DfT, 2015), compared to 2010 figures. This will directly and indirectly impact the SRN, both through increased pollution, more delays, and the associated negative impacts of increasing traffic flows on assets (including geotechnical assets).

We are also aware that Task 694, Risk-based Serviceability Indicator, is also investigating the risk criticality and associated consequences of asset failures. This will establish and quantify the impact on road users, their safety, on the environment and the strategic impact.

Likewise, climate forecasting is becoming more accurate as science and technology continue to develop more complex forecasting tools. UK Climate Projections 2009 (UKCP09) predict that the UK will experience more extreme and varied climatic conditions, which will result in more frequent and intense severe weather events. The accuracy of this information will be further developed when the UK Met Office released the updated suite of climate models and projections in 2018 (UKCP18). UKCP18 will enhance the information on climatic projections for the UK, and should be considered a useful source of data for the risk framework. For example, there will be the potential for use of 1km spatial resolution projections when assessing linear assets. Within recent international conference proceedings issued by the Transport Research Board (2016), delegates are noted as stating that ‘climate information needs to be translated into data that practitioners can understand and use', and so should therefore be embedded with risk and decision making frameworks.

It is therefore recommended that future development of the geotechnical asset resilience framework incorporates more precise information on future weather, demand and criticality projections.

5.2. Establish and quantify values and cost benefit of resilience measures

The Task 580 report (Arup, 2010) indicates that Highways England spend an estimated £20m annually on repairing slop instabilities, which has likely increased considering the current levels of investment and inflation. A presentation from Shannon and Wilson Inc. (2012) suggests that the benefits of effective geotechnical asset management and resilience for railroad and motorway embankments can include life-cycle costs savings of 60% – 80%. Their presentation also focusses on the indirect costs associated with geotechnical failures on communities in North America, and states that 'failures of geotechnical features have resulted in environmental damage (water quality, aesthetics, habitat etc.), significant repair costs, and even larger economic costs to corridor users and communities'. They quantify the costs of a number of geotechnical asset failures which occurred in North America, and two examples are listed below in Table 1.

Table 1 – Geotechnical Asset Failure Economic Impact

Ferguson Slide California	Tennessee & North Carolina Rock Slides
• 92 day closure on direct route to Yosemite • $4.8m in business losses • $8m short-term repair costs • $18m – $37m long-term (dependent on EIS)	• 6 month closure of an Interstate and US Highway • 30 to 90% reduction in restaurant, lodging and retail revenue • Estimated $197m cost due to increased vehicle operation, detour travel time, emissions, congestion, and pavement maintenance on alternative routes

Their risk model requires each geotechnical feature to be recognised, and the necessary actions and consequences identified. The likelihood of asset failure is then established, which forms the basis of the quantification of the required mitigation. This is then analysed against the expected cost after the improvement is applied/constructed in relation to the adopted improvement, and should be aligned with other relative performance measures, e.g. safety, cost and traffic flow. This approach is summarised within Table 2.

The associated route corridor where the geotechnical asset is located forms a crucial element to the assessment also, but this is addressed in more detail within Section 5.3.

Table 2 – Geotechnical Asset Cost Benefit Analysis (example from Shannon and Wilson Inc. (2012)

Feature	Action	Consequence	Annual Probability	Cost for Year of Improvement	Expected Annual Cost After Improvement
Landslide	No Improvement	**Mobility:** Long term lane loss **Economic:** Revenue loss for corridor **Preservation:** Pavement Damage	40%	$870,000	$870,000
	Install Ground Anchors		1%	$3,021,750	$21,750
	Install Groundwater Drains		5%	$608,750	$108,750
Rockfall Site	No Improvement	**Safety:** Fatality and injury of public **Economic:** Litigation and public perception	90%	$663,750	$663,750
	Scale Slope		60%	$842,500	$442,500
	Scale Slope and Install Rockfall Fence		25%	$2,184,375	$184,375

A regularly overlooked, but critical function, when prioritising resilience investment is to establish and understand the cost benefit of adopting mitigations to reduce the likelihood of incidents occurring. Therefore, it is suggested that the Highways England risk framework should provide a mechanism to quantify the economic impact of geotechnical asset failures, which include the costs related to the mitigation investment required. This could facilitate increased 'buy-in' from operational teams and senior decision-makers.

5.3. Identify and integrate interdependencies

Chapman (2015) indicates that 'cross-sectoral interactions add significant complexity to a risk assessment, but where these interactions lead to interdependencies they can be a cause of significant increased risk across several sectors'. The SRN is ultimately the key critical link between all modes of transport, which further exacerbates the variety of interdependencies.

Likewise, NERC (2015), explains that 'consideration of individual events is no longer adequate and future infrastructure design must take into account a much wider set of current and potential future hazards'. Shah (2014) also states that 'we live in a world where failure of one asset may directly (or indirectly) lead to the failure (or breakdown) of a set of surrounding assets, ultimately leading to failure of an entire section of the network'.

Recent events in the UK, such as the flooding in Cumbria in 2015 and the severe winter of 2013-14, have shown that infrastructure systems are increasingly dependent on each other, and incidents can have a disruptive and damaging cascade effect. A variety of incidents can impact infrastructure assets including short and intense or longer term incidents, or those that involve a number of hazards failing in unison.

Highways England's geotechnical assets can also host a variety of components for other infrastructure systems, including phone lines, power cables and drainage systems which all rely on the geotechnical asset in which they are located not failing. The presence of these systems within and parallel to geotechnical assets can also increase the risks and vulnerabilities to these assets. This could therefore form a focal element of the Developed Model, particularly to ensure a holistic approach to informing the geotechnical asset resilience.

It is therefore going to be increasingly critical that the framework actively considers the relationships of associated failures and the interconnectedness of all accompanying infrastructure systems, for example, as currently considered to an extent in the Geotechnical Maintenance Forms. This should also inform an analysis of the off network route corridors which are designated emergency diversion routes. For this to be effectively achieved the correct working group or combination of groups will need to be identified, such as members of the Severe Weather, Resilience, Climate Change and external stakeholder teams.

