Highways England

Resilience of geotechnical assets on the Strategic Road Network to severe weather events

Phase 2 – Final report

Issue 3 | 1 June 2016

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The Arup Campus
Blythe Gate
Solihull B90 8AE

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		Signature			

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Glossary of terms

Adaptation	Actions to reduce the vulnerability of natural and human systems to increase system resiliency in light of expected climate change or extreme weather events
Coping Capacity	The ability of the network to continue to function if asset performance is compromised. It is inversely proportional to criticality
Criticality	The importance of the network proximate to the asset
Exposure	A measure of the extent of geotechnical asset that would be subjected to a severe weather event
Failure	(1) Failure of an asset to fulfil its required duty (2) Reaching a Limit State
Frequency	A measure of likelihood expressed in terms of the number of occurrences within a given unit of time.
Geotechnical Defect	A feature observed within a geotechnical asset that is assigned Class 1 (as defined in HD41/15)
Geotechnical Event	A geotechnical defect that poses a threat to the safety of users, workers or other parties or critical assets
Geotechnical Hazard	A feature which creates the potential for a geotechnical defect/event. May be natural or man-made
Hazard	An event or condition with the potential to cause adverse change in performance. The description of hazard should include as much information as possible about location, size, classification etc
Likelihood	The possibility that a specific outcome will occur as a result of a hazard, which may be expressed or measured as probability, chance or as a frequency. Can also be expressed using qualitative terms
Man-made hazard (due to presence of road)	A ground-related hazard which is related to the imposition of the road network on the landscape
Man-made hazard (non road-related)	A ground-related hazard created due to the activity of man, but not related to the imposition of the road network on the landscape
Natural hazard	A ground-related hazard relating to the natural environment in which the road is located. These hazards may be due to the behaviour of geological materials or the behaviour of natural slopes within the landscape

Resilience	The ability of assets, networks and systems to anticipate, absorb, adapt to and/or rapidly recover from a disruptive event
Risk	Generically, the likelihood of an event happening combined with the impact if the event does occur. In the context of this subject, risk is the likelihood of the weather event occurring combined with the expected level of impact the weather hazard has on the network (Threat x Vulnerability)
Severe weather	Any meteorological phenomena with the potential to endanger safe passage or cause disruption on the SRN
Susceptibility	A measure of inherent and external features of an asset which, if exposed to severe weather, may result in performance issues
Slope geotechnical hazard rating	The rating methodology by which Highways England gives a measure of the man-made hazard (due to the presence of the road)
Threat	The likelihood of a severe weather event occurring
Trigger	A natural or man-made occurrence, which, when combined with an existing hazard, may lead to a geotechnical defect or event
Vulnerability	The potential for an asset to 'fail' (i.e. fail to meet its performance requirements) as a result of a severe weather event, and impact on the network.

Executive Summary

This report presents a framework for the resilience of Highways England's geotechnical assets to the impact of severe weather events.

Geotechnical assets on the Strategic Road Network (SRN) have been resilient to severe weather events over recent decades, but without timely maintenance, specific geotechnical assets may be prone to increased deterioration rates. Climate change projections, which suggest an increase in potential severe weather events, may accelerate deterioration and manifest as unforeseen vulnerabilities on particular sections of the SRN.

The resilience assessments context is founded in the aspirations of the Department for Transport's, Transport Resilience Review (TRR) to *"ensure that our transport networks are as well prepared as they can be to minimise the impact of extreme weather events"* (DfT, 2014a). Importantly, being well prepared does not always mean that proactive improvement works should be undertaken to improve the performance of geotechnical assets, but that Highways England should understand the expected impacts of extreme weather events, and be able to respond and recover appropriately.

The resilience framework presented in this report therefore focuses on identifying and prioritising 'vulnerable' geotechnical assets. The aim of this resilience framework is to allow Highways England to prioritise those geotechnical assets which present the highest risk due to severe weather events and therefore require appropriate and proportionate resilience measures. For example, the framework could be used to inform reactive responses when severe weather is forecast or for planning pro-active interventions.

The proposed resilience framework follows a five-step approach:

1. **Identification of a severe weather hazard**, which subsequently informs the vulnerability assessment.
2. The **vulnerability** stage of the assessment incorporates inherent asset knowledge; this is a factor of an asset's exposure, susceptibility and the 'coping capacity' of the affected network. Susceptibility of an asset is different for different weather hazards, and coping capacity is taken to be the criticality of the part of the network affected.
3. The likelihood of a severe weather event occurring is then established. This could be an **imminent** weather event, used for operational response planning or a **future weather scenario,** based for example on climate change projections (e.g. UKCP09 or H++ scenarios).
4. The evaluation of **risk** is then simply a factor of the likelihood of the weather event and asset vulnerability.
5. Finally, appropriate decisions can be made around **adaptation, mitigation** and **recovery** based on the evaluated risk**.**

This approach is aligned with Highways England's climate change adaption framework as well as current thinking surrounding transport network resilience to severe weather in Europe and the United States. The principles are not limited to geotechnical assets and can be applied across asset groups (e.g. drainage, pavements and structures).

The framework considers available asset data and hazard information and has the ability for elements to be refined as modelling knowledge and capabilities mature.

Due to the current available information the **proposed framework is based on a simple model approach** and the focus is on the vulnerability assessment (Step 2) for specific severe weather types. It has been concluded that categorisation of all geotechnical assets in terms of their resilience is not currently possible, pending additional data being available within HAGDMS about ground-related hazards, and special geotechnical measures. Therefore at this stage, only an approach to categorising assets is presented, an actual categorisation is not yet done.

A number of recommendations are proposed, which, combined with related tasks ongoing within Highways England, will add maturity to the framework and enable earthworks to be categorised according to their resilience.

1 Introduction

In October 2015, Arup, as part of the Arup/URS Consortium, was commissioned through Highways England Framework for Transport-related Technical and Engineering Advice and Research to undertake Task 634 ***'Resilience of geotechnical assets on the SRN to severe weather events'***.

The overall objective for this task was to:

> Develop an improved categorisation of the resilience of Highways England's geotechnical assets to a range of severe weather events. The demand that these events can impose should be compared to the basis of design of geotechnical assets and to our understanding of their current condition (including underlying hazards).

This categorisation will ultimately assist Highways England decision makers seeking to understand the potential impact of severe weather events forecast in the short term and long term climate change on geotechnical assets and consequently on the SRN.

This Task was undertaken through a two-phased approach:

1. To undertake a scoping study to determine the current position in terms of infrastructure resilience, vulnerability, consequence and risk. This was reported in the Scoping Study report (Arup, 2015).
2. Using the recommendations established in the scoping study, develop a framework for assessing the overall resilience of SRN geotechnical assets to severe weather events and future climate change. Specific guidance and further recommendations are also provided. The framework has been tested against available information from HAGDMS.

The study concluded that at the time of writing, a full categorisation of geotechnical assets in terms of their resilience is not possible, pending the completion of two parallel tasks, looking at ground-related hazard information, and special geotechnical measures. Therefore only a high level framework is currently presented, with some proof of concept work using available data.

1.1 Report outline

Section 2 of this report provides background information from Phase 1 Scoping Study report. It also defines failure states and discusses the impact of severe weather events on the basis of design of geotechnical assets.

Section 3 summarises the scope of the work, the objectives and the methodology adopted to develop the framework, and the interfaces with other relevant tasks.

Section 4 presents the resilience framework, the modelling approach and its associated inputs.

Section 5 discusses the knowledge gaps and uncertainties associated with the proposed framework and its current state. It also outlines the potential adaptation

options available to Highways England and the interdependencies between geotechnical assets and other asset groups within the infrastructure system and/or with third parties.

Section 6 presents the conclusions and a series of recommendations which have developed from the task.

1.2 Benefits

Overall, this task will provide Highways England with a more informed assessment of the potential impact of severe weather on their geotechnical assets.

The following additional points are considered to represent the benefits of the work package to Highways England:

- Improved ability to deliver a more resilient SRN.
- Support Highways England's strategic outcomes such as safety, increased user satisfaction, ensuring the smooth flow of network and encouraging economic growth - in this context the ability to recover rapidly and safely from severe weather events.
- Improved understanding of causal links to enhance the effectiveness of interventions and make efficiency savings on whole-life costs.
- Using geotechnical information in a smarter way to support informed decision making and resilience planning.
- Opportunity to strengthen the asset management processes and policy of Highways England, e.g. resilience planning to prepare and plan for severe weather events and longer term climate change effects could be included in the Geotechnical Asset Management Plans (GeoAMPs, HD 41/15).
- Improved understanding of the impact of severe weather and future climate change on interconnectivities between assets and interdependencies with other asset owners.

2 Background

2.1 Transport Resilience Review

Following the severe winter of 2013/14, the Department for Transport (DfT) conducted the Transport Resilience Review, which stated that UK transport operators need to "*ensure that our transport networks are as well prepared as they can be to minimise the impact of extreme weather events*" (DfT, 2014a).

The DfT regard transport resilience to severe weather to comprise:

1. Physical resilience to extreme [or severe] weather (people and goods can continue to move)
2. Processes and procedures to restore services and routes to normal as quickly as possible after the event (recognising that 100% physical resilience to all hazards is prohibitively expensive)
3. Clear and effective communications to customers to minimise disruption

2.2 Highways England response

Highways England responds in the Delivery Plan (2015-2020) (Highways England, 2015) by recognising the need to:

- Mitigate the impact of the severe weather on programmes
- Commit to delivering and maintaining an enhanced, Integrated Severe Weather Information Service, to support effective decision making and management of response to severe weather.
- Address existing gaps in asset information
- Improve operational response to incidents, aiming for 85% of incidents cleared within 1 hour in order to meet the Government KPI.

Embedding physical resilience of geotechnical assets into the investment decisions will directly align Highways England with UK Government objectives.

Highways England's 'Climate Change Risk Assessment' (2011 and internal draft, 2016), the 'Sustainable Development Strategy' (2015) and 'Flood Risk Strategy - Our approach to flood risk management – Guidance' (Highways England, 2014) all discuss the need to prepare and adapt to severe weather and changing climate.

> *"In order to become more resilient to future changes in climate, which may result in more* frequent *and severe weather events, it is important that we adapt our network and make effective investment decisions. Climate adaptation today is tomorrow's resilience"*
>
> *(Highways England, Sustainable Development Strategy Vision, 2015)*

Severe weather plans set out the operational response to severe weather events, ensuring the continued running of the network. These plans currently focus on route-level winter service planning (e.g. ice and snow mitigation) but could be used to manage the impact of severe weather on geotechnical assets. For example, the plans could include locations of geotechnical assets that are potentially vulnerable to specific severe weather types and operational plans to prepare, respond and/or adapt should such severe weather events occur.

2.3 Definition of severe weather

Severe weather can generally be defined as:

> *"any meteorological phenomena with the potential to endanger safe passage or cause disruption on the SRN".* (Highways England, Severe weather plan template)

In the context of this task, severe weather includes:

i. Heavy and/or prolonged rainfall and consequent flooding (pluvial, fluvial and groundwater)

ii. Wind storms

iii. Periods of prolonged freeze and freeze/thaw cycles

iv. Snow

v. Periods of hot/dry weather

2.4 Defining resilience

Resilience has a number of definitions borne from the concepts of 'Ecological', 'Economic', 'Infrastructure' and 'Community and Societal' resilience (Rogers et al. 2012). For this task, we define resilience as:

> *"the ability of assets, networks and systems to anticipate, absorb, adapt to and/or rapidly recover from a disruptive event"* (Cabinet Office, 2011)

Resilience is secured through a combination of activities or components; the four principal strategic components are shown in Figure 1. A combination of responses from all four of these components should be used to develop a strategy that will deliver the most cost effective and proportionate risk management response to the hazards and threats.

Figure 1 – The four strategic components of infrastructure resilience (Cabinet Office, 2011)

A variation on this definition is included in CIRIA Report C688 'Flood resilience and resistance for critical infrastructure' where resilience is defined as "those systems of assets that will be able to survive and perform well in an increasingly uncertain future" (CIRIA, 2010).

CIRIA Report C688 highlights that the physical resilience is dependent on:

- Durability and robustness of infrastructure asset
- Appropriate approach to risk identification, assessment and management
- Whole-life investment in infrastructure construction and maintenance
- Reliability and defect avoidance in the construction and design process
- Pre and post event mitigation and recovery planning

The identification of potential hazards and assessment of risk are considered key aspects of any resilience planning (Hudson et al. 2012). Risk assessment helps identify the effective targeting of resources and makes the economic case for resilience measures (Parliamentary Office of Science and Technology, 2010). However, whereas risk assessments are primarily focused on the identification and ultimately prevention of disruptive events (i.e. maintenance and adaptation measures), resilience assessments also encompass the processes required to maintain functionality immediately following an event (e.g. severe weather) (Cagno et al. 2011).

2.5 Need for severe weather resilience planning

Highways England's geotechnical assets (Figure 2) have been resilient to severe weather events during recent decades; a factor of their relatively young age and appropriate design and construction methods. See Section 2.6 for further discussion of impact of severe weather on basis of design of geotechnical assets.

However, the scale of geotechnical assets on the SRN makes them particularly susceptible to severe weather events which are predicted to become more frequent and of higher magnitude under climate change projections for the 21st century (Jenkins et al. 2009). The inherent variability and complexity of geotechnical assets mean that they respond in different ways to severe weather events. Therefore, it is important to identify existing vulnerabilities so that the associated risk to the SRN can be properly assessed.

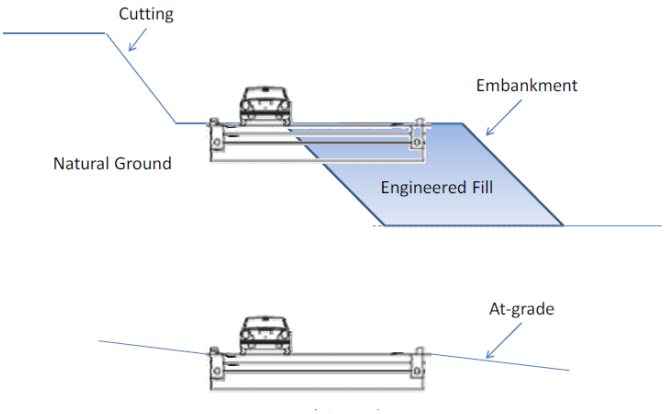


Figure 2: Definition of a 'geotechnical asset'

Glendinning et al. (2015) argue that Highways England need to understand those geotechnical assets requiring smaller interventions to improve their longer-term resilience to severe weather and climate change impacts. Moreover, Vardon (2015) argues that a thorough assessment of existing geotechnical infrastructure and changing environmental conditions is important for more efficient investment approaches.

In the case of geotechnical assets, remediation costs subsequent to slope failure are often several times higher than cost of corrective measures and repair if conducted prior to collapse (Glendinning et al. 2014). This is not considering potential additional damage to road surfaces, structures and bridges.

Anticipating and being prepared for the impact of ground-related problems will support Highways England's strategic objectives, particularly around safety, the smooth flow of traffic and supporting economic growth. Ultimately, this will also contribute to an overall resilient network.

2.6 Categorising 'failure' of geotechnical assets

CIRIA reports C591 'Infrastructure Cuttings' (CIRIA, 2003a) and C592 'Infrastructure Embankments' (CIRIA, 2003b) categorise the failure of geotechnical assets into two distinct states, which include:

- **Serviceability limit state failure** – *state of deformation of the cutting/embankment such that its use is affected, its durability impaired, or its maintenance requirements are substantially increased.*
- **Ultimate limit state failure** – *State of collapse, instability or forms of failure that may endanger people or property or cause major economic loss. Such movement would affect any adjacent infrastructure.*

Highways England's geotechnical assets are predominantly vulnerable to serviceability limit state failures, with few occasions of ultimate limit state failures to date. Geotechnical assets on the SRN support a number of other assets, made more prevalent by the establishment of smart motorway networks and it is therefore becoming increasingly important to maintain critical serviceability and functionality. As such, the *failure* of a geotechnical asset, in the context of this

report, should be predominantly be considered in terms of its *failure to meet performance requirements* (Arup, 2010).

Table 1: Common causes of loss of performance due to ultimate limit state and serviceability limit state failure (Source: CIRIA, 2003b)

Common causes of failure*	Ultimate limit state failure	Serviceability limit state failure
Softening of clays		√
Positive pore water pressure		√
Shrink/swell cycle		√
Over-steep slopes		√
Defective drainage	√	√
Overstressing	√	
Pre-existing rupture surface	√	
Culvert collapse	√	
Differential settlement		√
Wave erosion and scour	√	√
Burrowing animals		√

(*) not all common causes of failure are related to severe weather

Although discussed in parallel here, distinction must also be made as to the likely impact on performance posed by a cutting and/or an embankment. For example, embankment failure is likely to undermine the running lanes, and therefore affect ride quality, whereas a cutting failure will possibly result in debris causing a disruption to traffic. The recovery time will also be different for the two scenarios.

The majority of Highways England's geotechnical assets are engineered to modern standards, when compared to other national transport operators such as Network Rail, and it is argued that ultimate limit state failure is most likely to occur during, or shortly after, construction (CIRIA, 2003b).

However, Highways England should not be complacent regarding the potential for ultimate limit state failure to occur. Due to the relatively short period for which

condition data is available, and the limited number of defects and failures within this data set, understanding of the deterioration of geotechnical assets over time is incomplete.

The key factors which may increase likelihood of ULS failure in the future are:

- Changing weather patterns (see Section 4.5.1)
- Ageing geotechnical assets – where some slopes are now approaching 60 years old
- End of design life for strengthening measures (e.g. soil nails). Current work is being undertaken to categorise the performance of special geotechnical measures (e.g. soil nailing) reaching the end of their design life.

The generalised deterioration 'bath tub' curves (Figure 3) set out by Thurlby (2013) show Highways England's geotechnical assets to currently fall within the "reliable" phase. Severe weather and long term climate change are likely to have the effect of shortening the "reliable" stage of asset condition, moving into the "degenerating" phase earlier than anticipated unless no maintenance intervention is undertaken.

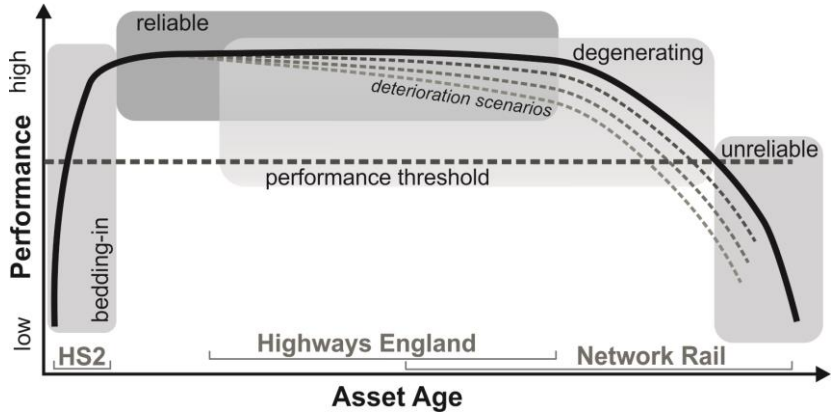


Figure 3: Generalised deterioration model for transport earthworks (Source: Glendinning et al. 2015; Thurlby, 2013)

2.7 Impact of severe weather on basis of design

Severe weather events will generally cause a shock to the geotechnical asset. This detrimental impact may lead to failure if the basis of design is exceeded. The impact is greater if the existing asset and boundary conditions are already worse than what was assumed for the design, e.g. the material strengths have deteriorated with time or the asset is nearing the end of its design life, or if known hazards are present and triggered by the severe weather event (Figure 4).