5.4. Consider implementation during initial design and upgrades

The Roads Investment Strategy sets out the £15.2 billion planned investment in the UK road network over the period of 2015 – 2020. This investment will enhance, renew and improve the network. Additional lane miles will be developed, the network will become more accessible and safer, and a core focus is reducing those killed or seriously injured.

As stated by Bles *et. al*. (2016), the CEDR 2012 Climate Change Call for Research indicated that 'road authorities need to evaluate the effect of climate change on the road network and take remedial action concerning design, construction and maintenance of the road network'. The prioritisation of measures in order to maximise availability with reasonable costs is one of the most important tasks of the road owners', and aligns with the Highways England strategic objectives and operating procedures.

Furthermore, a post-doctoral thesis on Resilient Geotechnical Asset Management, Shah (2014), discusses the integration of a geotechnical resilience framework at the initial design stage. This takes a proactive approach to resilience by integrating resilience into asset design, rather than addressing the vulnerability when it is identified. This essentially facilitates a number of whole life efficiencies and can help to prolong the asset life. The concepts can be implemented on existing assets but the core theme of this research was for the design of new assets.

Increasing the resilience of Highways England's geotechnical assets could be done through adopting and implementing the resilience framework at the initial design stage, and/ or when upgrade works are being completed.

This could lead to reduced requirements for regular and reactive maintenance, which would result in cost savings and efficiencies. Additionally, this could assist with identifying and further developing intelligence on the interactions and relationships between assets.

6. Conclusion

This benchmarking exercise was completed as part of the Discovery Phase of Task 1-085 (Geotechnical Resilience Enhancement Measures). It assesses the framework developed during Task 634 against other relevant industry approaches and information.

Generally the qualitative and semi-quantitative approach adopted by the Simple Model conforms to existing practices within industry. It has been analysed against approaches taken by Transport Scotland, and others, and reviewed against the approach within existing Highways England documents, such as the Highways England 2016 Climate Adaptation Risk Assessment, the Crisis Management Manual and their 2015 – 2020 Strategic Objectives to ensure consistency. Inconsistencies with some of the terminology have been identified, and are discussed in a separate, but complementary document.

Similarly the Developed Model is fit for purpose but could benefit from further inclusion of additional quantitative data sets to establish more informed decisions. The first recommendation is for greater involvement of future climate projections within the framework. Although this is recommended within this report we understand that an additional Highways England project, Task 694, is reviewing and establishing this information which will facilitate this in the future, once incorporated.

Task 694 can also assist with the development of the establishing and quantifying the values and cost benefit of implementing resilience measures to reduce the impact of geotechnical failures on the network, which has also been recommended.

The benchmarking exercise also identified the requirement for interdependencies to be identified and integrated, which are associated with urbanisation, which will result in reduced risk through informed analysis of the associated risks.

The final recommendation was for the framework to be considered at the initial design phase and during upgrade works to proactively implement resilience.

These four areas require more complex analytical solutions and more detailed data sets, which aren’t easily implemented at present, but Highways England should consider and understand these going forward. There are also a number of ongoing tasks and will likely be further research completed on these areas so it will be critical for Highways England and their suppliers to the be aware of the historical research and any future recommendations to ensure a consistent approach is achieved.

REFERENCE LIST

Arup (2010) Task 580 – A risk-based framework for geotechnical asset management: Phase 2 Report, November 2010.

Arup (2015) Task 634 – Resilience of geotechnical assets on the Strategic Road Network to severe weather events: Phase 1 Scoping Study, December, 2015.

Arup (2016) Task 634 – Resilience of geotechnical assets on the Strategic Road Network to severe weather events: Phase 2 Final Report, May, 2016.

Bles, T., Bessembinder, J., Chevreuilc, M., Danielsson P., Falemo S., Venmans, A., Ennesserc, Y., and Löfroth H. (2016) Climate Change Risk Assessments and Adaptation for Roads – Results of the ROADAPT Project. Accessible from < http://www.sciencedirect.com/science/article/pii/S2352146516300412 >

Chapman (2015) A Climate Change Report Card for Infrastructure, Transport: Road transport (inc. cycling and walking). Accessible from < http://www.nerc.ac.uk/research/partnerships/ride/lwec/report-cards/infrastructure-source02/>

Department for Transport (2015) Road traffic estimates Great Britain 2014, Revised December 2015. Accessible from < https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/487689/annual-road-traffic-estimates-2014.pdf >

Highways Agency (2009) Climate Change Adaptation Strategy and Framework. Accessible from < http://assets.highways.gov.uk/about-us/climate-change/CCAF_Strategy_and_Vol_1_Rev_B_Nov.pdf >

Highways England (2016) Climate Adaptation Risk Assessment Progress Update – 2016

Highways England (2016) Crisis Management Manual 2016, Version 2.0

Highways England (2015) Highways England Delivery Plan 2015-2020, Accessible from < https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/424467/DSP2036-184_Highways_England_Delivery_Plan_FINAL_low_res_280415.pdf>

Meteorological Office (2016) UK Climate Projections, UKCP 18. Accessible from < http://www.metoffice.gov.uk/services/climate-services/uk/ukcp>

NERC (2015) Infrastructure Climate Change Impacts Report Card 2015. Accessible from < http://www.nerc.ac.uk/research/partnerships/ride/lwec/report-cards/infrastructure/ >

Risk Management for Roads in Changing Climate (2010) A guide to the RIMAROCC Method. Accessible from < http://www.cedr.fr/home/fileadmin/user_upload/en/Thematic_Domains/Strat_plan_3_2013-2017/TD1_Innovation/I1_Research/TGR_TPM/Transnational_calls/2008%20Call%20Road%20Owners%20Getting%20to%20Grips%20with%20Climate%20Change/RIMAROCC/01_Rimarocc%20Guidebook.pdf >

Shah, J. P. (2014) Resilient Geotechnical Asset Management . Accessible from > http://etheses.bham.ac.uk/6644/1/Shah16PhD.pdf >

Shannon & Wilson Inc. (2012) Incorporation of Geotechnical Elements as an Asset Class within Transportation Asset Management and Development of Risk Based and Life Cycle Cost Performance Strategies. Accessible from < http://onlinepubs.trb.org/onlinepubs/conferences/2012/assetmgmt/presentations/Geotechnical-Vessely-DeMarco-Barrows.pdf >

The Scottish Government (2009) Scotland's Climate Change Adaptation Framework. Accessible from < http://www.gov.scot/Resource/Doc/295110/0091310.pdf >

Transport Research Board (2016) Surface Transportation System Resilience to Climate Change and Extreme Weather Events First International Conference.

WRA (2015). International Climate Change Adaptation Framework for Road Infrastructure. Accessible from < https://www.piarc.org/en/order-library/23517-en-International%20climate%20change%20adaptation%20framework%20for%20road%20infrastructure.htm >

APPENDIX 2– Review of Terminology and Definitions

Terminology: Task 1-085 Geotechnical Resilience Enhancement Measures

Clarified Terminology

Through a review of previous Highways England project outputs relating to geotechnical asset resilience, and the processes and terminology used in the following documents and sources, a clarified terminology for the assessment of the resilience of geotechnical assets has been developed.

- Defra (2011) Climate Resilient Infrastructure: Preparing for a Changing Climate[6];
- Transport Scotland's climate change adaptation and resilience study (currently ongoing and being delivered by AECOM)[7];
- Highways England (2009, 2011 and 2016) Climate Change Adaptation Framework and Risk Assessments[8],[9],[10];
- Committee on Climate Change – Climate Change Risk Assessment (2017)[11];
- Lexicon of UK Civil Protection Terminology - Version 2.1.1, February 2013[12];
- Highways England Crisis Management Manual, v2.1 (2016);
- Natural Hazards Partnership Hazard Impact Framework[13];
- Landslide Risk Assessment: Second Edition. ICE Publishing (2014)[14].

The clarified terminology is as follows:

Term	Definition
Adaptation	Actions to reduce the vulnerability of natural and human systems or to increase systems resiliency in light of potential or expected hazards.
Asset Health	The current asset state, in terms of condition and age, and inherent properties that influence an asset's ability to fulfil its function.
Impact/Consequence	These terms are interchangeable and define the extent of the adverse effects or benefits arising from the realisation of a **hazard**. This may include harm, damage or losses to people, systems or property, and/or disruption to the environment and/or to economic, social and political structures. The impact of an asset loss of function is a function of the **criticality** of the affected location, and how badly the asset is affected (its **vulnerability**).
Criticality	The function and importance of an asset or network location in delivering Highways England's strategic objectives – focusing on

[6] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/69269/climate-resilient-infrastructure-full.pdf
[7] Ongoing work by AECOM
[8] http://assets.highways.gov.uk/about-us/climate-change/CCAF_Strategy_and_Vol_1_Rev_B_Nov.pdf
[9] http://assets.highways.gov.uk/about-us/climate-change/HA_Climate_Change_Risk_Assessment_August_2011_v2.pdf
[10] https://www.gov.uk/government/publications/climate-adaptation-reporting-second-round-highways-england
[11] https://www.theccc.org.uk/tackling-climate-change/preparing-for-climate-change/climate-change-risk-assessment-2017/
[12] https://www.gov.uk/government/publications/emergency-responder-interoperability-lexicon
[13] http://www.naturalhazardspartnership.org.uk/hazard-impact-framework/
[14] Lee, M., and Jones D.K.C., (2014). Landslide Risk Assessment: Second Edition. ICE Publishing

	the themes of safety, capacity, environment, customers and efficiency.
Exposure	Exposure provides an important link between hazard threat and consequence. Exposure encompasses two issues: • The spatial extent to which the receptor(s) are exposed to a hazard (spatial exposure) • The amount of time that receptor(s) are exposed to a hazard (temporal exposure)
Failure	(1) Failure of an asset to fulfil its required duty (2) Reaching a Limit State.
Frequency	The number of occurrences of a hazard within a given unit of time.
Hazard	Accidental or naturally occurring event or situation with the potential to cause harm, damage or losses to people or property, and/or disruption to the environment and/or to economic, social and political structures[15].
Likelihood	The possibility that a specific event will occur. Often measured quantitatively; as probability (out of 1), as chance (as a percentage) or as a frequency (per set period of time). May also be expressed using qualitative terms.
Receptor	Receptors are the assets/ people/ properties/ networks/ land that may be impacted by a hazard. The locations of the receptors are used to calculate exposure[16],[17]. The features of the receptors are used to consequence, via susceptibility.
Resilience	The ability of assets, networks and systems to anticipate, absorb, adapt to and/or rapidly recover from a disruptive event[18]. Resilience is secured through the four principal strategic components of: Resistance, Reliability, Redundancy and Response & Recovery[19].
Risk	Risk represents the likely occurrence, scale and magnitude of impact arising from the occurrence of a hazard. Risk is a function of the impact (or consequence) and the likelihood of that impact occurring.
Susceptibility	Inherent and external features of an asset which, if exposed to a hazard, may result in performance issues. These features can include inspected condition (as per HD41/15), inherent factors (e.g. geotechnical special measures), asset health, composition of the asset (materials etc.), interdependent or interconnected infrastructure (such as utilities), and traffic flow on surrounding part of the network.
Vulnerability	Vulnerability describes how severely a receptor (or set of receptors) is affected by a hazard. Asset vulnerability refers to the effect a

[15] https://www.gov.uk/government/publications/emergency-responder-interoperability-lexicon
[16] https://www.theccc.org.uk/tackling-climate-change/preparing-for-climate-change/climate-change-risk-assessment-2017/
[17] http://www.naturalhazardspartnership.org.uk/hazard-impact-framework/
[18] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/69269/climate-resilient-infrastructure-full.pdf
[19] http://www.naturalhazardspartnership.org.uk/hazard-impact-framework/

	hazard can have on a specific asset; network vulnerability refers to the effect a damaged asset can have on the wider network, which considers the criticality of the affected location.