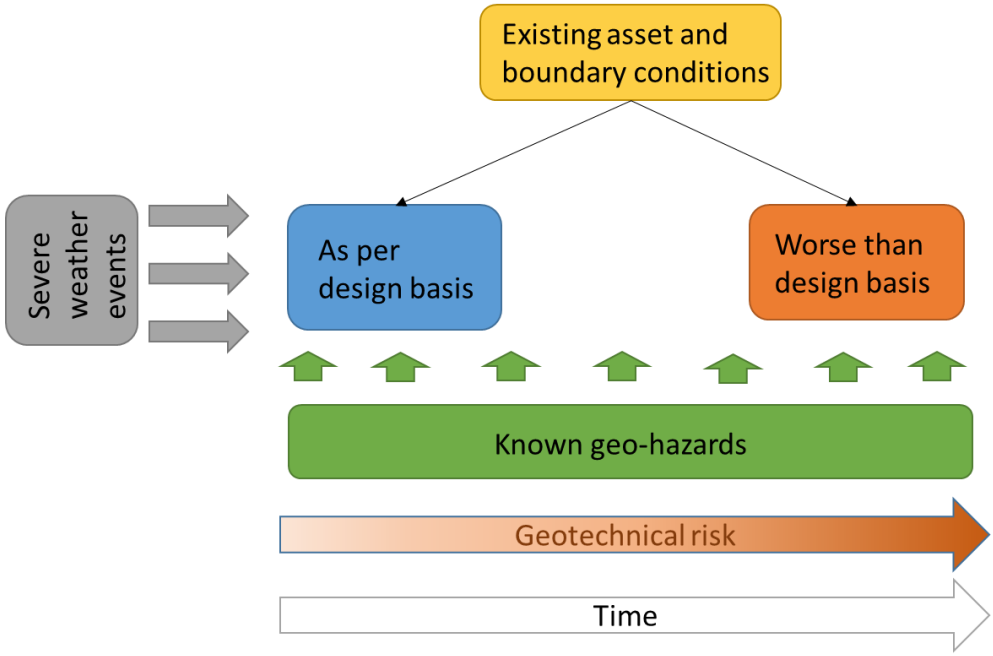


Figure 4: Potential impact of severe weather events on the basis of design.

For example, rainfall events may cause changes to the groundwater level. The estimation of groundwater regime used in the design may not be representative of the worst case over the asset design life although engineering judgement may have been used in assuming a conservative groundwater level. Moreover, climate change impacts, i.e. estimation of groundwater levels using UKCP09, were not considered in the asset's original design basis.

Another example is the effect of severe weather on the deterioration of material strengths assumed in the design. Cohesive deposits are most susceptible to changes in pore water pressure and to the cyclic action of soil drying and wetting, which in over consolidated clays can result in shrink-swell action of the soil (in the top 1-1.5m) leading to progressive slope failure. In contrast, granular deposits are not as susceptible to changes in moisture conditions. However, excessive pore water pressures can lead to internal and external erosion leading to serviceability issues.

A cutting exposes natural material and as such cannot be engineered to the same standards as an embankment and could therefore be affected to a greater extent by severe weather and resultant natural weathering processes. For example, a rock cutting may be particularly subject to weathering due to freeze-thaw processes, whereas an engineered soil embankment would not respond in the same way.

3 Scope

This report develops recommendations from the Phase 1 Scoping Study report (Arup, 2015) and sets out a resilience framework for the SRN's geotechnical assets. The overarching aim of the proposed framework is to enable Highways England to plan response or prioritise interventions to enhance the resilience of geotechnical assets.

Wherever possible, work undertaken in Phase 2 has built on previous work from related tasks and has aligned with current approaches of Highways England, such as HD41/15 and the Climate Change Risk Assessment.

Key development activities have included:

1. Develop a logical framework to assess the resilience of geotechnical assets and to severe weather events
2. Review of severe weather hazards that may affect the performance of geotechnical assets
3. Develop a methodology to establish the vulnerability of geotechnical assets to severe weather events
4. Consider how underlying ground-related hazards may respond to severe weather-related triggers
5. Investigate current and future weather types and threats, considering climate change projections (e.g. UKCP09) to understand return periods of potential severe weather events
6. Consideration of interdependencies and integration with other activities

3.1 Task interfaces

Related tasks are outlined in Appendix A.1.

Consultation with selected experts, including Highways England representatives from the Environmental, Drainage and Sustainable Development teams and other members of the Arup/URS Consortium was also undertaken throughout the course of the task, see Appendix A.2.

4 Resilience framework

Developing a resilience framework will allow Highways England to prioritise those geotechnical assets which present the highest risk due to severe weather events and therefore require appropriate and proportionate resilience measures.

Following recommendations from the scoping study report (Arup, 2015), the proposed resilience framework should align with other similar severe weather resilience approaches across transport networks in the UK, Europe and the USA. In addition, the framework should use and build on established processes within Highways England.

Highways England's existing Climate Change Adaptation Framework (Highways Agency, 2009; Highways England, 2016) satisfies the above requirements and it is therefore largely applicable. However, it requires some focus on the resilience of geotechnical assets.

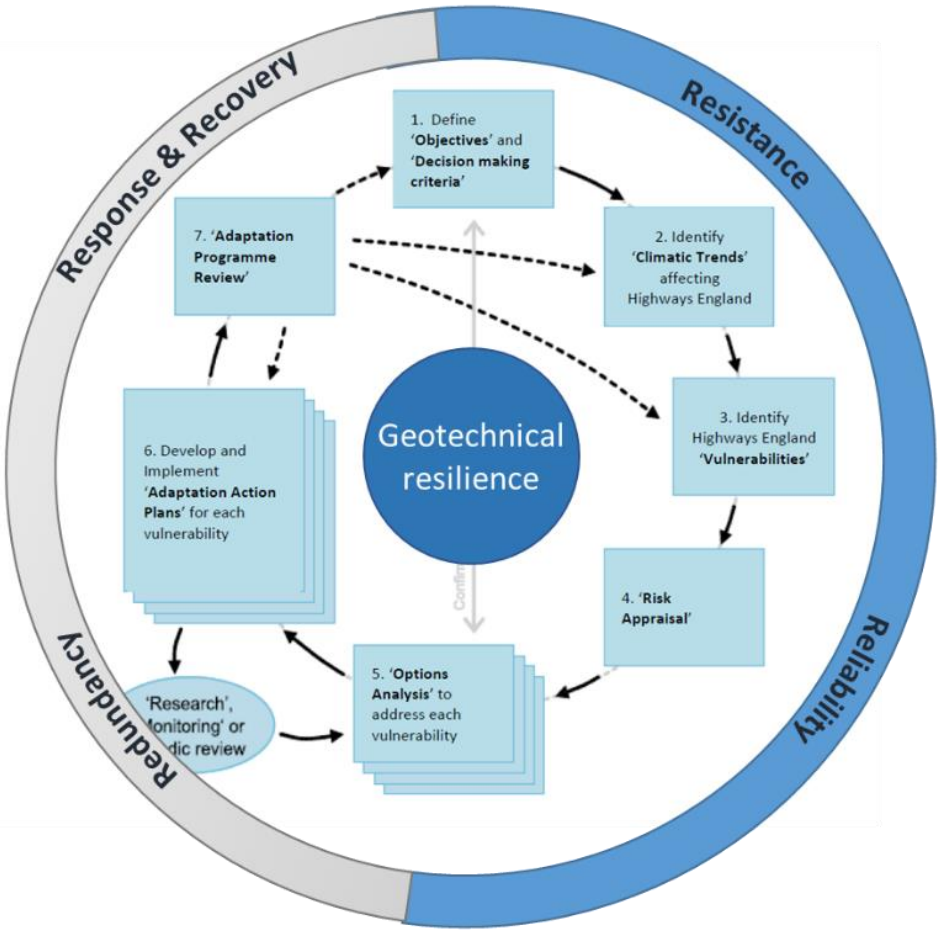


Figure 5a: Overall resilience framework and the four strategic components of infrastructure resilience

It is recognised that a resilience framework should comprise a combination of the four strategic components of infrastructure resilience and extend to include the broader adaptive capacity gained from an understanding of the risks and uncertainties as discussed in Section 2.4 (Figure 5a). Risk assessments are used

not only to plan for (i.e. avoid and mitigate before the event) but also to integrate the capacity to deal with, recover from and adapt to severe weather events.

The initial steps of the overall resilience framework relate to the resistance and reliability components and have been developed in the following sections in the context of the resilience of geotechnical assets.

4.1 Proposed resilience framework for geotechnical assets

Based on the literature review, and the conclusions of the scoping study (Arup, 2015), a five-step resilience framework is proposed (Figure 5b).

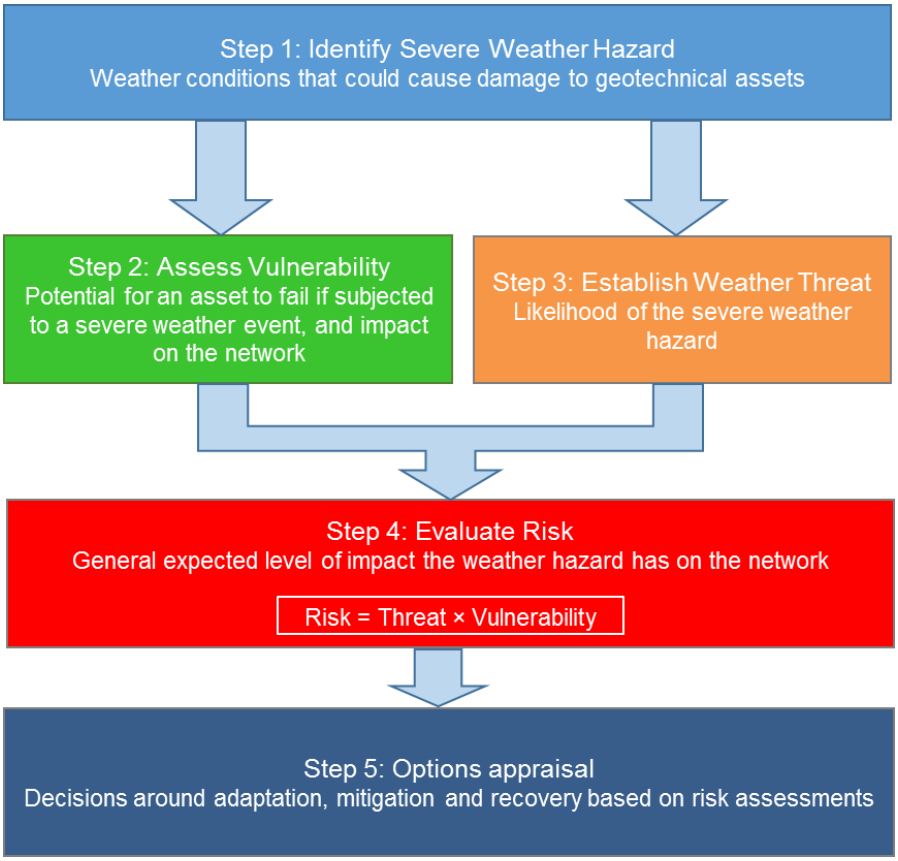


Figure 5b: Proposed resilience framework

The basic concepts underpinning the proposed methodology are applicable across all asset groups, albeit the details of the vulnerability assessment should be tailored to the specific asset group.

4.2 Modelling approach

The first step in developing a framework model is to select the most appropriate modelling approach.

The overall maturity of the proposed framework will be governed by the minimum level of sophistication of any one part. There is the ability for elements to be refined as modelling knowledge and capabilities mature. It is important however, to consider that development of one model should be proportionate to the others.

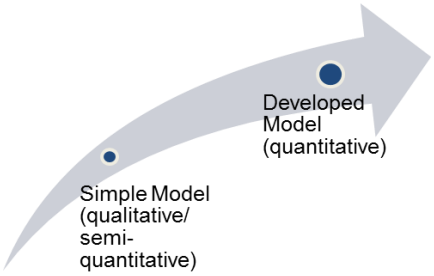


Figure 6: Modelling approach for the proposed framework

The findings of the Scoping Study report and a further review of available input data and related tasks has indicated that a 'simple model approach' is currently the most appropriate for the proposed framework. Based upon information available to the user at the time of assessment, a quantitative model is only feasible at a site specific evaluation level, which is beyond the scope of this task.

The proposed modelling approach is set out in the following sections, with commentary on future model improvements.

This task is aligned with other ongoing work streams that are looking to achieve a better incorporated and more informed asset knowledge base. When available, outputs from these related tasks will help refining the proposed model.

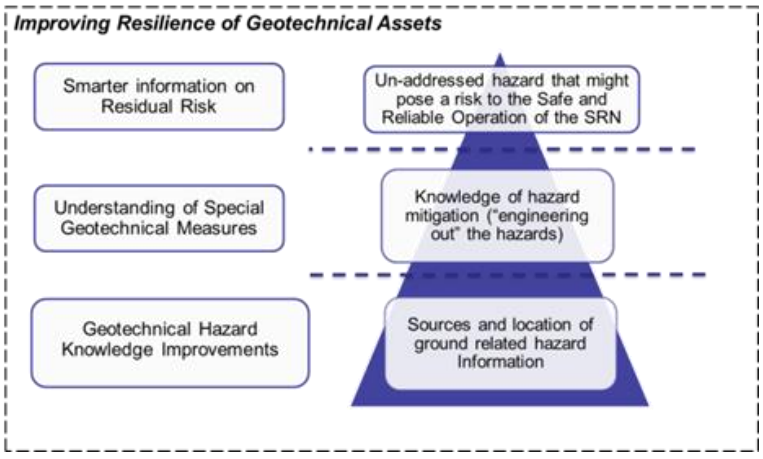


Figure 7: Management of residual ground-related risk on the SRN (Power et al. 2016)

4.3 Step 1: Identify severe weather hazard

Severe weather in the context of this task is generically defined as *"any meteorological phenomena with the potential to endanger safe passage or cause disruption on the SRN."*

The task specification identified several severe weather types which have the potential and have resulted in prior damage to the performance of the SRN's geotechnical assets. These were supported by the findings of the Scoping Study (Arup, December 2015). The severe weather types identified are listed in Table 2.

For assessment purposes, severe weather events are differentiated by whether they are based upon a single occurrence (e.g. heavy rainfall), defined as a **'simple'** weather type, or whether it is a combination of more than one severe weather event (e.g. hot/dry spell followed by an intense rainfall event), defined as a '**complex**' weather type. The significance of complex weather conditions was discussed in the Scoping Study report and indicated that "*as recurrence intervals shorten, recovery time of slopes (and drainage) could diminish*" (Dijkstra and Dixon, 2010).

Table 2: Severe weather types

Simple	Complex
Heavy or prolonged rainfall, which may also lead to flooding Hot/dry periods Heavy snow Freezing conditions Wind storms*	Hot/Dry followed by heavy rainfall Prolonged rainfall followed by a heavy/intense rainfall event Repeated cycles of dry and wet weather for a prolonged period of time Freeze/thaw cycles

(*) not considered of significant relevance for geotechnical assets and therefore not included in vulnerability assessments

Complex weather events are not considered in detail within this Task but their potentially significant impact on long-term performance of Highways England's geotechnical assets should be considered further as appropriate information becomes available.

Identification of a particular severe weather hazard will be established through HA WIS or its equivalent.[1]

The Met Office Warning is issued by the Met Office National Severe Weather Warning Service and is an indication of the intensity of the forecast weather on a particular geographic region. It offers some associated guidance for the general public on what impact they can expect in that region. A Met Office Warning will

[1] It is understood that a new weather information system will be put in place during 2016

often precede a Highways England Severe Weather Alert and may be a prompt for Highways England to begin planning for the forecast severe weather event.

A Highways England Severe Weather Alert is issued in consultation with the embedded Met Office Forecaster based at National Traffic Operation Centre (NTOC) and is issued once there is a reasonable degree of confidence in the likely impact of the weather event(s) on the SRN. It was developed specifically to provide advice to customers and stakeholders using the SRN, in particular those most at risk from the severe weather conditions such as high sided vehicles, motorbikes and caravans.

The current weather information service (HA WIS) is supported by the Environmental Sensor Stations (ESS) network which are located at a number of locations around the SRN and provide real-time weather information to Highways England, primarily used to update road-users on driving conditions (Centre for Lean Projects, 2015).

Flood warnings are provided by the Environment Agency, and are made available through the HA WIS website.

The Natural Hazards Partnership (NHP) was established in 2011 as a strategic partnership that represents a collaboration of a number of government agencies and public sector research establishments (e.g. Met Office and British Geological Survey). The purpose of the NHP is to provide daily hazard assessments, for category 1 and 2 emergency responders, for the coming 24 hours, as well as 5 and 30 day outlooks; such assessments encompassing severe weather. The framework allows such information to be readily incorporated.

Specific weather types will affect different geotechnical assets. This is a result of an asset's inherent condition, material properties and underlying hazards. These will be evaluated during the 'vulnerability assessment' (Section 4.3).

Figure 8 proposes stages of increasing maturity for estimating severe weather hazards.

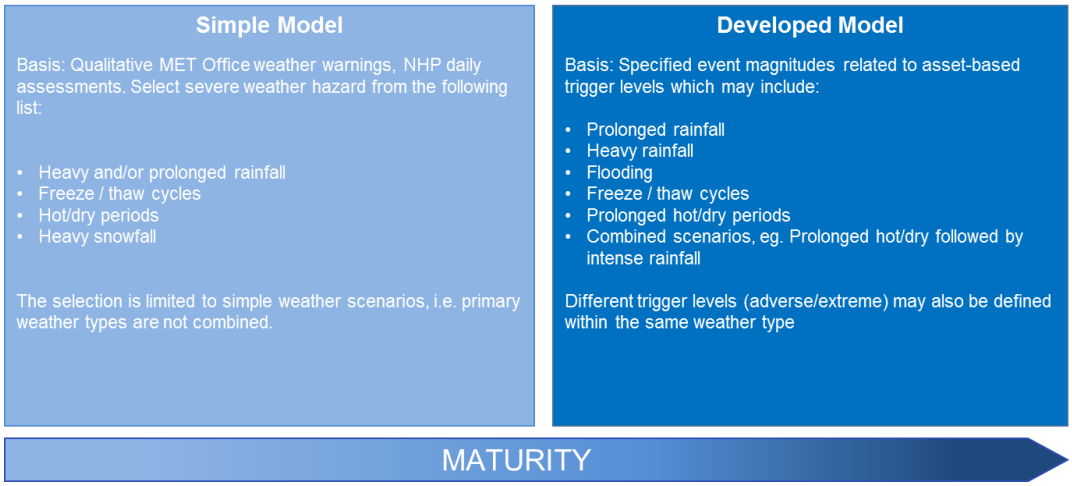


Figure 8: Modelling maturity for establishing severe weather hazards

4.4 Step 2: Assess vulnerability

Vulnerability is defined in the context of this task as *"the potential for an asset to 'fail' (i.e. fail to meet its performance requirements) as a result of a severe weather event, and impact on the network."*

The purpose of the vulnerability assessment is to combine the asset and climate information to identify vulnerabilities. In the context of this task, the focus is on the links between geotechnical assets and weather to assess their combined impact to the SRN. However, the basic concepts are transferrable to other asset groups.