APPENDIX 3– SWIS Rain Forecasting Screenshots

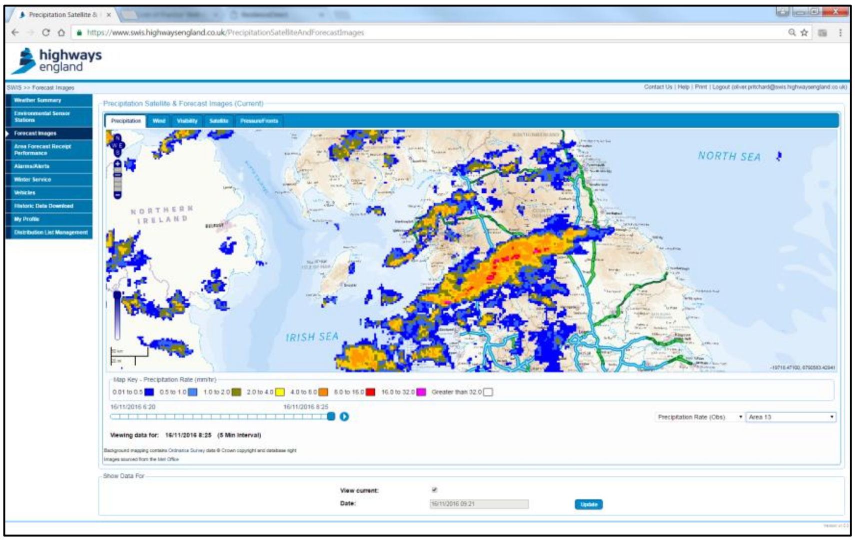


Figure A-1: Forecasted precipitation rate (mm/hr) as viewed in SWIS

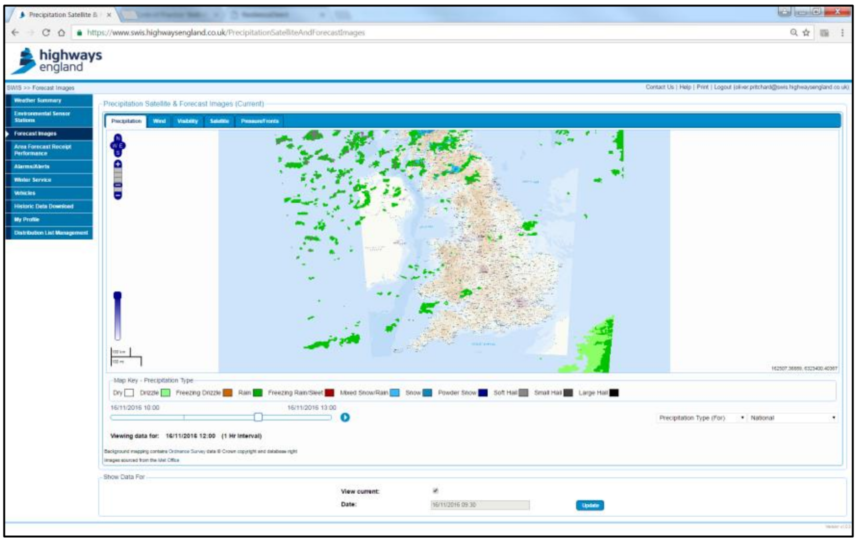


Figure A-2: Forecasted precipitation type as viewed in SWIS

APPENDIX 4 – Vulnerable Location Template

Vulnerable Locations			
Location	**Reference** *To individual mitigation plan*	**Problem**	
		Type	**Very brief summary**
[Road No. and marker post]	**Plan 1**	Heavy Snow 	
[Road No. and marker post]		Low Lying Fog 	
[Road No. and marker post]		Heavy Rain 	
[Road No. and marker post]		Ice 	
[Road No. and marker post]		High Winds 	
[Road No. and marker post]		Airport 	

APPENDIX 5 – Frequency and intensity of forecast information

.Field	Frequency	Data Intensity
Morning Summary	06:00 Daily	Single Field
24 Hour Forecast (Text)	Operational Winter Period: 06:00, 12:00 and 18:00 Daily Operational Summer Period: 06:00 Daily	Single Field
24 Hour Forecast (Domains)	Operational Winter Period: 06:00, 12:00 and 18:00 Daily Operational Summer Period: 06:00 Daily	For each domain, daily.
2-10 Day Forecast	12:00 Daily Operational Summer Period: 06:00 Daily	Day 2 to 5 – Area based, daily Day 6 to 10 – Single Field
Site Specific Forecast	Operational Winter Period:12:00 Daily Operational Summer Period: None	For each domain, hourly.

APPENDIX 6 – Forecast parameters required for summer and winter

Forecast Parameter	Winter	Summer
Minimum road surface temperature	✓	✗
Maximum road surface temperature	✗	✓
Minimum air temperature	✓	✗
Maximum air temperature	✗	✓
Dew point / Relative humidity	✓	✗
Surface state	✓	✗
Wind speed (various)	✓	✓
Wind direction	✓	✓
Accumulations of snow (depth)	✓	✗
Visibility	✓	✓
Pollen count	✗	✓
UV factor	✗	✓
Snow level (ht above sea level)	✓	✗
Hazard – Ice	✓	✗
Hazard – Heavy Rain	✓	✓
Hazard – Freezing Rain	✓	✗
Hazard – High Temperature	✗	✓
Hazard – Hoar frost	✓	✗
Hazard – Fog	✓	✓
Hazard – Snow	✓	✗
Alert Level	✓	✗

APPENDIX 7 – Vulnerable locations identified in severe weather plans

Table A-1: Vulnerable locations highlighted in Severe Weather Plans (note: there may be duplicated locations dependent on vulnerabilities identified)

Area	Number of vulnerable locations	Directly Weather-related							Non directly weather-related				
		Low Sun	Heavy Rain	Ice/ Snow/ Hail	Mist and Fog	Flooding	High Wind	Heat	Gradient	Radii	Interdependent networks/assets	Technology	Landslip /subsidence
1	13	0	2	6	1	0	1	1	0	0	Many (consideration given to diversion routes)	0	0
2	47	0	0	13	3	10 (including seepage and run-off)	5	0	15	7	4 (Avonmouth and Portbury Docks; Exeter Airport; carriageway distortion)	0	0
3	13	0	1	12	0	0	0	0	0	0	0	1 (Hindhead Tunnel)	0
4	26	0	0	14	3	3	7	0	0	0	7 (Port of Dover; Channel Tunnel; Operation	0	0

Area	Number of vulnerable locations	Directly Weather-related							Non directly weather-related				
		Low Sun	Heavy Rain	Ice/ Snow/ Hail	Mist and Fog	Flooding	High Wind	Heat	Gradient	Radii	Interdependent networks/assets	Technology	Landslip /subsidence
											Stack; Bluewater shopping; Channel Tunnel)		
5	66	0	25	38	0	0	2	0	0	0	1 (Gatwick Airport)	0	0
6	36	0	0	18	0	10 (including seepage and run-off)	1	4	7	0	3	0	0
7	16	0	6	7	2	0	0	0	0	0	1 (East Midlands Airport)	0	0
8	12	0	1	9	0	1	0	1	6	0	1 (Luton Airport)	0	0
9	55	4	0	15	13	20	8	0	9	0	3 (Manchester & Liverpool Airports; Seaforth Dock)	0	0

Area	Number of vulnerable locations	Directly Weather-related							Non directly weather-related				
		Low Sun	Heavy Rain	Ice/ Snow/ Hail	Mist and Fog	Flooding	High Wind	Heat	Gradient	Radii	Interdependent networks/assets	Technology	Landslip /subsidence
10	37	0	21	17	0	0	0	0	0	0	0	1	0
12		0	0	0	0	0	0	0	0	0	0	0	0
13	5	0	3	2	1	0	2	0	0	0	0	0	0
14	4	0	0	3	0	1	1	0	0	0	0	0	0
29	1	0	0	1	0	0	0	0	0	0	0	0	0
30	9	0	1	4	1	0	1	0	1	0	2 (Hard Shoulder running required)	0	0
31	10	0	0	5	1	0	0	0	0	0	4 (Queuing/slow traffic)	0	0
Total		4	60	164	25	45	28	6	38	7	26	2	

APPENDIX 8 – M2 J 5-6 Vulnerable Location Schedule

VULNERABLE LOCATIONS SCHEDULE	
Reference Number: VL A4 – 21	
Location	M2 Jct 5-6
Problem	Susceptible to sudden ground surface subsidence
Is the problem particularly HGV related (Yes / No)	No
Has this site experienced problems before or is it an identified risk?	Recent history of subsidence from sinkholes and deneholes from the 1990s to 2014. Subsidence appears to occur at approximately 5-6 year intervals, but is heavily influenced by prolonged and severe rainfall. This location is identified as a medium geotechnical risk in the Geotechnical Asset Management Plan and appears on the Area 4 Asset Risk Register.
Detailed Mitigation Measures	
When enacted	Due to the nature of the defects the subsidence will occur suddenly and is most likely to be identified by an MRT or safety inspection.
Who enacts	MRT and Operations Team implement immediate response.
Who will manage the response	Gold command
Are diversion routes to be used?	If the live lanes are affected then diversion may be required. Likley to require A249 to M20 J7, M20 to Junction 9 then A251 to M2 J6 (or A28 to A2?)
Pre-deployment of resources	No
Use of VMS	Use of Motorway VMS
Other measures put in place	No
Assistance from Service Provider resources	Geotechnical Asset Champion and members of the Geotechnical Team. Construction Team.
Assistance from additional Highways England resources	Netserv – Jan Marsden, Senior Geotechnical Advisor
Assistance from External Sources	Concept Consultant and/or CET (ground investigation contractors)

APPENDIX 9 – Climate Change Risk Assessment – Vulnerabilities and Adaptation Progress Tables (Highways England, 2016)

Activity category	Area	Aspect	Primary climatic changes	Secondary impacts of climate change	Highways England risks resulting from identified climatic changes	Score	Adaptation action	Progress of action
Maintenance and management of existing assets	Geotechnics	Increased scour and erosion of earthworks	Increase in winter precipitation Increase in extreme precipitation	Flooding	There is a risk to the geotechnics asset of scour and erosion resulting from flood waters.	0.22	**Do minimum** Erosion of existing earthworks is insignificant at present with only a few isolated examples. Any potential increase due to increased precipitation is likely to be limited and will be identified during the regular earthworks inspections linked to work being undertaken with respect to flooding hotspots on the network. Geotechnics MM05 - Increased scour and erosion of earthworks	N/A
Maintenance and management of existing assets	Geotechnics	Stability of slopes, change in water levels/pore pressure	Increase in extreme temperature Increase in winter precipitation	Flooding Change in ground water level	In the maintenance and management of existing geotechnical assets, the risks to the stability of slopes from flooding include: Increased erosion and instability at the base of embankments. The risks to slope stability from increased precipitation are linked to increased pore pressures/water levels which can give rise to a reduction in the factor of safety and a greater risk of instability.	0.11	**Do minimum** Slope stability is well understood. Existing regular inspections are sufficient. Geotechnics MM06 - Stability of slopes, change in water levels/ pore pressure	N/A
Maintenance and management of existing assets	Geotechnics	Drainage ditches	Increase in winter precipitation Increase in extreme precipitation		Risk of volume of water exceeding the capacity of ditches.	0.22	This aspect is considered as part of drainage. Drainage MM08 - Capacity of drainage system	N/A

Activity category	Area	Aspect	Primary climatic changes	Secondary impacts of climate change	Highways England risks resulting from identified climatic changes	Score	Adaptation action	Progress of action
Maintenance and management of existing assets	Geotechnics	Earthworks construction across existing landslip	Increase in winter precipitation Increase in extreme precipitation	Change in ground water level	This represents a very limited part of the asset. The risk here relates to a reduction in the factor of safety and higher probability of instability.	0.33	**Do minimum** Such locations are rare on the network. Each Managing Agent should assess the specific situation as part of their regular HADGMS inspection and risk assessment. It is very difficult to predict the effect of increased precipitation and, more importantly, identify the need for pro-active measures to address any perceived risk. Geotechnics MM07 - Earthworks construction across existing landslip	N/A

APPENDIX 10 – Coal Mining Hazard Guidance Note (October, 2016)

Coal Mining Hazard on the Strategic Road Network of England

This note provides context and guidance to accompany the Coal Mining Hazard map on HAGDMS. The two products (note plus map) should provide those responsible for maintaining and improving the Strategic Road Network (SRN) with **an improved understanding of the potential for coal mines to impact the safety or performance of the network**, and provide **additional guidance to support decision making as to appropriate risk mitigation measures**. This should not replace the need for local and site specific assessment. Of the mining-related hazards present on the SRN, coal mining is the most prevalent, and historic coal mining presents the most significant hazard, for the reasons set out below.
A detailed commentary on the history, geography and hazards presented by, coal mining in the UK can be found in the CIRIA publication SP32 (1984) which is currently being updated (see www.ciria.org for further details).