Vulnerability has been defined in the Scoping Study report as a function of three component elements: exposure, susceptibility and coping capacity. They are the building blocks of the vulnerability assessment (Figure 9) and are further discussed in sections 4.4.1 to 4.5.

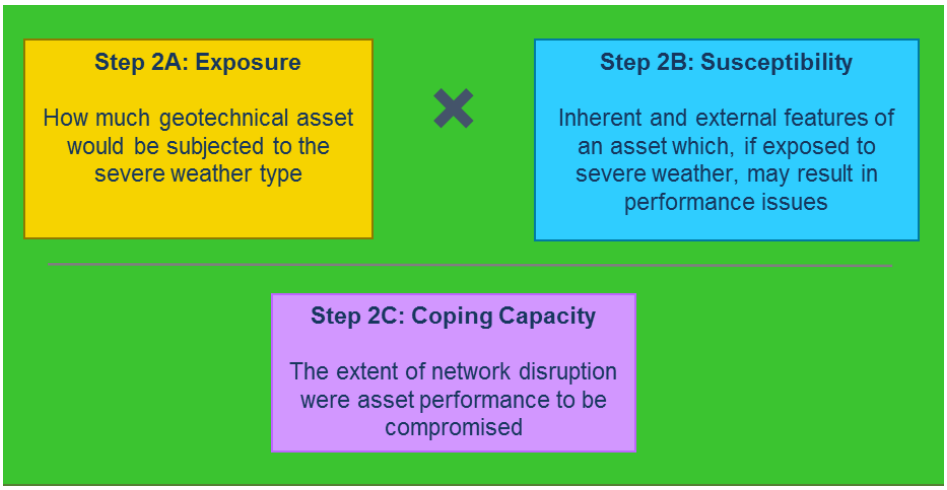


Figure 9: Vulnerability model

4.4.1 Step 2A: Exposure

Exposure is defined in the context of this task as *"a measure of the extent of geotechnical asset that would be subjected to a severe weather event."*

The modelling maturity for exposure is shown in Figure 10 below.

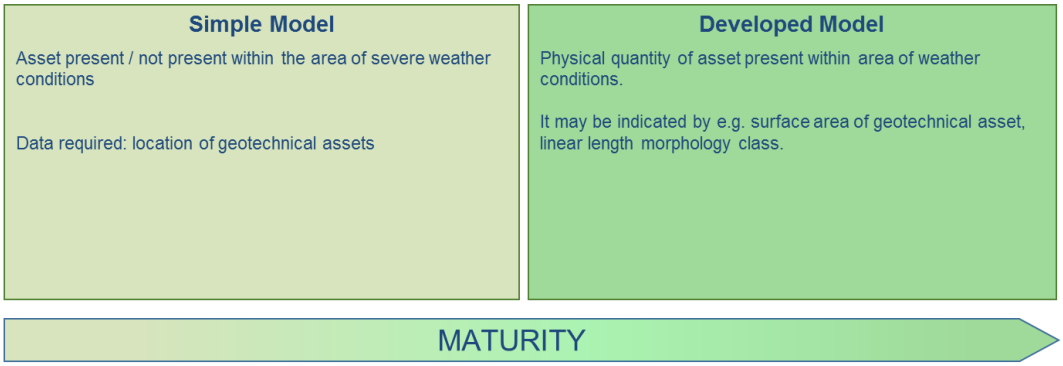


Figure 10: Modelling maturity of exposure

At the time of writing, we would determine exposure to be in the realms of a '**simple model**' whereby a qualitative factor for the presence of assets in the area of a weather event. A '**developed model**' would seek a more quantitative approach. One suggestion may be to use geotechnical asset surface area as a unit measure of exposure. This requires further consideration using a pilot study.

Consideration could be given to surface water catchments, for example, if the weather event is intense rainfall, then identifying cuttings in a catchment area where rapid water flow could result in erosion of a geotechnical asset would provide improved granularity over simply identifying all cuttings present in the area of the rainfall event. Network Rail's Washout and Earthflow Risk Mapping System tool is an example of this consideration.

4.4.2 Step 2B: Susceptibility

Susceptibility is defined in the context of this task as *"inherent and external features of an asset which, if exposed to severe weather, may result in performance issues."*

The factors to consider when assessing susceptibility are summarised in Figure 11 below. Some factors are currently not available within HAGDMS. The figure also shows what other input data (e.g. presence and condition of drainage, which is currently only available for 25% of the SRN or presence of Special Geotechnical Measures) could be integrated in future developments of the proposed model as they become available.

The inclusion of specific factors is informed by the weather type identified in Step 1 of the framework. For example, in the case of freeze/thaw cycles weather hazard, drainage data is less critical.

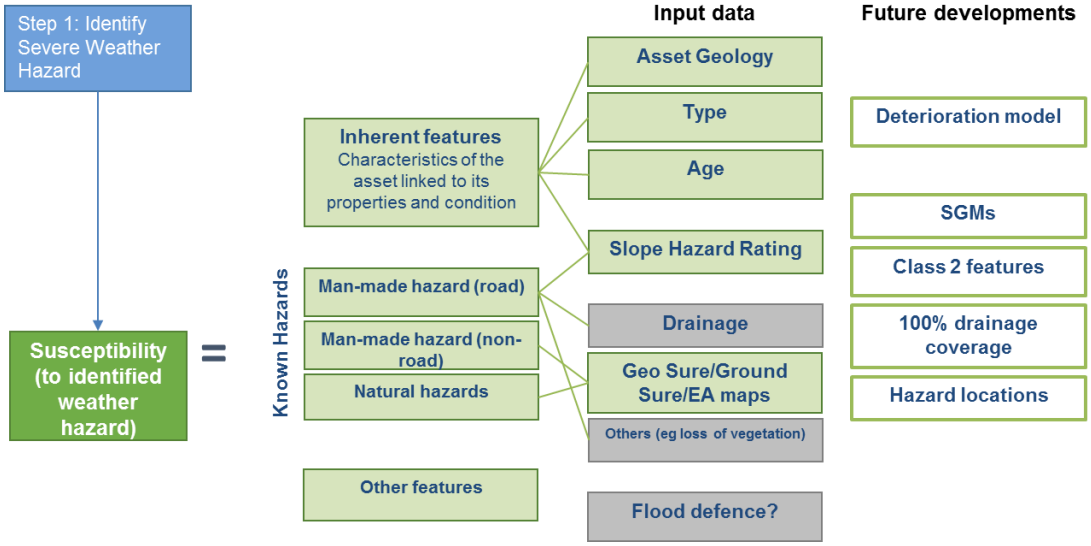


Figure 11: Susceptibility model

HD 41/15 makes reference to severe weather events acting as triggers for potential defects on the network. Tasks 197 and 580 have identified potential ground hazards and their possible triggering mechanisms, including weather hazards. The summary table in Appendix B.1 shows how severe weather hazards considered in this task relate to geotechnical events and, for each severe weather hazard, which factors would be considered in the vulnerability assessment.

The spatial location of all potential ground-related hazards is not fully known. For example, the British Geological Survey's GeoSure mapping uses qualitative scales from 'very likely' to 'very unlikely', where even the lowest category does not say that there is no potential for this hazard. Moreover, this assessment does not represent an exhaustive list of the potential ground-related hazards facing the SRN. Continuing work as part of the geotechnical knowledge development programme is seeking to enhance understanding in this area.

4.5 Step 2C: Coping Capacity

Coping capacity is defined in the context of this task as *"the ability of the network to function were asset performance to be compromised and it is inversely proportional to criticality".*

One of Highways England's strategic objectives is for efficient and effective delivery to improve journey times which will subsequently support UK economic growth. As such, Highways England will be required to give "*more weight to the impact of disruption when making investment decisions*" (DfT, 2015b).

The proximity of geotechnical assets to the carriageway is assessed where defects have been identified as per the guidelines of HD41/15. This aspect is particularly important to consider for smart motorway schemes which utilise hard-shoulder running. A geotechnical asset failure could potentially cause greater disruption to traffic and to other assets where there is hard-shoulder running within them. Severe weather events can result in significant disruption to the SRN. For example, during the 2007 floods, the SRN experienced 2% of its delays, for one year, on one day (20th July) alone.

Task 419 (Arup, 2015) developed a user criticality index for the SRN based upon traffic flow data. This index has been incorporated into our definition of coping capacity.

In the context of this study and following Task 419, there are two measures currently used to define criticality:

Criticality - "The importance of the network proximate to the asset". (Arup, 2015)

1. *Strategic Criticality (the strategic importance of the affected section of the network).* The European Ten-T network, which includes a number of Highways England SRN routes, is used as a proxy for the strategic criticality of the network (Figure 12). This results from their linking the ports, airports and key industrial areas between Ireland, the UK and mainland Europe.

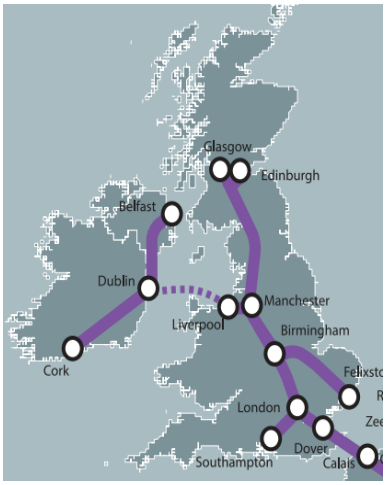


Figure 12: The UK Ten-T network

2. *User Criticality – the potential for delays and disruption to road users as a result of asset performance.* A measure based on traffic data has been defined to represent 'user criticality' i.e. the importance for the users of the affected location.

Improvement and development of a criticality measure, to be used for prioritising asset management decisions is ongoing within Task 694. We recommend that this be incorporated into the framework as the classification of criticality is defined further. For example, an important component of understanding the criticality of an affected location is the interdependencies with other infrastructure assets, such

as local authority roads, rail, energy corridors etc. Currently the proposed criticality measure focuses only on the impacts to Highways England's objectives, but interdependencies should be an essential part of further developments.

4.6 Step 3: Establish weather threat

Weather threat is defined in the context of this task as *"likelihood of occurrence of the severe weather hazard"*.

Once a particular weather hazard has been established (see Section 4.2), if information is available, then a likelihood of occurrence should be assigned to it. A distinction should be made for:

a) **Imminent weather**, this can be assessed by a weather alert system and level of warning, e.g. Red / Orange / Yellow alerts issued by MetOffice.

b) **Future weather events** e.g. through the probabilistic scenarios of climate change projections (e.g. UKCP09 and/or H++ scenarios). These provide users with a range of potential likelihoods of occurrence e.g. number of days per year of severe rainfall.

Model complexity will be based on:

- Level of detail of the weather conditions that can be assessed e.g. 'Severe Rainfall' vs '4 day average of more than 30mm/day'.
- The ability to quantify the likelihood, e.g. 'Low likelihood' vs '100 year Return Period'.

Figure 13 proposes stages of increasing maturity for estimating severe weather threats.

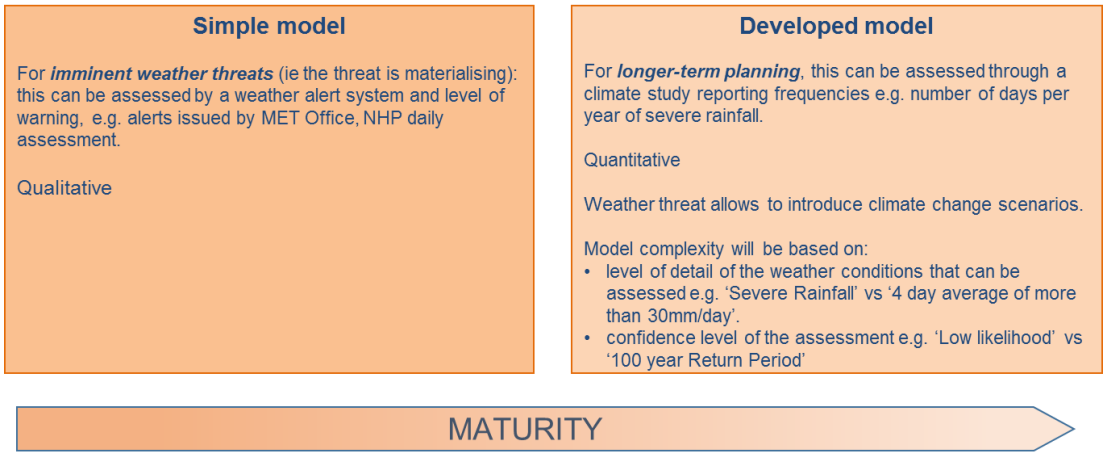


Figure 13: Modelling maturity for weather threat

4.6.1 Incorporation of climate change

Geotechnical assets have long design lives, often in excess of 60 years (Highways Agency, 2011). As such, the impact of future climate change on the frequency and magnitude of severe weather events requires consideration, otherwise such a study is prone to 'serious weakness' if we assume that conditions will remain similar to present (Jaroszweski et al. 2010). It has also been argued that changing weather conditions exacerbated by climate change may also create new 'problem sections' where performance issues have not previously occurred (Chapman, 2015).

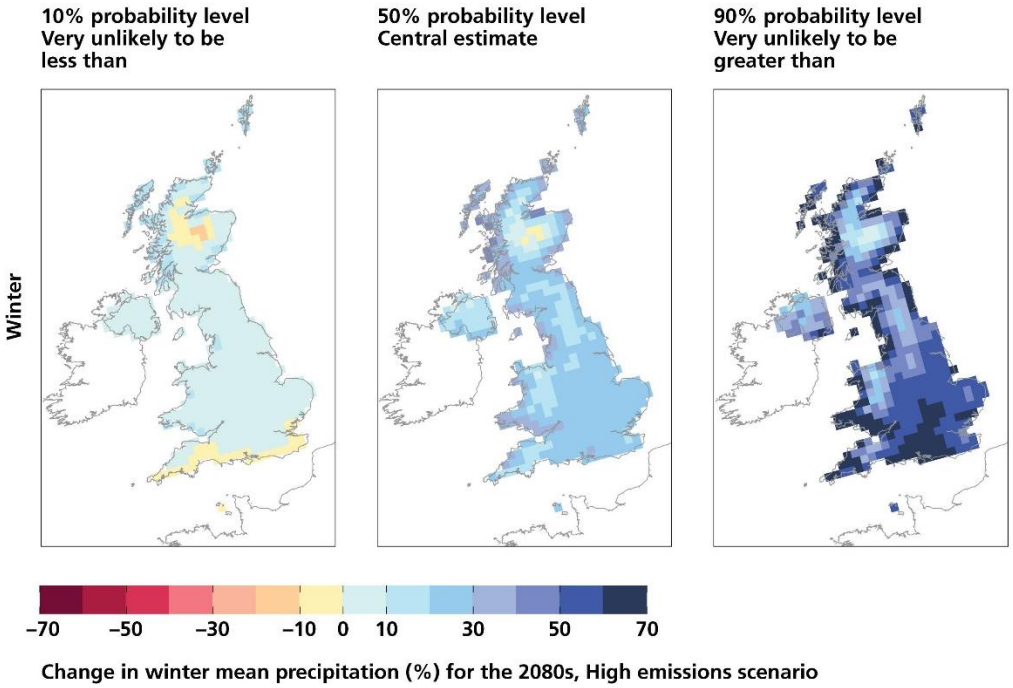


Figure 14: Changes in winter mean precipitation (%) for the 2080s, High Emissions scenario (Source: UK Climate Projections)

United Kingdom climate change projections (UKCP09) suggest that the UK will experience more severe weather throughout the 21st century (Jenkins et al. 2009). In particular, UKCP09 indicates more frequent wetter, warmer winters and hotter, drier summers, with increased periods of heavy rainfall for certain areas of England. These are summarised in Figure 14 above.

Figure 15 shows the impact that potential climate change would have on severe and extreme weather events, effectively changing the probability of occurrence of a severe weather event. Other transport network owners in the UK, such as Transport for London (TfL) have already used the UKCP09 projections to assess

the future risk and return periods of severe weather for assessing potential impacts on the London Underground (TfL, 2015).

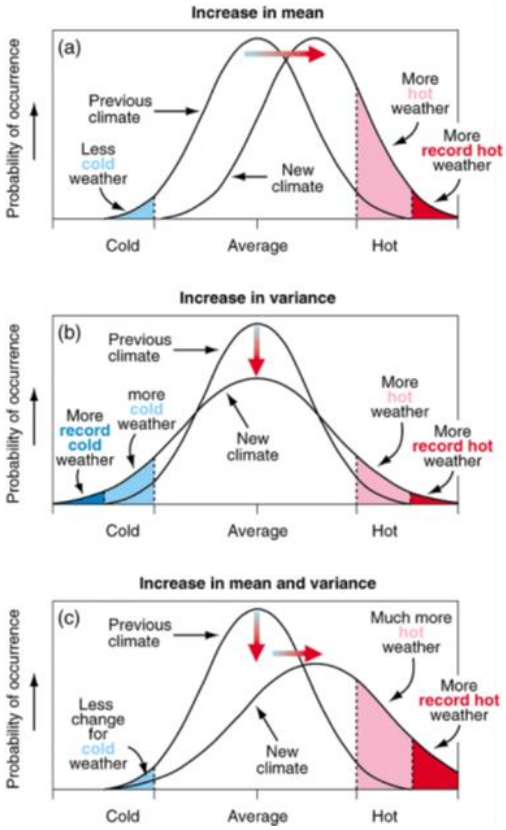


Figure 15: Impact of climate change on severe and extreme weather probability (Source: Solomon, 2007)

Climate change projections have been incorporated into Highways England design standards for pavement design, a result of previous high temperature events causing damage to pavement surfaces. In the future, new regulatory requirements will mandate a future-proof design that takes into account projected climate variations, an example is DfT's requirements for critical infrastructure that already exists as well as and the design of new build infrastructure projects such as those incorporated into HS2 design standards

Climate change is also likely to have an impact on maintenance regimes, as illustrated in Figure 16 below. Academic research projects, including Futurenet (Dijkstra et al. 2014) and iSMART (Glendinning et al. 2015) have begun to attempt incorporating climate change data into assessing the resilience of geotechnical assets along transport route corridors; this remains an active area of research.