Part I Highways England's approach to managing coal mining risks

Coal has been mined in the United Kingdom since Roman times (or even earlier), and has left a legacy of past activity across a large proportion of Highways England's network. The history of coal mining and its impact on the SRN is summarised in Part III. The risk presented by the legacy of coal mining is not new to Highways England. Any new assessment of the risk should make due consideration of the following factors:

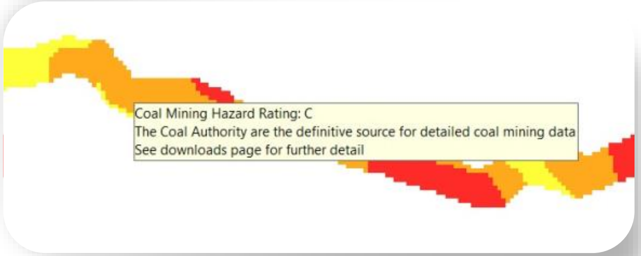
- At the time of construction of the SRN or at the time of undertaking improvement schemes, coal mining hazard, and related risks would have been investigated and mitigated appropriate to the Standards or Advice that applied at the time.
- The Geotechnical Risk Management Procedures were introduced in the 1990s. Specifically, HD22 (Managing Geotechnical Risk) was first published within the Design Manual for Roads and Bridges (DMRB) in 1992. It is therefore reasonable to assume an improvement in completeness and effectiveness of studies, investigation and mitigation works related to Improvement Schemes post 1992.

1.0 Current ground risk management requirements:

HD22/08 (DMRB Volume 4.2) presents a framework for geotechnical risk management and is a mandated requirement on all highway schemes where a ground investigation or geotechnical design is required. It establishes the principles of early risk identification and continuity of the geotechnical risk register through the project life cycle from concept to handover.
HD41/15 (Maintenance of Highway Geotechnical Assets) provides guidance on the identification and management of 'At Risk Areas' (Class 2 features) including those related to areas of potential mining instability. Consideration of the hazard posed by coal mining to the existing SRN should form a part of the GeoAMP (Geotechnical Asset Management Plan) process. The GeoAMP is prepared by the Operations service provider, reviewed on an annual basis (at a timeframe agreed with Highways England), and is submitted for agreement by HE.
For guidance on the application of current requirements please refer to the Advice contacts below.

2.0 The Highways England Coal Mining Hazard Map

An HE specific Coal Mining Hazard Map for a 1km corridor centred on the Strategic Road Network has been prepared. This can be accessed on the HA GDMS (HE Geotechnical Data Management System) and on HAGIS (HA Geographical Information System). This initial version of the hazard map is a synthesis of information relating to coal mining obtained in 2010 from the Coal Authority. Later revisions will consider further information, from the Coal Authority and other providers. The means of derivation of this initial map is explained in detail in a companion note available on the HA GDMS download page (HAGDMS Coal Mining Hazard Rating data description (Sep 2016)).



The map is intended as a high level hazard awareness map only. It **does not** replace the need to seek expert advice from within Highways England, or from the Coal Authority. As noted above, consideration of coal mining and other mining related instability is an inherent part of Highways England's geotechnical standards.

3.0 Further advice

To obtain further advice on the hazard coal mining poses to the Strategic Road Network, or for any other issues associated with ground-related hazards, please contact one of the Geotechnical Advisors available within Highways England's Geotechnics and Pavement Group.

Highways England Geotechnical Advisor	Area of responsibility	Contact E-mail address
Mark Shaw	Areas 1&2	Mark.Shaw@highwayseengland.co.uk
Jamie Codd	Areas 6 & 8	James.Codd@highwaysengland.co.uk
Jan Marsden	Areas 3,4	Jan.Marsden@highwaysengland.co.uk
Raphael Lung	DBFO Area 5	Raphael.Lung@highwaysengland.co.uk
Dennis Sakufiwa	Areas 7,9	Dennis.Sakufiwa@highwaysengland.co.uk
Richard Shires	Areas 10,13	Richard.Shires@highwaysengland.co.uk
Lesley Benton	Area 12	Lesley.Benton@highwaysengland.co.uk
Shaun Clarke	Area 14	Shaun.Clarke@highwaysengland.co.uk
The Coal Authority	All	thecoalauthority@coal.gov.uk 0345 7626848 (Monday-Thursday 0845-1700, Friday 0845-1630)
The Coal Authority surface hazards emergency service	All	24 hour number for reporting public safety hazards and incidents associated with coal mining 01623 646 333

Role of Highways England's Geotechnical Advisors:

- Technical oversight of schemes, to ensure the technical input is appropriate, complies with HE standards and delivers good value.
- Cascading local knowledge and good or bad experiences from other projects
- Evaluating and supporting innovation opportunities to promote efficient delivery.
- Providing asset data and information management services
- Managing knowledge improvement for the geotechnical discipline, including Standards and Advice Notes and supporting Integrated Asset Management in Highways England.

Part II Using the Coal Mining Hazard Map in a Risk Management Framework

Resilience of the Strategic Road Network comes from both adequate design and mitigation of hazards, and having appropriate response and recovery measures in place should the hazard event materialise. Selection of appropriate mitigation (pro-active, pre-event) measures versus response and recovery (reactive, post-event) cannot be prescriptive, but the guidance below can be used to support risk-based decision making.