> *"Where transport infrastructure has safety-critical elements and the design life of the asset is 60 years or greater, the applicant should apply the UK Climate Projections 2009 (UKCP09) high emissions scenario (high impact, low likelihood) against the 2080 projections at the 50% probability level."*
>
> (Department for Transport, 2014b)

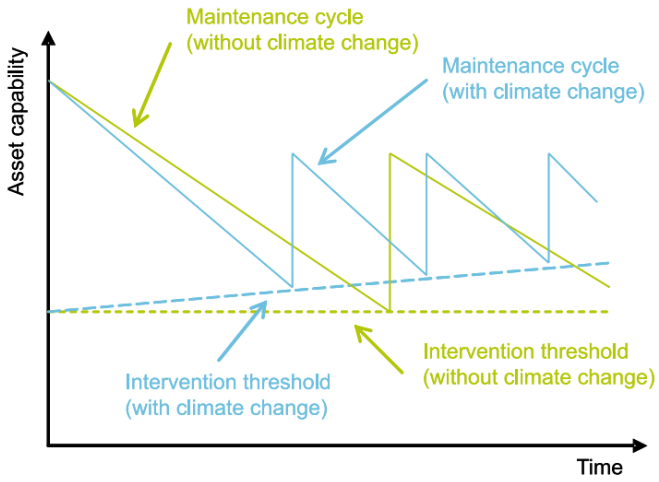


Figure 16: Representation of influence of climate change (or severe weather) on maintenance cycles (Source: Highways Agency, 2009)

Therefore, climate change projections available within UKCP09 could be incorporated into Step 3 of the resilience framework. Future model developments could include a 'Current weather scenario' looking at the likelihood of severe weather events with a 20-40 year time horizon (e.g. UKCP09 2030 (2020-2049) scenario) and 'Future weather scenario' for 40-60 year time horizon (e.g. UKCP09 2080 (2050-2099) scenario).

4.7 Step 4: Evaluate risk

Due to the many uncertainties (epistemic and aleatory) associated with severe weather impacts on geotechnical assets, a risk-based approach is required for the purposes of this assessment.

Risk is defined in the context of this task as *"the likelihood of the weather event occurring combined with the expected level of impact a resulting geotechnical event has on the network (Vulnerability)*

Risk is therefore defined as:

$$Risk = Threat\ x\ Vulnerability$$

An illustrative risk framework is shown in Figure 17.

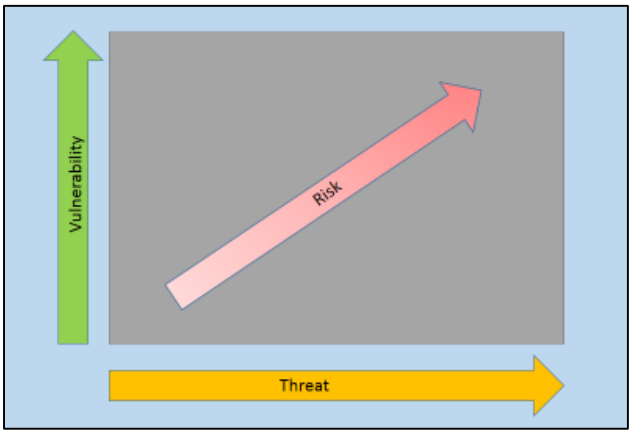


Figure 17: Illustrative risk framework

It is recommended that a 'tolerable risk' level that geotechnical assets present in severe weather events is defined and agreed with Highways England in terms of minimum acceptable level of performance (e.g. safety, customer experience, smooth and free-flowing network). This approach would help to focus and prioritise resilience enhancement interventions.

A similar approach has already been adopted by others, see example from Network Rail where tolerable risk is defined in terms of safety (Figure 18).

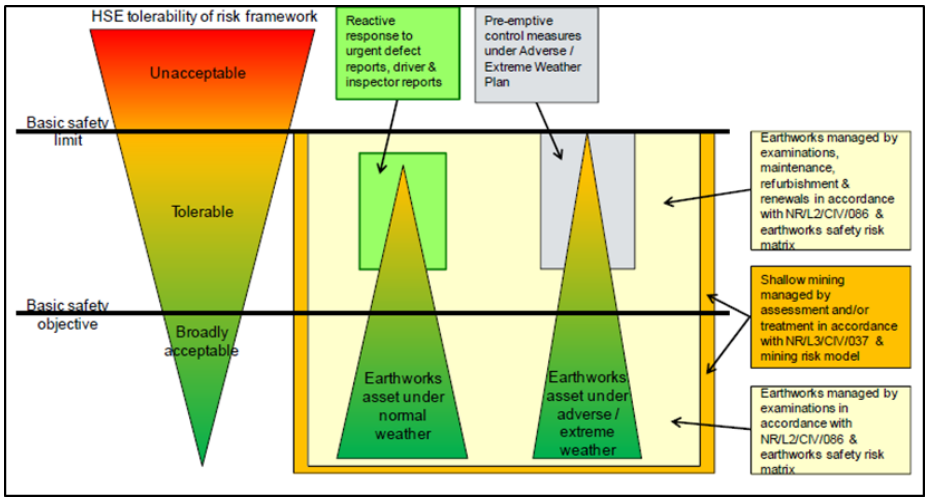


Figure 18: Network Rail tolerability of risk framework mapped against the HSE framework

4.8 Step 5: Options appraisal

The final stage of the assessment is to use the understanding of risk, i.e. the likelihood and the impact on the network of geotechnical events due to severe weather, and combine this with potential options in order to provide a tolerable level of resilience. For example, high risk scenarios may require proactive interventions to prevent their occurrence, whereas low risk scenarios may provide acceptable resilience simply through provision of reactive solutions such as temporary road closures. Results of the assessment will not only help planning

prevention, adaptation and mitigation of disruptive events but will also inform the recovery processes required to maintain functionality immediately following the severe weather event.

Resilience management goes beyond risk management to determine how a system can adapt to and recover from shocks, not only avoid or mitigate them. For those assets assessed to present a low risk to the SRN during severe weather events, it is argued that their resilience is tolerable, and no further assessment is required. For those assets assessed to present a moderate or high risk, additional categorisation in terms of their ability to respond and recover from an event is required in order to provide an overall categorisation that will allow options to be identified.

DfT (2014a) regard the restoration of services and routes as quickly as possible to near pre-event levels as an indicator of an asset's resilience (recognising that removing all risk is prohibitively expensive). As such, those assets which are at 'High Risk/Low Resilience' (Figure 19), where resilience in Figure 19 is essentially the time taken to respond and recover to an event, should be prioritised, these assets are not only more likely to suffer potential failure and loss of critical functionality, but would also likely result in significant disruption to the SRN (e.g. road closure for weeks/months) because they take the longest to recover from the adverse event.

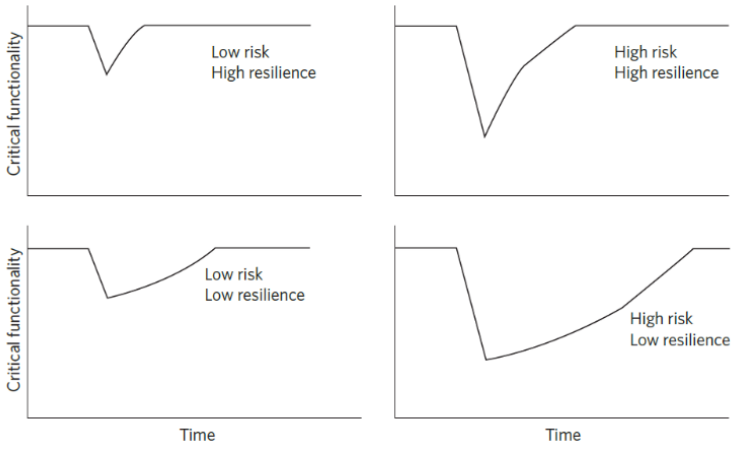


Figure 19: Schematic representation of changes in critical functionality over time and interplay of risk and resilience in during an adverse event (Linkov et al. 2014)

4.8.1 Response and recovery

Categorisation of response and recovery requires an understanding of:

(a) Time to resume normal operation at the affected location

(b) Cost of response and recovery options

Typically, these two will be strongly correlated, since more expensive repairs for example, are also likely to take longer. The response and recovery 'ratings' will relate to the type and mode of failure.

4.8.2 Adaptation

Adaptation is a key component of a resilience framework, see also Highways England's adaptation framework (Section 5.3).

Adaptation strategies should not be particularly focused around specific severe weather types, but rather be able to cope with a diverse range of events (Bollinger et al. 2014). For example, the UK may see a reduction in days subjected to freezing conditions according to UKCP09, thus potentially lowering the risk of failure of rock slopes to freeze-thaw processes (Jenkins et al. 2009). Adaptation should also consider the impact of changing socio-economic conditions (e.g. road-users) which could increase the criticality and hence vulnerability of a particular geotechnical asset (Section 4.3.3) **(**Jaroszweski et al. 2010).

When selecting and prioritising those assets requiring adaptation measures, it is important to consider the level of risk and resilience of an asset in response to a severe weather event. Potential adaptation options

Potential adaptation options presented below have been informed by the latest CCRA update (Highways England, 2016). They are presented here with a focus on geotechnical assets resilience to severe weather.

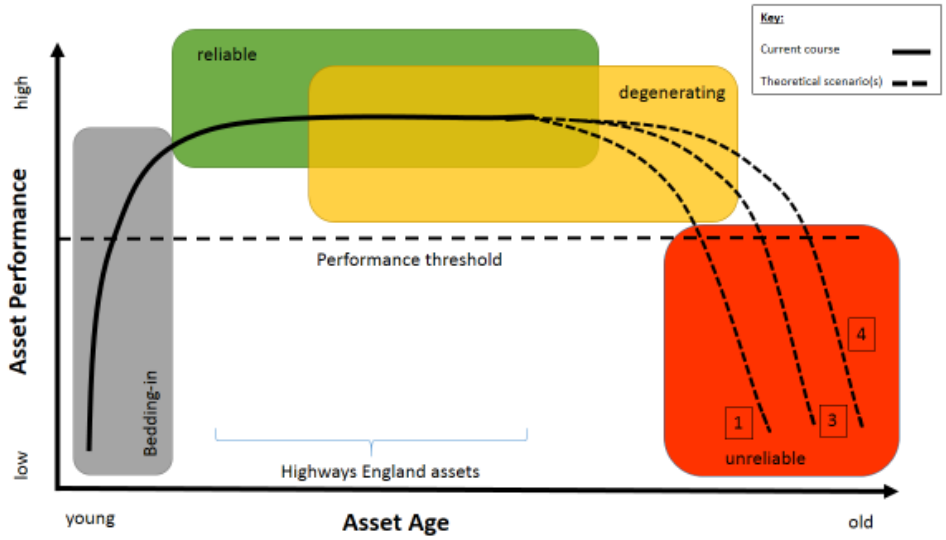
Table 3: Potential adaptation measures

Adaptation measure	Description	Pre-event	Post-event	Suitability
1 - Do minimum	Do not implement any adaptation plans or resilience measures. Overall asset vulnerability would be low, meaning that at present they appear resilient to severe weather events. Suggest that continued monitoring of vulnerability and risk is undertaken.	N/A	N/A	Low risk assets
2- Develop contingency plans	Development of a pre-planned response for when a severe weather risk is realised. Such a pre-planned response may include the re-routing of traffic or closure of the hard shoulder. Monitoring, including remote monitoring of geotechnical assets can be used in combination with response planning.	N/A	Y	Medium to high risk assets with moderate resilience (i.e. recovery time is relatively short) Should be incorporated in organisational procedures

Adaptation measure		Description	Pre-event	Post-event	Suitability
3 - Retro-fit solutions (proactive maintenance)	3A - Incremental adaptation	Incremental adaptation is decided and implemented over successive short timescales (10 years for instance). The advantage is to manage climate change uncertainty iteratively, based on gradually increasingly reliable climate change, reducing the risk to commit to highly expensive investment which could turn out to be inadequate	Y	N/A	Medium to high risk assets with low resilience Increased resilience achieved through gradual investment
	3B - One-off adaptation	Assumes that adaptation is undertaken once to deal with long-term (e.g. over asset life). This could take the form of construction of special geotechnical measures to remediate an existing hazard. However, there is potential for the uncertainty associated with climate change projections resulting in adaptation measures which are not future proof.	Y	N/A	High risk assets e.g. critically important to the smooth running of the SRN Requires substantial investment
4 - Develop future-proof designs		This adaptation measure is aimed at construction of new assets, but also equally applicable to assets that undergo improvement measures. Knowledge of severe weather impacts on vulnerability and risk could be used to assess how climate change projections would impact on potential designs. Technology solutions, e.g. remote monitoring may be incorporated in to future design solutions.	Y	N/A	All assets

Figure 20 provides an interpretation of how particular adaptation options may affect (adversely or positively) the deterioration of a geotechnical asset.

At present, Highways England's geotechnical assets fall within the reliable and degenerating phases. However, without consideration of the adaptation options discussed above, then continued severe weather and long-term climate change may result in accelerated deterioration and ultimately result in an asset becoming unreliable; a future potential scenario under a 'do minimum' scenario could be reflected by the state of Network Rail's current earthwork portfolio (see Figure 20).



Adaptation options:
[4] – 'Do Minimum' [3] –'Retro-fit solutions' [1] – 'Develop future-proof designs'

Figure 20: Generalised deterioration curves for Highways England adaptation options

4.8.3 Maintenance

Nemry and Demirel (2012) argue that potential damage and failure of transport network assets as a whole are often due to sub-optimal maintenance. Maintenance, such as maintenance of defective drainage, is low cost and easily implemented. For example, an ongoing Highways England task has found correlations between drainage defects and geotechnical asset performance (Mott Macdonald, Task 434, April 2016).

4.9 Outputs

Resilience outputs are envisaged to be presented spatially on HA GDMS. The HA GDMS interface could be developed to visualise a particular geotechnical asset's vulnerability and risk to severe weather. This information can also then be displayed alongside other relevant assessments (e.g. drainage) to prioritise maintenance activities.

The example below (Figure 21) shows similar visualisation of at risk slopes with real time readings of rainfall and wind from weather stations.

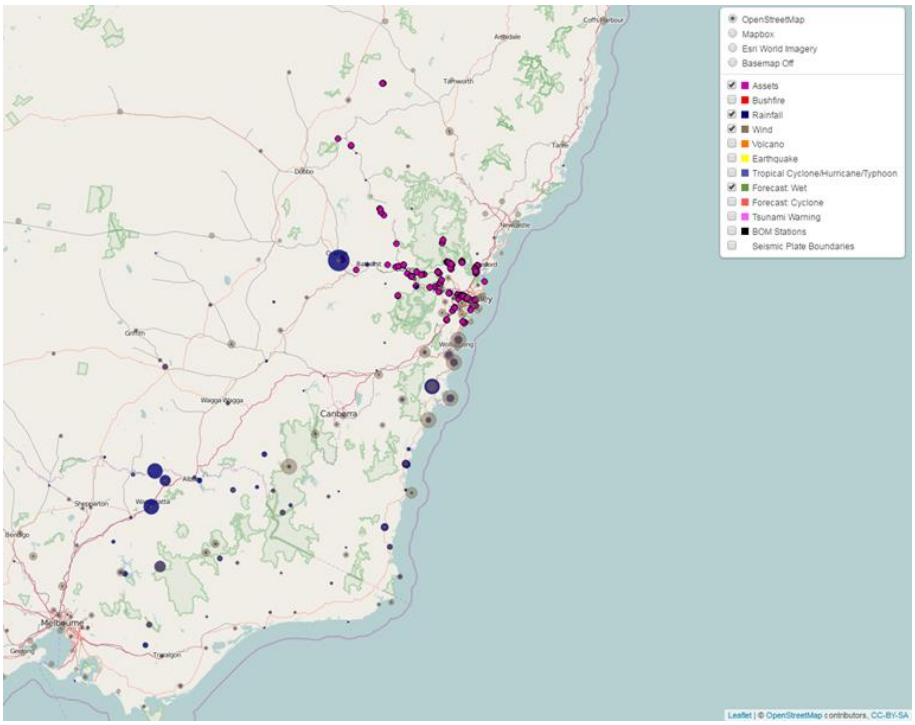


Figure 21: Arup Hazard Owl, visualisation of at risk slopes and weather information in the Sydney area

Currently, geotechnical asset data is available through HA GDMS and the Geotechnical Asset Database (GAD); weather data through HA WIS, with data sourced from Highways England's ESS's, NHP, Met Office and other recognised weather service providers; and climate change projections through UKCP09 and when available, the forthcoming UKCP18.

However,several data layers within HA GDMS allow for visual interpretation only (e.g. BGS Geosure layers), with work ongoing to spatially intersect relevant hazard attribute information with particular geotechnical assets.

Consequently, we propose a similar approach to that defined in the previous sections in terms of modelling maturity for the creation of the overall assessment outputs. These maturity levels are presented in Figure 22.

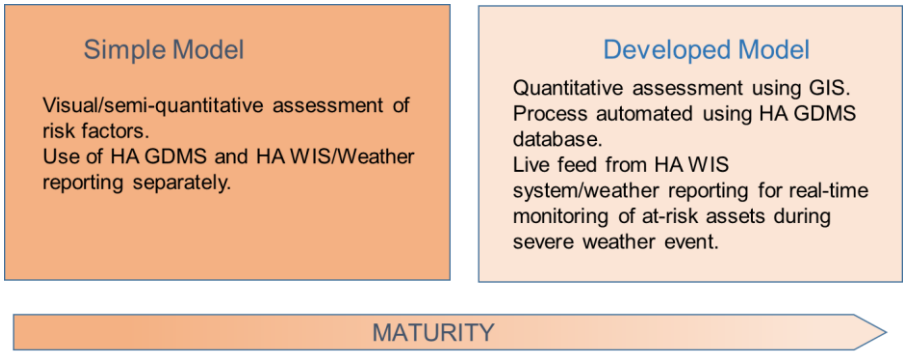


Figure 22: Modelling maturity of risk assessment output mapping

Presently, Highways England are only able to implement the '*simple model*' approach. It is proposed to present the individual factors as layers within HA GDMS which during a severe weather event can be assessed using the five-step framework approach (see Figure 5b).

Potential also exists to incorporate rapid response monitoring of particular assets using weather data of increased granularity, which is a similar approach that Network Rail takes on its most vulnerable slopes. The network of ESS's under ownership of Highways England could form the basis of such monitoring, which would be coupled with external weather information providers for forecasting purposes (e.g. Met Office and NHP).

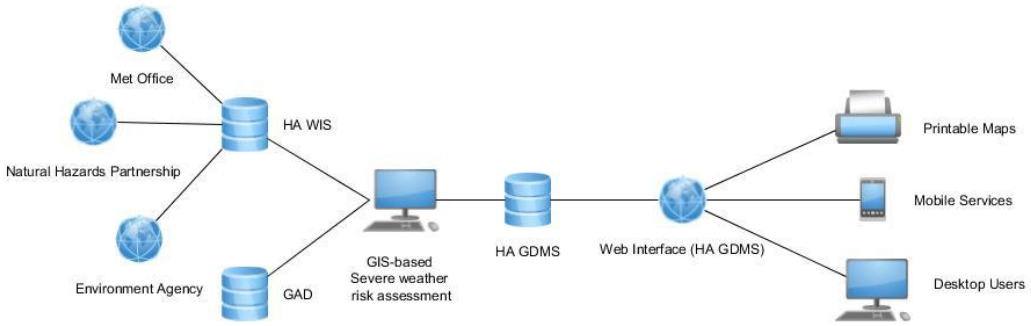


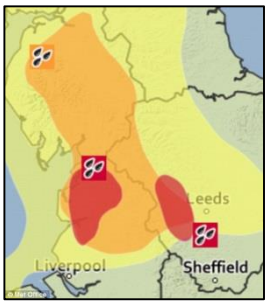
Figure 23: Potential GIS architecture for real-time estimation of severe weather risk to geotechnical assets

The proposed '*developed model*' relies upon an integrated system, whereby geotechnical asset information and real-time or near real-time severe weather information can be used for rapid and automated GIS assessment to provide assessment of asset risk. This supports and aligns with Highways England's proposal for an integrated asset management system (i.e. IAM-IS). An example architecture of such an integrated GIS system for assessing the risk of severe weather to Highways England's geotechnical assets is given in Figure 23; this could also be extended to mobile devices for those tasked with monitoring slopes in affected management areas.

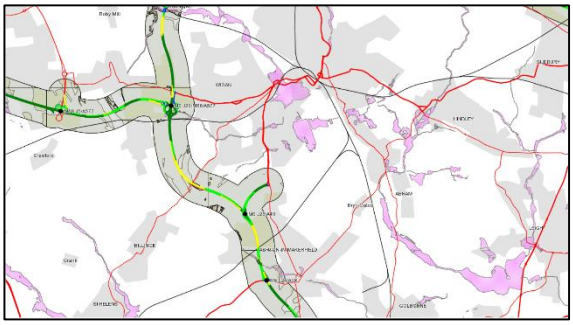
4.9.1 'Proof of concept' pilot study

This section presents an example methodological approach, using the '*simple model*' approach, to assess the *risk* of geotechnical events due to severe weather.The approach represents an '*off-line*' demonstration of the potential for mapping vulnerability and risk using the framework outlined in the preceding parts of this section.

Using the current *simple model* approach, a user would take the following steps:



1. Severe weather warning given by e.g. HA WIS, Met Office (e.g. an amber rainfall warning), Natural Hazards Partnership or similar organisation.
2. Establish severe weather hazard, informing vulnerability assessment (e.g. heavy rainfall)
3. Undertake vulnerability assessment
   (a) Exposure – regarded as **geotechnical assets exposed to severe weather event** (i.e. spatial extent of severe weather event – see step 1), and identify all geotechnical assets in that area.
   (b) Susceptibility – **use layers provided within HA GDMS or data available within GAD** (e.g. see Figure 19) to identify those geotechnical assets susceptible to rainfall related problems.



   (c) Coping capacity (i.e. 1/Criticality) – **Information not currently available** within HA GDMS to prioritise those assets identified in (b) above according to their potential to impact on the network.
4. **Categorise** those assets vulnerable to the severe weather event. This may be classed qualitatively (High-Low); or assigned categories (e.g. A-E). This would require analysis of the data to understand the distribution of vulnerable assets to make a meaningful assessment of risk to severe weather.

Following the steps outlined above, a 'proof of concept' pilot study has been undertaken using a simple model approach, Geotechnical Asset Data (GAD) from HA GMDS only. Results and limitations are summarised in Appendix D and sample outputs are shown in Figure 24. The pilot could be enhanced in future by incorporating outputs from the knowledge improvement tasks (in particular the work related to Special Geotechnical Measures and Geo-Hazards).

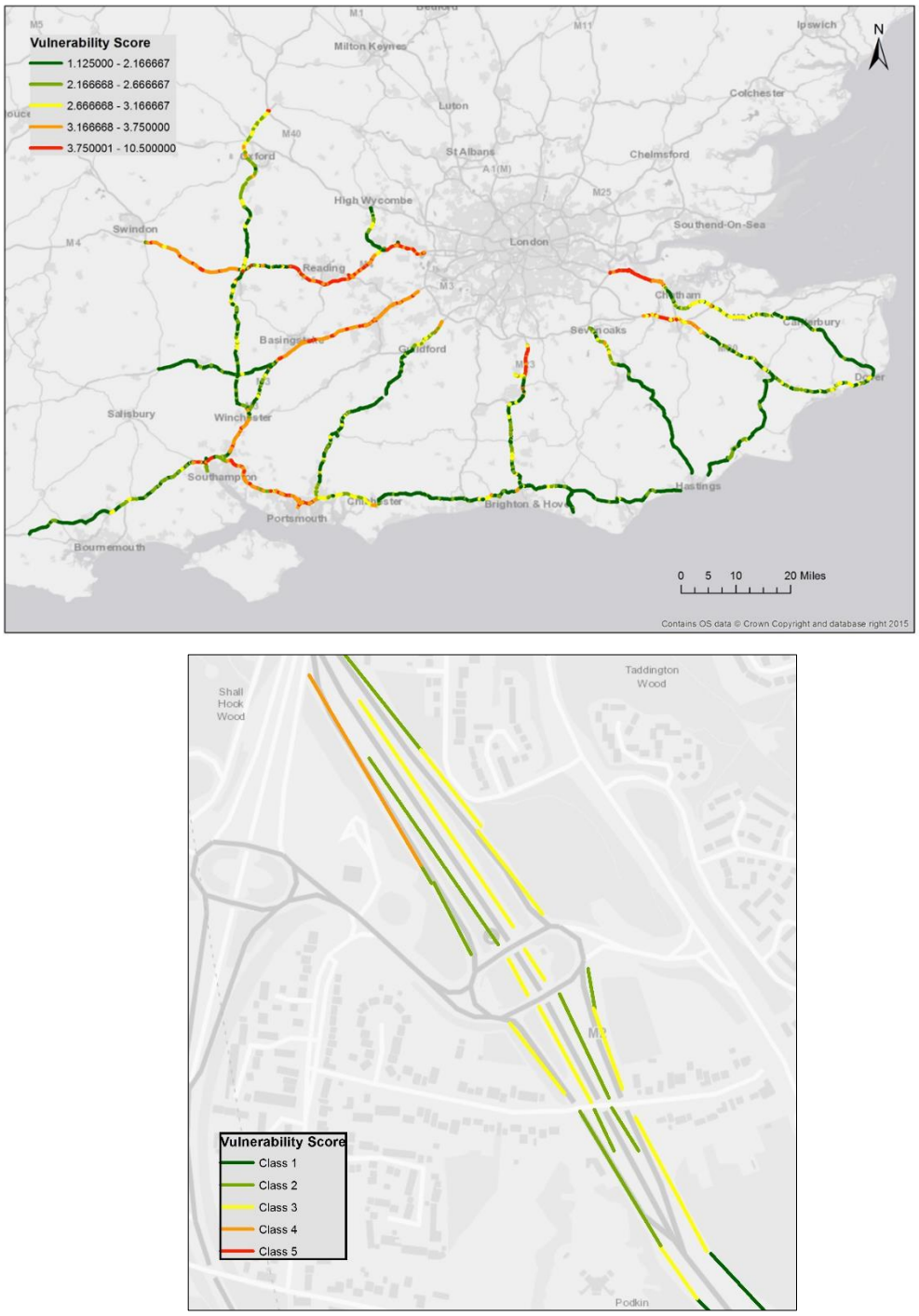


Figure 24: Example spatial outputs from the 'proof of concept' pilot study.

5 Discussion

5.1 Knowledge gaps and uncertainties

Highways England have suffered relatively few geotechnical asset 'failures' (see Section 2.4) to date. The inherent overall resilience of geotechnical assets to severe weather is predominantly a factor of their construction to 'modern standards' associated with the relatively young asset age, in fact only 1.1% of assets predates 1960. However, this is not to say that failures don't occur, and several significant events have manifested themselves on the SRN (Arup, 2015). One such example was the formation of a cavity in the central reservation of a section of the M2 (between junction 5 and 6) in Kent in February 2014. This resulted in the formation of a 4.5 metre deep hole (Figure 25).

Figure 25: M2 Sinkhole, Kent (Source: Highways England)

Such reported issues are estimated to result in costs to Highways England of £20 million per annum (Arup, 2010). Problematically, relatively few geotechnical incidents mean that **it is difficult to associate, with statistical accuracy, a particular weather event and establish how it contributed to or triggered a ground-related response**.

A number of **asset knowledge gaps** are highlighted in the following sections.

5.1.1 Susceptibility factors

Some of the susceptibility factors identified in Section 4.3.2 either:

- are not represented spatially (e.g. SGMs)
- are of poor data quality (e.g. location of defective drainage)
- have poor geographical coverage within HA GDMS (e.g. drainage assets).

This **epistemic uncertainty around data and information means that the risk assessment cannot incorporate all known inherent properties at present** to establish an assets particular vulnerability to severe weather. However, ongoing work as part of Highways England's Geotechnical Knowledge Development Programme is currently addressing these gaps in asset knowledge, see Appendix A.1.

Added to uncertainty around the asset is the **natural variability, or aleatory uncertainty, associated with ground conditions and ground-related hazards**, **further exacerbated by severe weather and climate probabilities**; climate modelling by its nature is very uncertain (Vardon, 2015).

5.1.2 Impact of weather events

The Scoping Study report identified that severe weather and climate change will have a profound effect upon the long-term performance of geotechnical assets if appropriate intermediary action is not undertaken (Chapman et al. 2015; Glendinning et al. 2015; Vardon, 2015). Academic research projects such as iSMART are assessing slope response to daily and seasonal weather (e.g. A34 Newbury Bypass). This will establish, through continued monitoring, particular weather thresholds that may have an adverse impact on geotechnical assets. However, these have been carried out at discrete locations and for particular geologies, and not as part of a network-wide study. Research projects are currently ongoing in this space but **we are not currently in a position to extrapolate asset response to severe weather at network or route level**.

5.2 Current state and next steps

As discussed in Section 4.4, the likelihood of the severe weather event (weather threat) element of the framework needs to be established in order to be able to fully assess the risk of the long-term impact of severe weather on Highways England's geotechnical assets (see Figure 26 below).

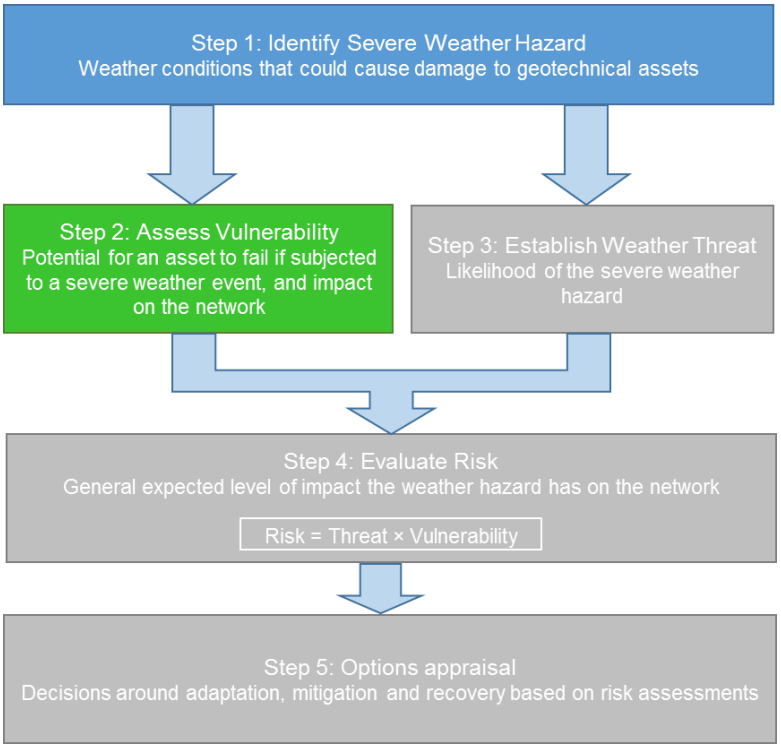


Figure 26: Current state of resilience framework

At present the first two steps of the proposed framework can be used to **categorise assets and inform strategic decision making on prioritisation of interventions on the basis of asset vulnerability to a given severe weather type** (i.e. assuming a likelihood of the weather event of 1.0, or certainty). Outputs from related knowledge improvement tasks (in particular the work on Special Geotechnical Measures and Geo-Hazards) will inform the vulnerability assessment in the future.

Proposed next steps in (from simple to more developed models) are highlighted in Sections 4.2 to 4.8. The ongoing suite of tasks by Highways England will increase their knowledge regarding residual geotechnical risk on the SRN, with the ultimate aim of guiding investment to maintain performance and increase network resilience.

5.3 Towards a resilient approach

Climate change projections suggest that the SRN will be subject to a higher frequency of severe weather events, albeit with significant uncertainties encompassed within such projections. Highways England is recognising the need

to address this issue and stated in their Climate Change Risk Assessment (CCRA) (Highways England, 2016) that they would:

> *"adapt its network to operate in a changing climate, including assessing, managing and mitigating the potential risks posed by climate change to the operation, maintenance and improvement of the network."*

The task outputs have been formulated to align with the longer term climate change adaptation objectives stated above. Climate change has been factored in through incorporation of weather type probability within the risk assessment (Step 3, Section 4.4).

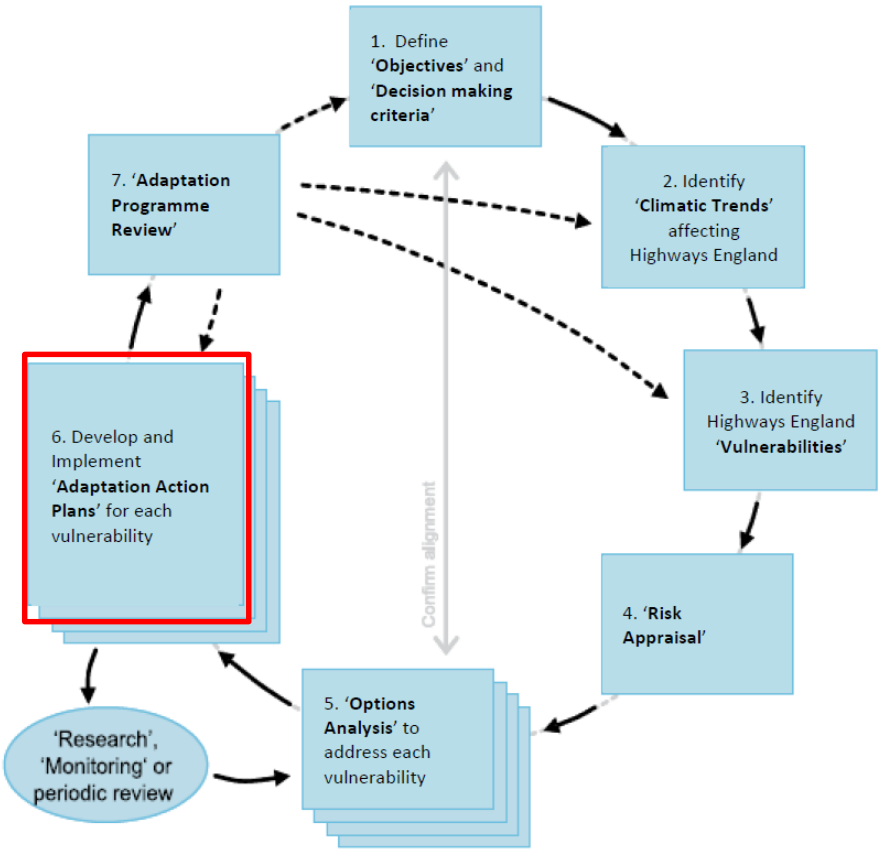


Figure 27: Highways England climate change adaptation framework (Highways England, 2016)

Highways England's CCRA (Highways England, 2016) suggests that geotechnical assets should be classified as low vulnerability to climate change and that the resultant action is to 'do minimum'.

However, the following considerations are true for geotechnical assets:

- They have long design lives and are therefore more likely to be exposed to longer-term climate change. Climate change impacts having not been considered in the original design basis.

- They have been built over, or through, areas of ground related hazards
- Measures designed to 'engineer out' these hazards are aging, and are subject to deterioration (as are the assets themselves) (Power et al, 2016).

The resilience framework set out in Section 4 proposes a more focussed assessment of the vulnerability of geotechnical assets whilst using existing asset knowledge base and incorporating work from related tasks (e.g. Review of geotechnical asset data (Task 416), Strengthened earthworks (Task 594), Specification for Priority Drainage Assets (Task 433), Sustainable Drainage Strategy Phase 3 and Drainage Panel of Experts (Task 434), National Geotechnical Hazard Review (Task 197)).

5.4 Interdependencies of geotechnical assets

The primary function of geotechnical assets is to support other assets (see Appendix C.1). Therefore, establishing an asset's resilience should rarely be considered in isolation (Hudson et al. 2012). Interdependencies are now recognised by Government, infrastructure operators, and within academic projects (e.g. Infrastructure Transitions Research Consortium (ITRC) and International Centre for Infrastructure Futures (ICIF)).

> *"Understanding of the vulnerability of the organisation to these risks, their primary impacts, and to secondary impacts including through dependencies on other infrastructure and essential service providers."* (Cabinet Office, 2011)

In their natural hazard resilience framework, the Cabinet Office (2011) argue that understanding infrastructure dependencies is key to a particular asset's vulnerability.

It is likely that even more equipment will be supported by eotechnical assets (e.g. cabling, signs, noise barriers) in future (Arup, 2010). For example, smart motorway networks, following the investment announcement for 1,300 miles of additional capacity in the 2014 National Infrastructure Plan (HM Treasury, 2014) impose additional demands on geotechnical assets. This may lead to an increased likelihood and frequency of minor geotechnical asset performance issues to result in network disruption. Predominantly because running lanes will move closer to embankment crest or base of cutting, but also due to the increased reliance on telecommunications and energy networks for controlling smart motorways which are buried within the geotechnical asset. Mott Macdonald (2014) argue that poor installation of telecommunications ducting could lead to geotechnical issues arising; similar is suggested of drainage.

Highways England are aware that geotechnical assets form part of a system, as included in the CCRA (Highways Agency, 2011), and that the SRN system is part of the UK transport infrastructure 'system-of-systems'. Identification of interdependencies both between Highways England's assets, and between the SRN and other infrastructure, will help to increase the overall resilience of Highways England and its co-dependent stakeholders (Cabinet Office, 2010 and 2011).

Highways England (2016) has identified a number of key stakeholders who are important for delivering a resilient network, including:

- Freight organisations (users of network, on which UK Plc. economy, society and commerce depends)
- Local authorities (especially important when considering diversionary routes during an incident)
- Technology and innovation partners
- Sustainability and environmental bodies
- Motorway service operators

Interdependency analysis is recognised as being an important component of criticality, and should be incorporated into an asset's coping capacity (or criticality).

6 Conclusions

This task has developed a framework for the categorisation of Highways England's geotechnical assets according to their resilience to a range of extreme weather events. To ensure the continued resilience of Highways England's geotechnical assets and the SRN overall, a number of steps are required to be implemented. Within the scope of this task we have developed an **approach for assessing the vulnerability of Highways England's geotechnical assets** to severe weather events, and the risk this presents. This approach sits in a wider resilience framework (see Figure 5a) and could equally be applied to other asset groups across the SRN (e.g. structures).

A **five-step resilience framework** has been developed. As a whole, the proposed assessment methodology has been designed to align with other similar severe weather resilience approaches across transport networks in the UK, Europe and the USA (Arup, December 2015).

The currently proposed framework is based on a 'simple model' approach.