1 Define the Hazard Event

There are different hazard events related to the presence of coal mines below the SRN, and these present different risks to the network. A hazard event can be defined as 'the event that could occur due to the presence of the hazard'. For example:

- Collapse of a *very* shallow mine working (may be either sudden or progressive)
- Collapse of a shallow mine working (may be either sudden or progressive)
- Subsidence related to presence of deep mines (typically progressive)
- The collapse of a mine shaft or mine adit (typically sudden)

2 Consider potential external triggers of the hazard event

Often there is little or no warning of a coal mine-related failure, but if specific triggers have been identified, these can be monitored to improve the management of the risk. For example the following features may indicate an increased susceptibility to failure:

- nearby underground water mains or drainage (which may leak)
- surface flooding events
- chemical changes which may have degraded any treatment measures
- erosion (surface or groundwater flow)
- surcharging
- groundwater level change
- note that the above water related features (surface or groundwater, flooding etc.) may be exacerbated by climate change

3 Assess the likelihood of the hazard event occurring

It is important to note that the hazard rating given on the Coal Mining Hazard map is not an absolute indicator of the likelihood of a coal mining collapse to occur, but a relative indicator of the presence of the hazard compared to the rest of the network. There are too many uncertainties to be able to define the likelihood of a coal mine related collapse, but the following factors can be considered as indicators of an increased likelihood:

- Coal mines closed before 1872 will have more incomplete records. After that date, the Coal Mines Regulation Act of Parliament required mine owners to deposit their mine plans with the State after mine closure. Incomplete records signifies an increased likelihood of unidentified and hence untreated mines and mine openings. Furthermore, older mines tended to be shallower, with increased number of shafts.

- Knowledge of the presence, quality and current condition of any works undertaken to make coal mines safe after their closure. Such works may comprise the capping of shafts, and the backfilling of workings. The age of treatment is not always known, but it is reasonable to assume a correlation between the date of construction of the section of the SRN in question, and the date of treatment – historical reports on HAGDMS may provide further information on this. As noted above, for all parts of the SRN it is reasonable to assume that investigation and treatment will have been carried out, with the following broad observations:

- Mine treatment undertaken before the publication of the documents by the National Coal Board 'Treatment of Mines and Adits' (1982) and CIRIA SP32 (1984) may have been less effective and more ad hoc.
- Also, mine treatment undertaken before 1984 has now been in place for over 30 years and therefore carries uncertainties about the deterioration either due to ageing, or external factors such as chemicals or movement of water (see also Step 2, triggers).
- Between 1984 and the first publication of the DMRB in 1992, there should have been an improvement in the investigation and treatment of coal mines based on the level of guidance available.
- Since the publication of the DMRB in 1992, particularly HD22, management of geotechnical risks) less uncertainty, better records on HAGDMS and more effective and consistent investigation and treatment.
- Where treatment has been undertaken in the last 10 years, and has experienced less age-related deterioration the above-mentioned issues of deterioration of treatment are less significant, and records should be easily accessible to confirm adequate investigation and treatment.

An understanding of the likelihood of a mining hazard event occurring may also be assessed from historical records and frequency of similar problems on the strategic road network and the surrounding area although the causal link is at best rather flimsy. Where HAGDMS contains reliable information showing mines or mine entries to have been investigated and capped according to current standards, it is reasonable to assume a lower likelihood of a hazard event. There is planned research into the use of pavement deflection data to identify the presence of ground-related hazards, which would support the likelihood assessment described above.

4 Consider the potential impact on the safety and/or performance of the SRN

A quantitative assessment of impact on a national scale is not possible, but at a local level, the following factors should be considered to understand the potential impact:

(A) Factors specific to the hazard event

- The rate of failure and the amount of warning available. A rapid, catastrophic failure presents the highest safety consequence.
- The size of the potential failure. An increasingly large void presents an increasingly large safety risk to users of the network. This requires local consideration and expert input. For example, considering mine shafts, the depth of the shaft, the nature of the superficial deposits, the type of treatment and the shaft diameter will all influence the size of the potential void although for unrecorded shafts this data will necessarily be unknown.
- The location of the potential failure. A void in a main running lane presents both higher safety impact, and higher performance impact than one in a hard shoulder or beyond. The 'Location Index' in HD41/15 can be used as guidance.
- Consideration of potential investigation and remedial works – the longer these could take, the longer the performance impact.

(B) Factors specific to the location of the hazard event on the network

- The speed and volume of traffic using the road will typically correlate to an increased safety impact
- The strategic importance of the road will increase the performance impact
- The type of road, with smart motorways being the most important in terms of performance, down to All Purpose Trunk Roads (APTR) being the least
- The type of pavement – a sudden/catastrophic failure is more likely where overlain by a rigid pavement whereas there may be early signs of a failure event occurring where there is a flexible pavement.
- Presence of technology – smart motorways could be assumed better able to respond to an event in terms of traffic management**.**

5 What is the risk (considering likelihood and impact) that the coal mining hazard presents to the SRN

This can be qualitatively assessed, and should inform subsequent decision making. Uncertainty should be recognised and decisions should typically be cautious, particularly where there are high levels of uncertainty (lack of data)

6 Select appropriate risk response measures

Risk response measures may be either pro-active or reactive. Typically, the greater the risk to the safety or performance of the SRN in terms of both likelihood and impact of a failure, the greater the benefits of undertaking pro-active investigation and mitigation measures. There should be early engagement with Geotechnical Specialists from both Highways England and service providers and the Coal Authority. They should detail the required responses to manage an appropriate risk-based response to a ground related hazard.

High level risk response measures would fall into the following categories:

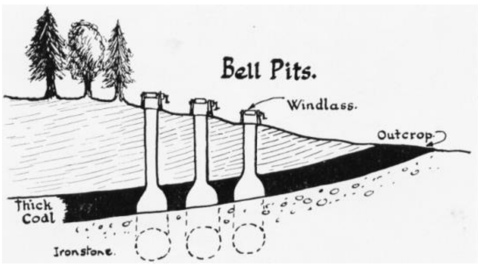
- **Investigation.** To understand the current condition and therefore likelihood of the hazard event. Investigation may reduce the uncertainty and hence reduce the need for additional mitigation measures.
- **Intervention.** Where there is an evident cost-benefit in implementing measures (barriers) to prevent the hazard event from occurring
- **Monitoring.** To allow appropriate operational responses to be implemented in anticipation of a potential hazard event.
- **Response and recovery.** Development of response plans, to be followed if a coal mining hazard event, e.g. a void opening up, does occur, that will mitigate the impact of the event, and are recommended in areas of known coal mining risk. In all such areas there is the potential for an unexpected event, albeit less likely in some. Response plans should include:
  - **i.** Contact with the Coal Authority (who have responsibilities for responding to events of this type) and engagement with Highways England technical specialists. Named focal points (and responsibilities) should be clearly identified.
  - **ii.** Being prepared to close lanes and/or implement diversions, and have an understanding of the potential duration of these measures until the risk is mitigated and the SRN is fully operational. This includes a broad range of communications, which may include Highways England's Supply Chain(s), road users and the general public.
  - **iii.** The Coal Authority aim to provide an effective and long-term mitigation solution. In order to ensure that the solution is appropriate to Highways England there should be early coordination with Highways England specialists. The agreed solutions (or combination of solutions) will be based upon an engineering based

judgment of safety (particularly to operatives) and effective long-term risk mitigation.

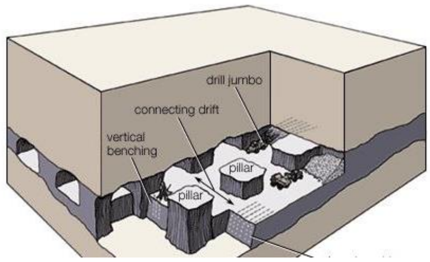
iv. Following initial recovery, it will be important to ensure a full record of the mitigation works (as part of Health and Safety file recording), the cause of the event assessed, the risk of similar events occurring elsewhere on the network evaluated, and appropriate actions taken to manage the incident.

Part III The legacy of coal mining across England
1.0 History

Early mining was opportunistic, extracting coal from surface outcrops. As these sources were exhausted mining began to move underground, following seams in simple drift mines (adit mines) and shallow excavations known as 'bell pits'. Coal mining increased significantly during the industrial revolution, and rose to a peak of production in 1913, before declining slowly to the 1960s and rapidly declining thereafter as North Sea oil and gas began to replace coal as the main energy source for the UK. With increasing production, the means of excavation became more mechanised and took place at greater scales, and to ever increasing depths. Excavation by room and pillar techniques (where some coal is left in place in pillars to support the roof above) allowed large volumes of coal to be removed. This was largely replaced by longwall mining, where full extraction of the available coal is carried out, and the ground behind the mining is allowed to collapse. In addition, advances in plant and extraction techniques allowed large scale opencast mining to be undertaken for coal near to the surface. Following a long decline, the last deep coal mines in England closed in 2015. Opencast mining continues, but at much smaller scales than previously.



Coal mining with Bell Pits



Room and Pillar mining

2.0 Coal mining hazard and the Strategic Road Network

The hazard posed can be considered to arise from a combination of:

- The potential for voids beneath the Highways England estate with the potential to either collapse suddenly and catastrophically or to cause subsidence. These voids could be present due to (a) unidentified, and hence untreated, mines or mine shafts (often older mines or mine entries are more difficult to locate), (b) inadequate treatment methods (compared to current practice/guidance), which again may correlate to the approximate date of treatment, (c) the treatment measures employed have deteriorated subsequently due to changes unforeseen at the time of treatment (e.g. chemical, groundwater or surface flooding) or d) undetected fissuring in certain surface rocks resulting from ground strains caused by longwall mining at depth.
- The potential for abandoned coal mine workings to produce potentially dangerous emissions, such as mine gas or polluting mine waters.

This note focuses on the potential for voids and subsidence, but the potential release of hazardous gas should not be ignored.

The type of hazard that the presence of these mines presents to the SRN is further significantly influenced by the age and depth of the mines. Broadly speaking, the hazard type can be grouped as follows:

- **Outcrop and very shallow mine workings** (typically within 50m of the seam outcrop, although the location of the outcrop and exact distance to mine workings are both uncertain), exploited via open excavations, bell pits and perhaps local underground workings. These can date back to Roman times or earlier. Workings may be unconsolidated, and there is a greater likelihood of unrecorded workings and mine entries. There is also a risk of spontaneous combustion from some seams if exposed to air.

- **Shallow (typically less than 30m deep) mines**. These will be a mix of recorded and unrecorded mine workings, mined using a variety of support solutions. These typically date from the early 1800s to the early 1900s. The hazard to the SRN is again due to the likelihood of unconsolidated mine workings or entries that could allow voids to migrate to the surface and affect highway infrastructure. The risk increases if the mine workings or entries are unrecorded and therefore have not been assessed and mitigated in the past. Previously identified workings may have had mitigation works undertaken (to mine workings and entries). However, these may become compromised where measures were incomplete, have deteriorated and/or are influenced by external factors (e.g. water infiltration) representing a further hazard to the SRN.

  Deep mining, largely undertaken during the 20th century using longwall techniques. In deeper workings the likelihood of a hazard of void migration from mine workings is significantly lower due to higher overburden pressures and the method of mining used. Ground settlement also generally occurs contemporaneously with the workings and is therefore less likely once mining has ceased. This may change should underground coal mining resume in the future. The hazard is therefore primarily from mine entries. The available information on deep mining is typically of better quality (hence reduced uncertainty), but hazards exist where the shaft de-commissioning did not adequately mitigate risks appropriate to a location beneath or close to SRN. Moreover, shaft de-commissioning methods are susceptible to similar compromises as identified for mitigation measures on shallow workings.

Acknowledgement and contact details

This work has been informed by two tasks currently being undertaken as part of HE's Innovation Programme: Task 1-084 Resilience enhancement measures for geotechnical assets and Task 1-062 Geotechnical Hazard Knowledge. The Coal Mining Hazard map will provide an improved understanding of the potential for coal mines to impact the safety or performance of the network, and additional guidance to support decision making as to appropriate risk mitigation measure.
For further information or queries please contact david.patterson@highwaysengland.co.uk.