Aspirations and next steps for refining and further developing the proposed model have been set out in Sections 4 and 5. A more developed model will deliver a greater understanding of the vulnerability of geotechnical assets supporting the SRN to severe weather events (particularly locations of residual risk).

A number of high level resilience adaptation options have been presented (Section 4.8), which align with Highways England's current thinking regarding the latest update to the CCRA. The proposed framework provides Highways England with the ability to categorise and prioritise those geotechnical assets which require adaptation measures to increase their resilience to severe weather events (**currently on the basis on their vulnerability**). This will become particularly pertinent when incorporating longer-term climate change impacts.

Related tasks are being undertaken to better understand the performance of special geotechnical measures (SGMs) and improve datasets providing information on geotechnical hazards. Combined with this and follow-on activities about resilience, this 'knowledge programme' will provide Highways England with an enhanced understanding of their risk and resilience, through smarter use of data (see also Section 4.2 and Figure 7).

6.1 Recommendations for further work

6.1.1 Severe weather plan update

Highways England's severe weather plans set out the operational response to severe weather events, ensuring the continued running of the network. These plans currently focus on route-level operational planning e.g. ice, snow, cross winds and flooding events.

There is scope to incorporate the findings of the resilience assessment into severe weather plans. This would require an understanding of the frequency of

geotechnical events related to severe weather. This would enable the area teams to be prepared for the potential impact(s) of severe weather on geotechnical assets.

6.1.2 Enhance understanding of weather thresholds

Establishing a specific weather trigger, which causes a hazard to occur (e.g. sinkhole, rock fall or slope instability) is of importance to Highways England. This is particularly so when attempting to establish emergency response measures to forecast severe weather events, as well as understanding the frequency of geotechnical events, both currently and in the future. However, the limited number of failures of Highways England Geotechnical assets mean that it isn't possible to do this at present.

Highways England are currently working with academic organisations and research projects (e.g. iSMART) to assess particular responses of their geotechnical assets to weather events and longer-term climate change. This is an active area of research, which requires further work and input from Highways England to bring it to an appropriate standard for application across the SRN's highly variable geotechnical assets.

Once information is available, such recognition of potentially hazardous weather thresholds would allow a more detailed prioritisation of assets which are classified at-risk of such severe weather events.

6.1.3 Further assessment of climate change projections

The long design life of geotechnical assets (i.e. > 60 years) requires Highways England to undertake an assessment of climate change projections, as stated in the DfT's National Policy Statement for National Networks (DfT, 2014b).

Although not assessed quantitatively in this resilience assessment, downscaled climate projections (e.g. 5km resolution) could be used to assess future risk to Highways England's geotechnical assets. Assessment of potential return periods of climate variables (e.g. rainfall) is required to understand future vulnerability and risk to a geotechnical asset. This will become particularly pertinent once specific weather thresholds (Section 6.1.2) are established.

Moreover, the forthcoming UKCP18 will provide sub 5km resolution outputs which would be appropriate for assessing individual or route asset groups. A 'watching brief' on the CP18 projections, and their significance for geotechnical assets, is recommended.

6.1.4 Updating of coping capacity assessment

The definition of coping capacity, which is simply the inverse of criticality (Task 419) has been included in the resilience assessment. It was stated in Section 5.4 that geotechnical assets' primary function is to support a range of other assets, both associated with Highways England as well as other infrastructure networks (e.g. energy and telecommunications) known as interdependencies.

Emergency planning measures, such as the re-routing of traffic should also seek cooperation with adjoining local authority road networks; lessons for this should be learnt by the recent events in Cumbria during the winter of 2015-16 and from Traffic Scotland following multiple landslides on the Rest and Be Thankful section of the A83. Moreover, specific assets also serve secondary purposes (e.g. flood management) which is not currently categorised by Highways England. The analysis of multiple link failures, in regards to what emergency measures should be applied when multiple geotechnical assets potentially fail during a severe weather event should also be explored. Once again, lessons can be learnt from recent severe weather in Cumbria and Scotland.

To an extent, some of these issues will be addressed in Task 594.

Another possible development is extending the definition of coping capacity to include adaptation aspects. For example, if adaptation measures are already in place for a given asset, its ability to cope with the shock caused by a severe weather event would be greater, hence its vulnerability would be reduced. This would provide a feedback loop into the assessment post-implementation of adaptation measures.

6.1.5 Assessment of an asset's resilience to a severe weather event

Section 4.8 established that an asset's resilience is associated with its ability to recover quickly from a potential shock (e.g. severe weather event). As such, an important area of further research is establishing the recovery, repair time and costs associated, for a particular asset from a failure that affects the safety and smooth operation of the network. This information would then be incorporated into a more refined asset resilience categorisation. For example, a rockfall from a cutting which deposits material onto the road surface will generally be easier to repair and restore traffic flow compared to the formation of a sinkhole under the road surface.

6.1.6 Improve asset data knowledge

A number of recommendations regarding asset knowledge and condition have been suggested as a result of this reports progression. These are detailed below:

Drainage – Drainage plays a key role in maintaining a geotechnical assets integrity (e.g. Preliminary results from Task 434, Mott Macdonald). However, drainage asset condition and knowledge is currently limited for the SRN.

Special geotechnical measures – A parallel task has been ongoing to establish the type and location of special geotechnical measures on the SRN. Once this information is available on HA GDMS, this can be incorporated into the assessment. Further work may then consider the impact of severe weather events on the deterioration of such special measures, which over time may result in an increased vulnerability of a geotechnical asset, considering their long design lives.

Flood risk mapping – the outputs of Task 433 have at the time of writing, gone live on HA GDMS. Comprehensive flood risk maps will require incorporation into the resilience assessment framework described in this report.

6.1.7 Integration of HA WIS with HA GDMS

The resilience framework presented in this report relies upon combining information about weather events, sourced from HA WIS, with geotechnical data contained within HA GDMS. Currently, these are distinctly separate processes within Highways England and more information is required as to the capabilities of HA WIS in respect of the resilience framework presented.

Ultimately, further integration and use of network weather data to inform vulnerability and subsequent risk analysis of geotechnical assets would be sought. The forthcoming IA-MIS system may work towards this aim, and Figure 23: provides a potential GIS architecture for such an integration in terms of severe weather management.

6.1.8 Further trial of the outputs

Section 4.9 details the methodology for implementing the resilience framework on data available within HA GDMS It is recommended that further work is undertaken to test the framework on firstly a particular route and/or management area. On successful validation of the framework outputs, the assessment could be extended to national-scale.

As the modelling maturity increases, further trialling of the resilience framework will be required.

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Appendices

Appendix A

Appendix A.1 – Related tasks

Task No.	Task title	Author	Date	Scope	Relevance/Inclusion
197	Slope geotechnical hazard rating	Mott Macdonald	2014	Incorporates asset condition, geology and morphology to provide a 'slope hazard rating' for the SRN.	The slope hazard rating provides an established proxy for potential vulnerability of a slope to performance failure. Data is currently available within HA GDMs.
197	National Geotechnical Hazard Review	Arup	2014	Defines strategy for managing and using geotechnical hazard information, the terminology and relevant classification	Used to identify relationship between geo-related hazards and weather-related triggers
408	As-built geotechnical asset data	Mott MacDonald	2015	Develop methodologies, data sets and tools to advance understanding of ground-related hazards	Incorporation of new search tools and information layers relating to ground hazard information into HAGDMS
053	Risk-based asset management	Arup	2014	Initial proof-of-concept of a risk-based approach for prioritising assets, comprising asset health and criticality	Asset health scores and asset criticality scores presented in here
416	Review of geotechnical asset data	Atkins	2015	Extensive review of reports available within HAGDMS to categorise and establish what special geotechnical measures are implemented on SRN.	Special geotechnical measures will increase the resilience of geotechnical assets to severe weather. However, data is currently not available within HA GDMS.
419	Risk based portfolio planning: A framework for assessing the	Arup	2010	The method combines information on asset health and criticality into an indicator that	The criticality rating proposed in this assessment can be directly used as a proxy for potential network disruption

	serviceability of highway assets			represents the relative risk that asset groups present to Highways England's strategic objectives.	following a severe weather event and a loss of performance of a particular geotechnical asset. This data is not currently available within HA GDMs. Criticality is currently undergoing further review in a follow-on task.
433	Priority drainage assets	JBA	2015	Creation of models to categorise vulnerability of SRN to flood risk. Analysis of impact of culvert blockages	Models presented are specific to the SRN and therefore are a better representation than Environment Agency flood models. However, not currently available on HA GDMs; will require integration when available.
434	Sustainable Drainage Strategy Phase 3 and Drainage Panel of Experts	Mott Macdonald	Ongoing	Statistical analysis of drainage condition and geotechnical asset performance failures.	Task ongoing. Interim presentation materials provided.
580	A risk-based framework for geotechnical asset management	Arup	2010	Presented a risk based framework for management of Highways England's geotechnical assets.	
594	Strengthened earthworks	Atkins	Ongoing	This task builds upon that of Task 416, by implementing the recommendations proposed. Ultimately, geospatial output of the location and attributes of special geotechnical measures on the SRN will be incorporated into HA GDMS.	Task is ongoing. Draft briefing note supplied.
694	Implementation for Risk-based Portfolio	Arup	Ongoing	To make better decisions, asset related risk should	

	Planning (part of 'Risk-based Asset Management and Serviceability Indicator Programme')			be understood. The Serviceability Indicator enables the use of existing data sets to define the level of risk posed by assets, to inform decision making.	

Appendix A.2 – Consultation with SMEs

Name	Organisation	Relevance/inclusion
Dean Kerwick-Chrisp	Highways England	Highways England: Climate Adaptation Risk Assessment, Progress Update 2016; Highways England Sustainable development strategy
Chris Power	Mott Macdonald	Provided insights and reports on relevant supporting tasks and data availability/structure from HA GDMS
Andy Bailey	Highways England	Member of Drainage Team and sponsor of relevant Tasks 433 and 434.
Mike Whitehead	Highways England	Environmental Team Leader Provided advice on flooding risk management and CHE MEMORANDUM 299/12 – Designation of assets for flood risk management purposes
Paul Furlong	Highways England	Severe Weather Team Leader
Stephanie Glendinning	Newcastle University/ iSMART	A number of iSMART academic papers were provided and reviewed by the Task team.

Appendix B

Appendix B.1 – Trigger-hazard-susceptibility table

Severe Weather type (Trigger)		Hazards			Inherent susceptibility factors of interest
		Natural hazards	Man-made hazards (road)	Man-made hazards (non-road)	
Rainfall	Heavy Prolonged	- Flooding - Collapsible deposits - Compressible ground - Soluble rocks - Natural landslides (soil) - Natural landslides (rock) - Running sand - Swelling soil - Groundwater rise	- Instability of earthworks - Defective drainage - Loss of vegetation -	- Waste Materials (landfill) - Mining (non-coal) - Back filled opencast mining - Quarries (rock face instability)	Drainage Flood risk Asset type Condition/defects Slope hazard rating Geosure hazard layers (multiple) Mining hazard layers Geological code (asset) Flood defence asset Special geotechnical measures Vegetation
Freeze-thaw		- Natural landslides (rock)	- Instability of rock slopes		Geological code (asset) Asset type Geosure hazard layer (Landslide potential) Slope hazard rating Special geotechnical measures
Hot/Dry		- Soil shrinkage	- Instability of earthworks		Geology Slope hazard rating Geosure hazard layer (shrink/swell) Condition/defects Special geotechnical measures
Snow (melting problematic)		- Flooding - Collapsible deposits - Compressible ground - Soluble rocks	- Instability of earthworks - Defective drainage	- Waste Materials (landfill) - Mining (non-coal)	Drainage Flood risk Slope hazard rating Geosure hazard layers Geological code

Severe Weather type (Trigger)	Hazards			Inherent susceptibility factors of interest
	Natural hazards	Man-made hazards (road)	Man-made hazards (non-road)	
	- Natural landslides (soil) - Natural landslides (rock) - Running sand - Swelling soil - Groundwater rise			Flood defence asset Special geotechnical measures

Appendix C

Appendix C.1 – Assets that may interact with geotechnical asset

Asset	Particular components
Pavements	Carriageway – surface, Carriageway – structure, Hard shoulders
Footways and Cycle Tracks	
Roads miscellaneous	Centre islands, centre reserve, crossovers, kerbs, pedestrian crossings, ox-bow laybys
Structures	Bridges, large culverts, small span structures, retaining walls, walls <1.5m, service crossings, underbridge, overbridge, gantries, tunnels
Street Lighting	Lighting point, lit signs, lit bollards, gantry lighting, street lighting cabling, power supply cabling, feeder pillars, switchroom, distribution point
Drainage	Gullies, catchpits, channels, culverts, piped grips, manholes, balancing ponds, filter drain, grips, interceptors, ditches, counterfort drain
Safety fences and barriers	Safety fence, pedestrian guardrails
Fences, walls, screens and barriers	Boundary fencing, noise barriers, anti-dazzle screens, security fencing, environmental fencing (e.g. newt fencing, rabbit fencing), emergency access gates, boundary walls
Lines and studs	
Signs and safety bollards	
Traffic signals	
Communications	Cabling for overhead gantries, managed motorways, 3rd party structures, CCTVs

Appendix D

Appendix D.1 – 'Proof of concept' pilot study

highways england
driving forward

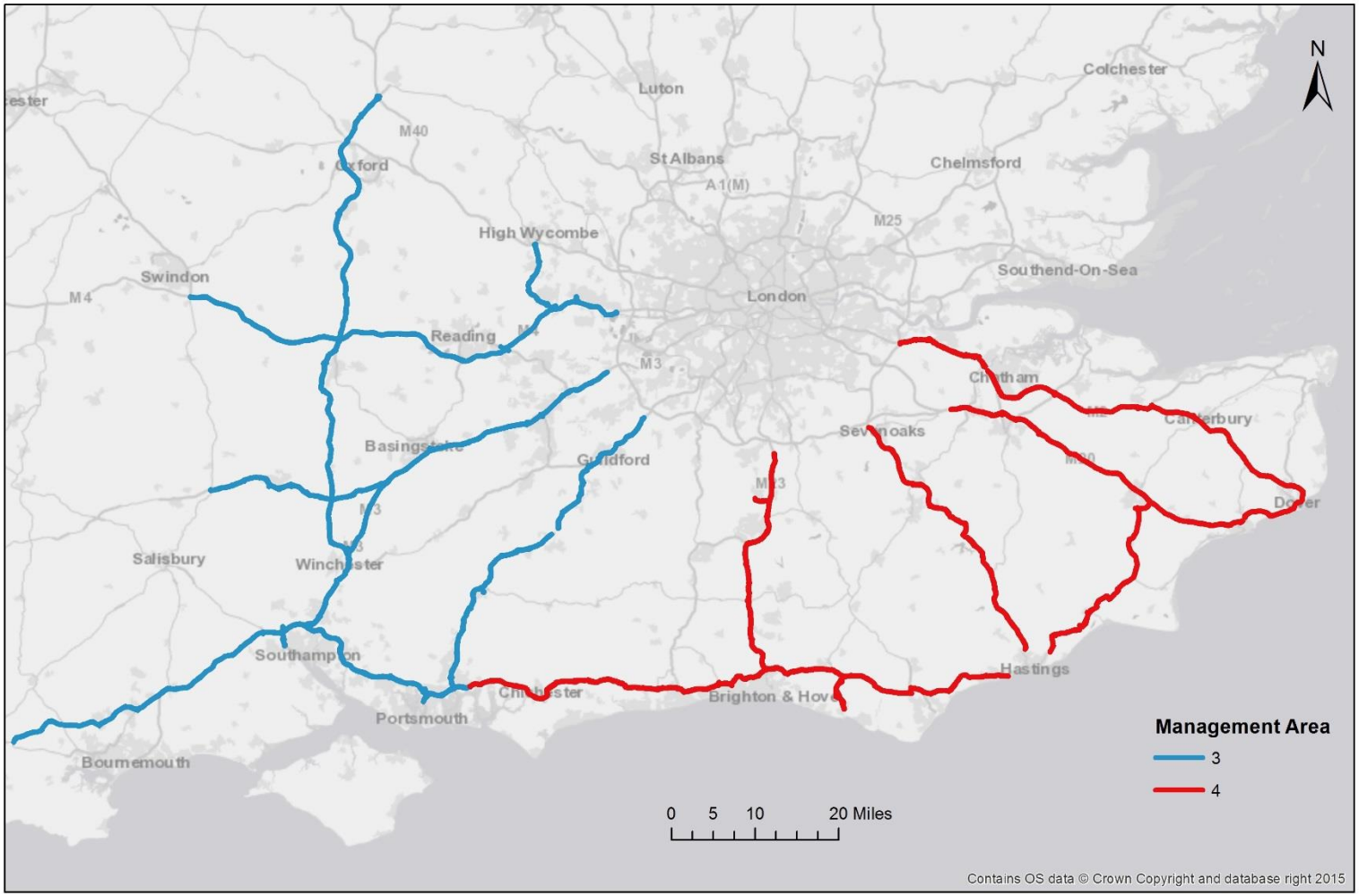
Task 634 - Resilience of geotechnical assets on the SRN to severe weather events

‘Proof of concept’ pilot study

May 2016

ARUP

Case study area – Management areas 3 and 4



Outputs – Assessment Framework

1. Severe weather warning given by e.g. HA WIS, Met Office, Natural Hazards Partnership or similar organisation.

2. Establish severe weather hazard, informing vulnerability assessment

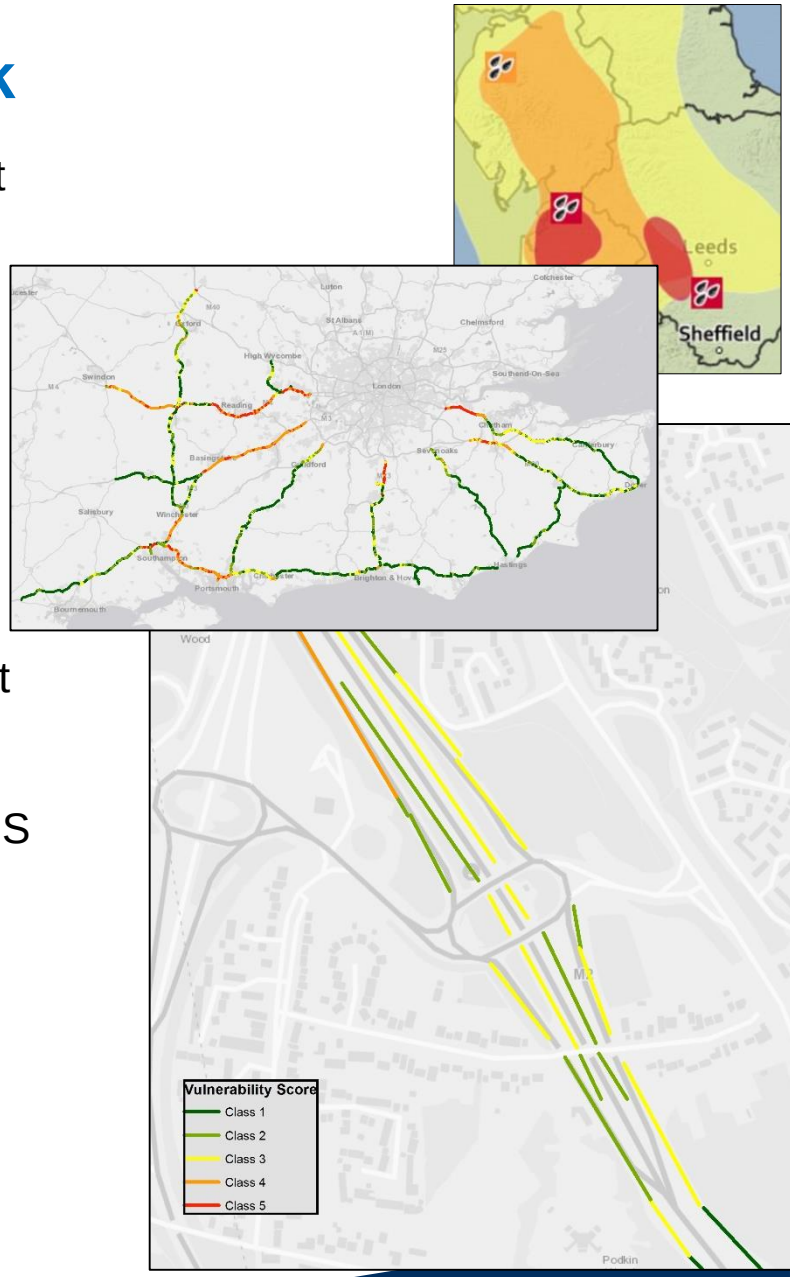
3. Undertake vulnerability assessment

(a) Exposure – regarded as geotechnical assets exposed to severe weather event (i.e. spatial extent of severe weather event – see step 1.).

(b) Susceptibility – use layers provided within HA GDMS or data available within GAD

(c) Coping Capacity or Criticality – Information not currently available within Highways England

4. Identify those assets vulnerable or at-risk (currently **limited to vulnerability** for longer-term planning) of severe weather to **categorise them** (e.g. vulnerability bands 1 to 5).



Vulnerability calculation

For pilot, assumed that a 'prolonged rainfall' event is affecting case-study area – informs…

Taken to be '1' for this assessment – i.e. asset is exposed

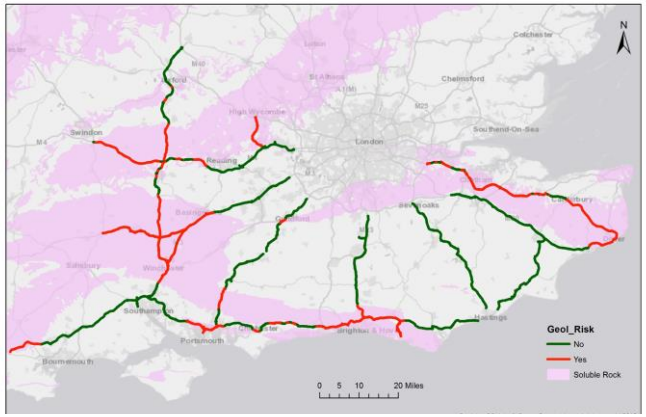
More factors can be added if necessary

$$Vulnerability = \frac{(1\ [exposure]\ x\ (F_1, F_2, F_3, \ldots . F_n\ [susceptibility]))}{Coping\ Capacity}$$

Inverse to user criticality index

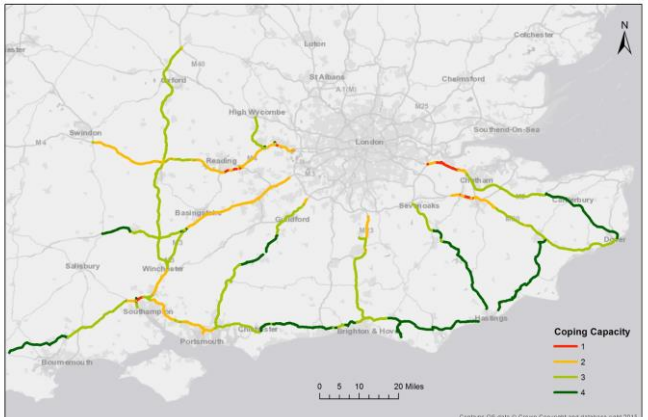
F_1- Geological risk
F_2- Flood risk
F_3- Asset age
F_4- Slope angle
F_5- Slope Height
F_6- Observation (HD41/15)
F_7- Geology (Assigned geology code)

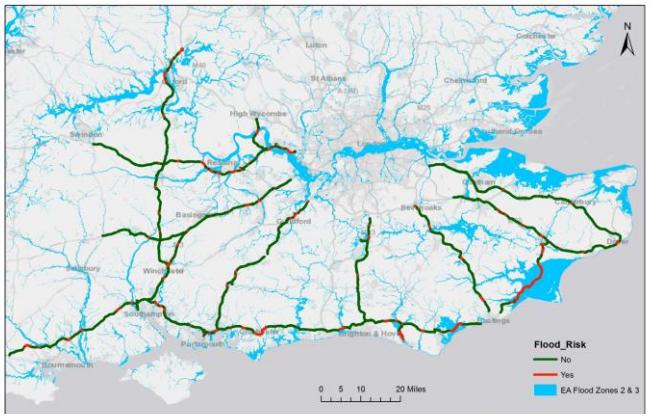
Susceptibility factors used in analysis



Soluble rock hazard

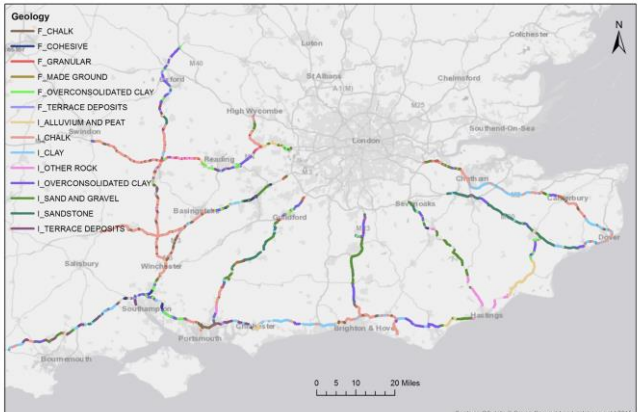
Coping Capacity





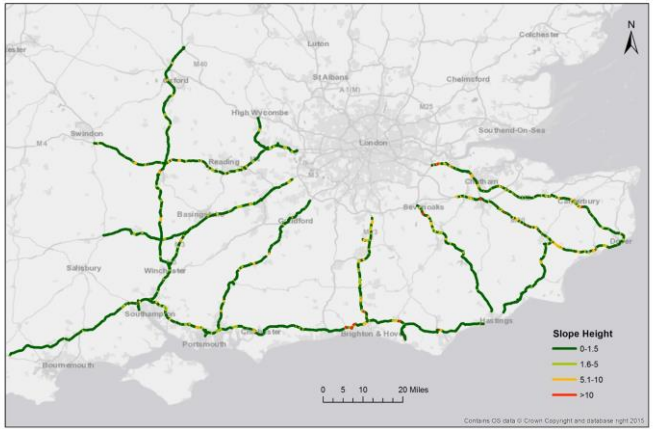
Flood risk

Geology

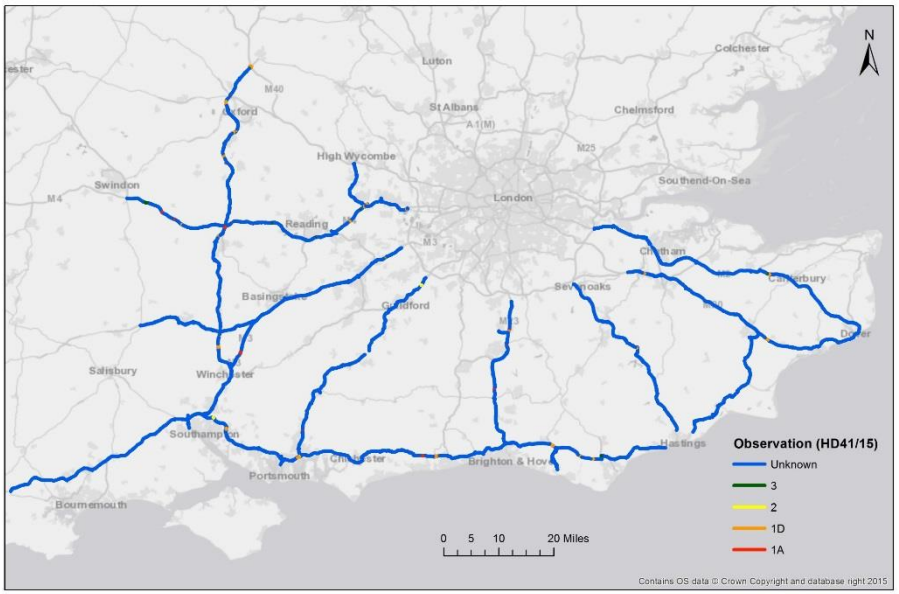


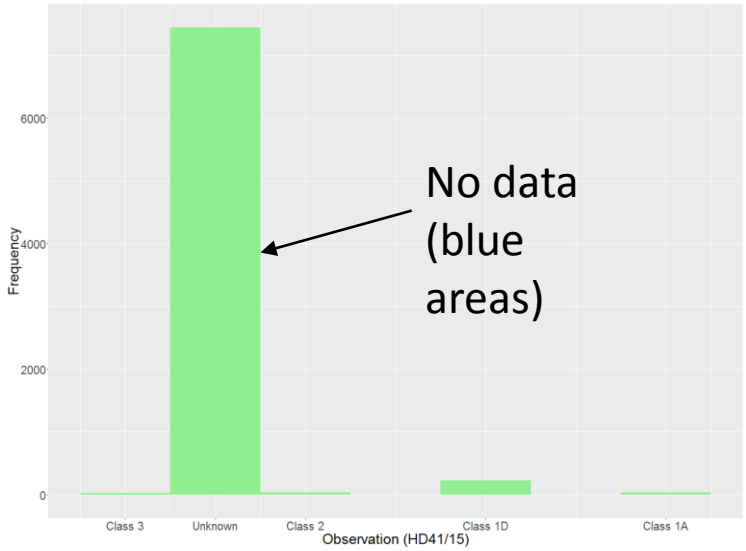
Asset age

Slope Height

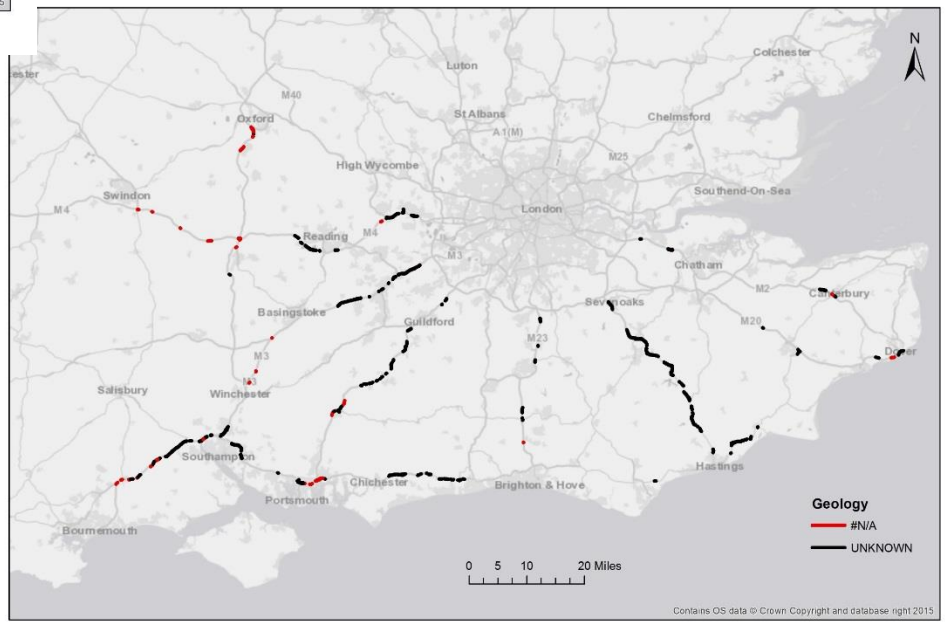


Data limitations





HD41/15
Observations
sparse in Regions
3 & 4



Missing geology codes/spurious codes

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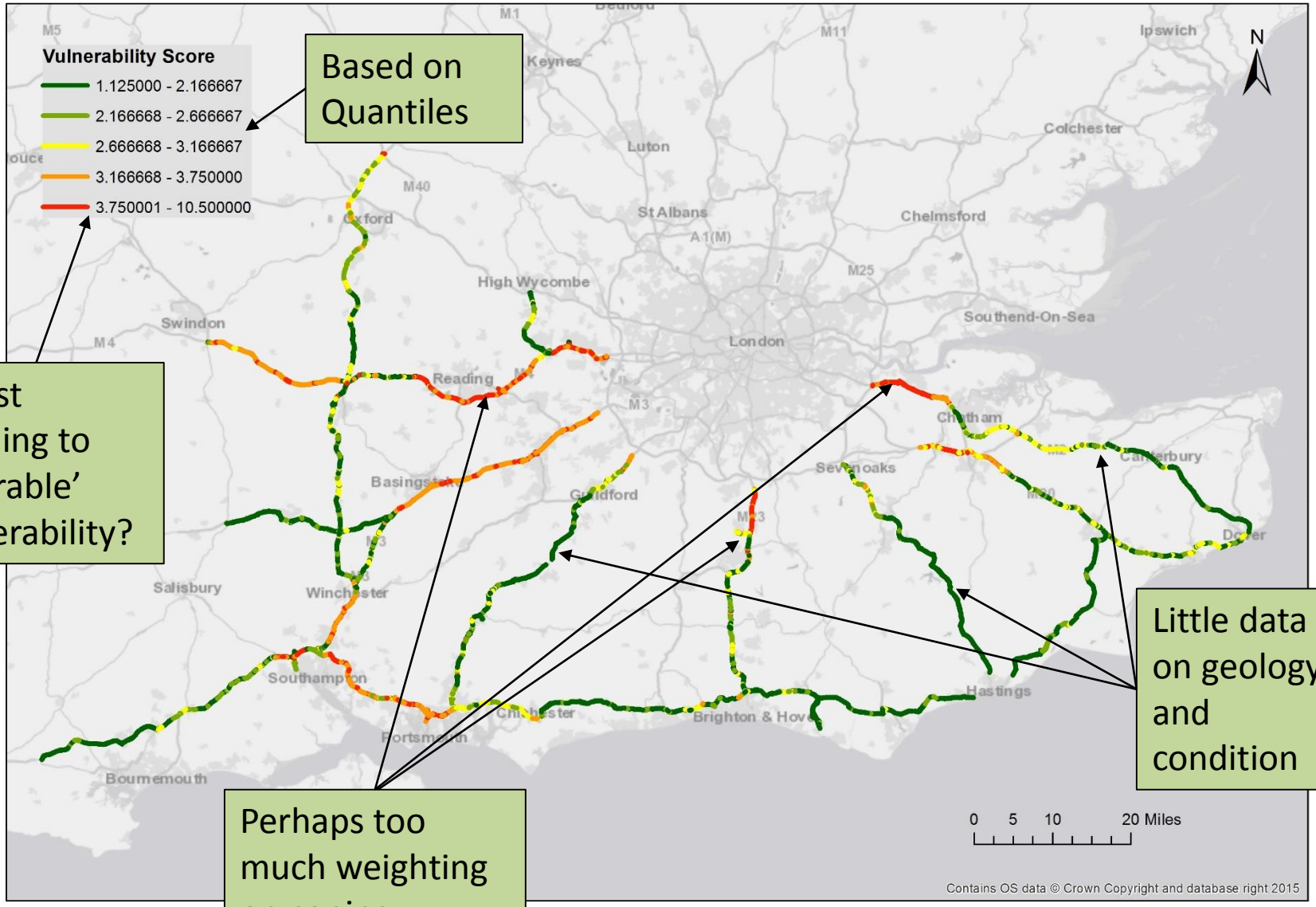

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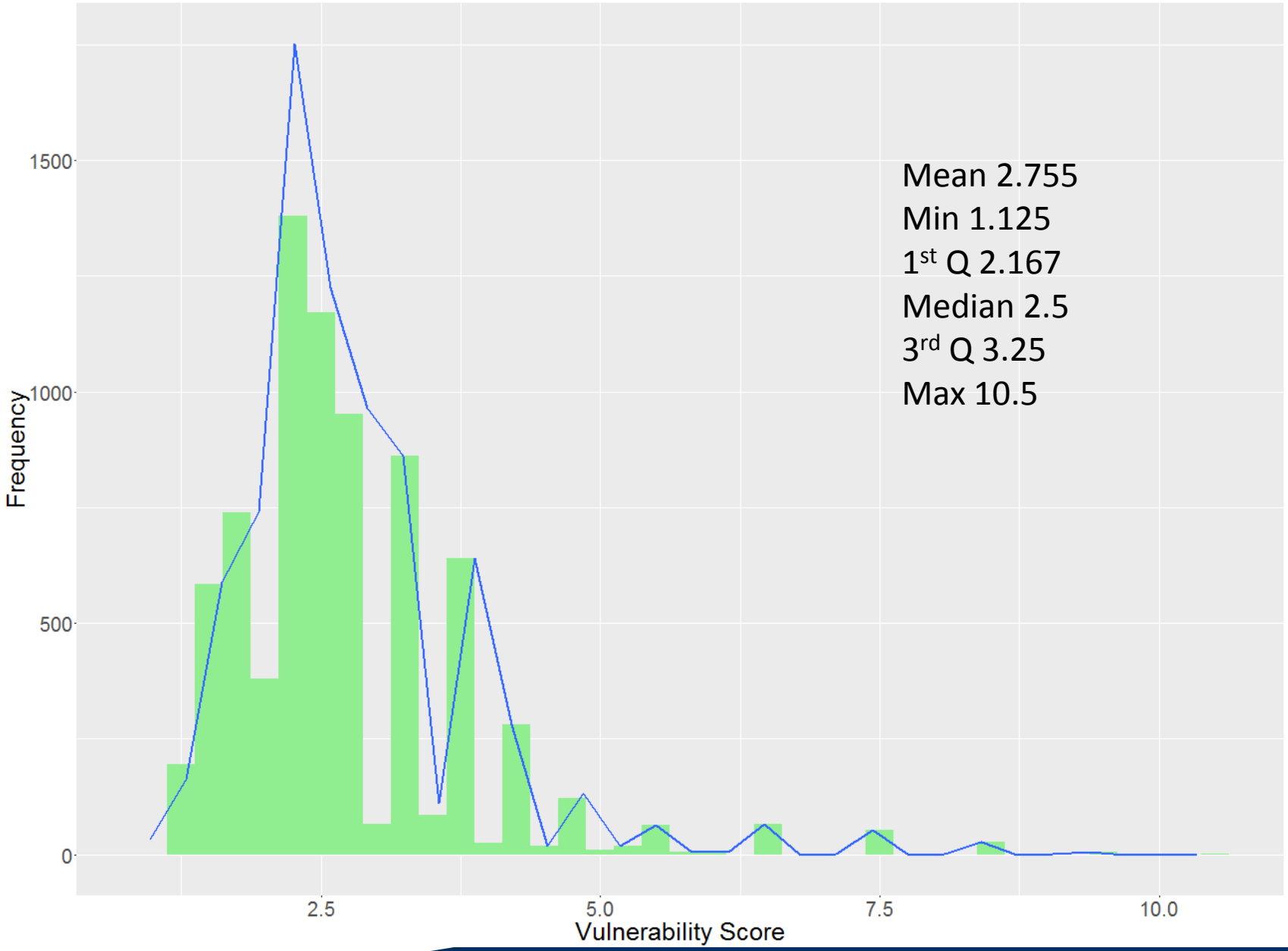
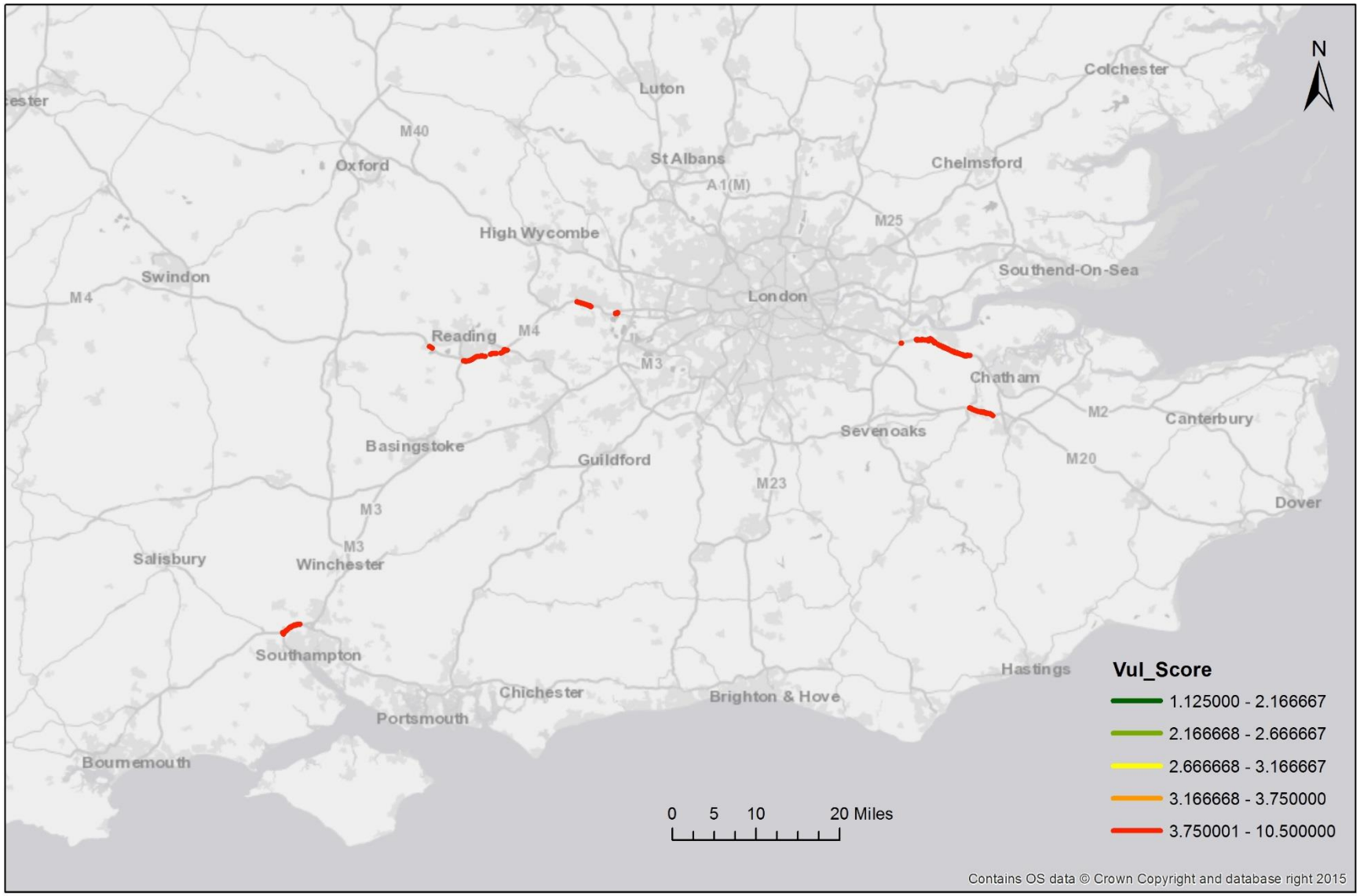
Vulnerability Scoring Frequency



High vulnerability assets (Vul_Score > 6)



Current constraints and limitations

- Unavailability of geohazard layers (i.e. Geosure, mining, landfill)
- No incorporation of slope hazard rating
- Condition data for Areas 3 & 4 is sparse
- Geology codes sparse in certain areas of 3 & 4 regions

Next Steps…

- Sensitivity weightings of input factors
- Establishment of '**tolerable**' vulnerability and risk

Appendix E

Appendix E.1 – Notes from stakeholder workshop meeting on 11th of May 2016

Agenda

ARUP

Project title	Highways England - Resilience of geotechnical assets on the SRN to severe weather events - Task 634	Job number	224175-84
Meeting name and number	HE Stakeholder workshop	File reference	
Location	IAM IS Model Office, Quayside Tower, Birmingham B1 2HF	Time and date	14:00-16:00 11 May 2016
Purpose of meeting	Share findings of Task 634 and agree next steps		
Attendance	David Patterson Paul Furlong (until 3pm) Dean Kerwick-Chrisp Robin Herringshaw Michael Whitehead James Codd David O'Connor Juliet Mian (Arup) Savina Carluccio (Arup) Oliver Pritchard (Arup)		
Apologies			
Circulation	Those attending		

Action

1. Introductions

2. Workshop objectives

- Present the work done for Task 634
- Discuss findings and obtain feedback
- Discuss linkages and alignment
- Agree next steps

3. Briefing on Task 634: 'Resilience of geotechnical assets on the SRN to severe weather events'

- Scope & context
- Presentation of findings
- Pilot study
- Recommendations for further work

Prepared by	Savina Carluccio
Date of circulation	11/05/2016

Agenda

Project title	Job number	Date of Meeting
Highways England - Resilience of geotechnical assets on the SRN to severe weather events - Task 634	224175-84	11 May 2016

4. Notes from discussion

Linkages and alignment with other HE initiatives

PF noted that there is more to the HE response to the DfT report than slide 6 suggests (to note for external presentations). — Project team

Add Task 634 and follow on in the Severe Weather Steering Group (SWSG) research summary to make sure it is aligned. Use briefing note to provide task description. — PF

HAWIS is being replaced by SWIS (Severe Weather information Service). Project team to request account for HAWIS to understand what information is available. Arup to liaise with PF and DO'C in terms of what information will be available from the new weather provider. Does it include historical as well as forecast rainfall, and antecedent conditions? – i.e. how much it rained in the last week. — Project team

RH noted that the use of the word 'threat' in his context is used for something malicious

A well as cost and time to repair, the dis-benefits of alternative routes is important. Atkins did work on this for DKC.

Action to chase what the outcome was from the discussion Nicola Debden had with the Exec on risk issues.

Next steps

Highways England 'vulnerable locations'. There are currently few, if any, geotechnical assets on the vulnerable locations list. There is a need for a consistent basis (i.e. likelihood and impact) for identifying these locations. Vulnerability should relate to frequency of events, e.g. which locations are vulnerable to an annual rainfall event? Currently there is not a 'tool' for identifying vulnerable locations, it is just a qualitative assessment but there may be a need for one. Vulnerable geotechnical assets (and other assets) could be mapped on the 'Resilience Direct' extranet site hosted by the Cabinet Office.

MW pointed out that if e.g. the hazard is a solution feature, groundwater levels and blocked drains could be looked at as the precursors. Is there potential to expand on the simple model using antecedent rainfall and groundwater levels?

A tool which, in case of extreme weather events, provides evidence on specific questions would be very useful e.g. questions from COBRA 'where on the network will this happen?' or 'does one sinkhole mean there will be 10 more sinkholes?'.

Agenda

Project title	Job number	Date of Meeting
Highways England - Resilience of geotechnical assets on the SRN to severe weather events - Task 634	224175-84	11 May 2016

MW noted that there is a very strong message that much of this should be carried out across assets and would be more cost-effective for Highways England to do it once, e.g. Slide 30 Recommendations 1 to 4.

RH suggested that an overarching group looking at resilience would be of value.

Actions specifically related to Task 634 Phase 2 Report/Summary Presentation and Pilot — Project team

Rainfall triggers - Red warnings are impact based and may not appropriate. There is a lack of appropriate triggers with current level of information – amber warnings may be the best current option. Previous occurrences would be a better way to establish triggers but there isn't a lot of information on historical failures.

New designs – the task report should describe the requirements for new design to consider climate change and note that there should be more resilience in new assets. Project team to action

Resilience categorisation - Project team to discuss with JC the definition of 'resilience categories' and agree how to close this our satisfactorily for this task.

Resilience framework - More clarity is needed in the report/slides on what the proposed framework could be used for – e.g. reactive checking when rainfall forecast vs pro-active interventions.

Flooding – Ensure that the report is clear on what EA flood maps we are using for the pilot and which kind of flooding? Future improvements will include using comprehensive flood risk maps.

Pilot – presenting the penultimate layer of asset vulnerability is useful, as it then allows changes in criticality, for example the A38 becoming super-critical once Dawlish had failed.

Attachment: Slide pack

Task 634 - Resilience of geotechnical assets on the SRN to severe weather events

Workshop briefing

11 May 2016

ARUP

Agenda

14:00 Introductions

14:10 Workshop objectives

14:15 Task 634: Resilience of geotechnical assets on the SRN to severe weather events
- Scope & context
- Presentation of findings (including pilot study)
- Recommendations for further work

14:40 Discussion sessions:
Alignment and linkages
Feedback and agree next steps

15:50 AOB

16:00 Close

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Workshop objectives

1. Present the work done for Task 634
2. Discuss findings and obtain feedback
3. Discuss linkages and alignment
4. Agree next steps

Introduction

The overall objective for this task was to :

Develop an **improved categorisation of the resilience** of Highways England's geotechnical assets to a **range of severe weather events**. The demand that these events can impose should be **compared to the basis of design** of geotechnical assets **and to our understanding of their current condition** (including underlying hazards).

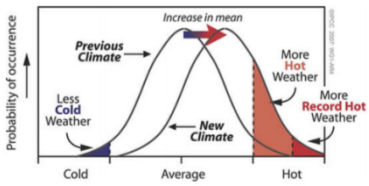
The proposed **resilience framework for geotechnical assets on the SRN** has been developed as follows:

1. Define study objectives and scope (**Phase 1** Scoping Report, Arup December 2015)
2. Assess weather hazard, asset vulnerability and, potentially, associated risk (**Phase 2** Final Report)
3. Refine the model and incorporate results into decision making for resilience and adaptation planning (**next steps**, outside the scope of this task).

Defining the problem

Geotechnical assets on the SRN have been **resilient** to periods of recent severe weather, however:

- geotechnical assets are susceptible to deterioration and potential failure ***without timely intervention***
- There is a difficulty in identifying **latent problems** (e.g. deterioration of special geotechnical measures)
- UK Climate projections suggest **more frequent and more extreme weather events**



Climate change and increased 'severe weather' events (IPCC, 2014)

Storm Desmond, November 2015 : landslide on A583 'Rest and Be Thankful' (Bear NW Trunk Roads)

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Key definitions

$$Vulnerability = f\left(\frac{exposure\ x\ susceptibility}{coping\ capacity}\right)$$

Exposure: [severe] weather type and duration

Susceptibility: Inspected condition as per HD41/15, inherent factors (e.g. geotechnical special measures)

Coping capacity: ability to cope with the consequences i.e. as a proxy to ***asset criticality (link to Task 419)***

"the degree of loss to each element should a hazard of a given severity occur"

Vulnerability

Adaptation

Resilience

"actions to reduce the vulnerability of natural and human systems or to increase systems resiliency"

"the ability of assets, networks and systems to anticipate, absorb, adapt to and/or rapidly recover from a disruptive event"

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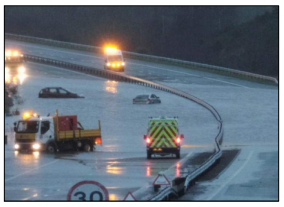
Severe weather risks to geotechnical assets

- **Instability of cuttings and embankments** - saturation of the geological materials (e.g. due to flooding)
- **De-stabilisation of solution features**, mine entries and mine workings
- Pavement subgrade/formation **softening**
- **Erosion** due to uncontrolled water movement
- **Flooding** leading to incapacitation of drainage (e.g. culverts) and resulting in **overtopping and scouring** of assets
- Higher **soil moisture deficits** resulting in **desiccation** of clay embankments causing possible instabilities
- **Freeze/thaw** events causing instability of rock slopes
- Degradation of **special geotechnical measures** (e.g. soil nails)

Solution feature on M2, Kent, 2005

Flooding on M90, Scotland, November 2015



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Approach to weather resilience

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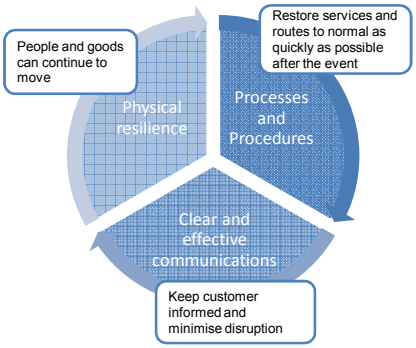
UK government on weather resilience

Recommendation to move toward long-term infrastructure investment and planning



DfT Transport Resilience Review (2014)

100% physical resilience to all hazards would be prohibitively expensive

Resilience planning

Highways England response*

- Traffic Officers
- Flood risk strategy
- 'White' and 'wet' severe weather plans
- Climate change risk assessment

Future challenges

Higher customer demand, increased interdependencies, budget constraints and increasing public pressure to deliver climate-resilient infrastructure

** Further consultation needed with Highways England to achieve alignment with wider weather resilience initiatives*

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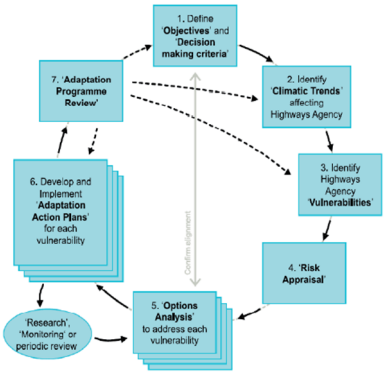
Current Highways England approach

'Wider' approach to weather resilience:

- Routine and winter service code
- Severe weather plan
- HAWIS – Weather information service
- Flood Risk Management Strategy and drainage-related projects (Tasks 433 and 434)
- Climate Change Adaptation Framework and Risk Assessment – developed for climate change but **largely applicable** to resilience to severe weather events

Geotechnics 'specific' approach:

- HD41/15 – severe weather will be trigger for failures
- HD22/08 – Managing geotechnical risk
- HA GDMS – Asset management database
- IAM-IS – integration of asset management systems
- Geotechnical Knowledge Development, including
  - Task 197 – performance of geotechnical assets
  - Task 408 – ground-related hazards
  - Task 416 – special geotechnical measures



Highways Agency Adaptation Framework Model (HA, 2009)

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Review of current academic research

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A number of research studies exist in the field of transport resilience to severe weather, such as:

iSMART – Infrastructure slopes Sustainable Management and Resilience Assessment

FutureNet – understand transport system in 2050

ITRC – long term planning and adaptation of infrastructure systems

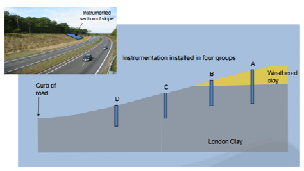
CSIC – Cambridge Centre for Smart Infrastructure and Construction

Highways England is actively involved in a number of initiatives including development of technical knowledge, experimental field sites (e.g. A34 Newbury) and case studies.

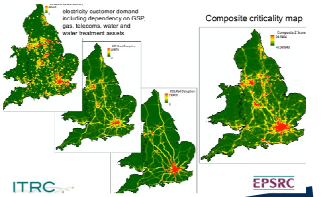
Further studies are needed to understand:

- Deterioration rates e.g. study on overconsolidated clay for Network Rail
- Impact of weather on geotechnical assets at a range of spatial scales
- Specific interactions of natural soils with severe weather and prolonged climate change

iSMART A34 experimental site layout



Critical infrastructure hotspots in England and Wales (ITRC, 2015)



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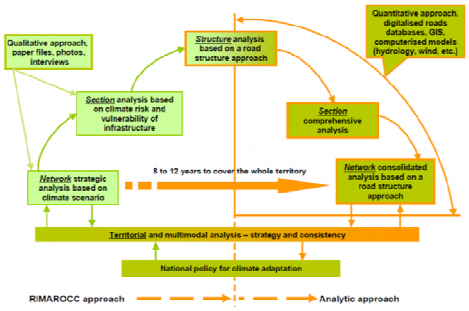
Benchmarking resilience best practice

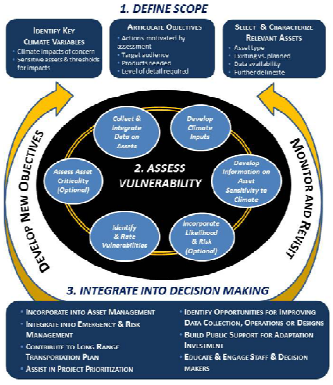
Several resilience frameworks have been reviewed to benchmark best practice:

- All frameworks have broadly similar concepts/outputs
- Applicable to transport but also cross-sector asset-owners and are
- Generally route-based rather than asset-based

RIMAROCC Framework (ERA-NET Road 2010)



Climate Change and Extreme Weather Vulnerability Assessment Framework Framework (FHWA 2012)



More mature models also include:

- Definition of severe weather thresholds
- Quantitative other than qualitative analyses
- Integration of weather and asset data to assess vulnerability
- Integration into decision making

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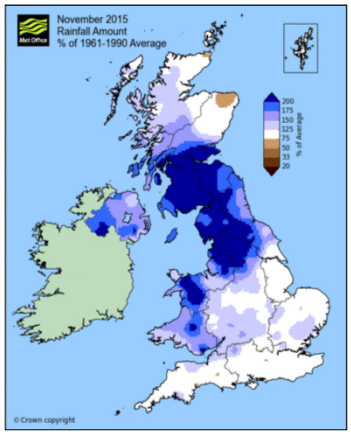
Key points from the scoping study

- Overall, **geotechnical assets** on the SRN so far **resilient** to severe weather events
- **Severe weather** events will become **more likely** according to climate projections (e.g. Storm Desmond)
- Long-term fluctuations in weather will cause **degradation**, with failure perhaps being **triggered by a single extreme weather event**
- Majority of severe weather and climate change mitigation frameworks reviewed have **same broad approach**
- Geotechnical assets constructed from **range of materials** and with **variable susceptibility** to severe weather events
- Existing Highways England Climate Change Risk Assessment framework (CCRA) appears **transferable** for this Task
- **Infrastructure interdependencies** – link to criticality from Task 419



Rainfall amounts over 1961-1990 average associated with Storm Desmond (Met Office)

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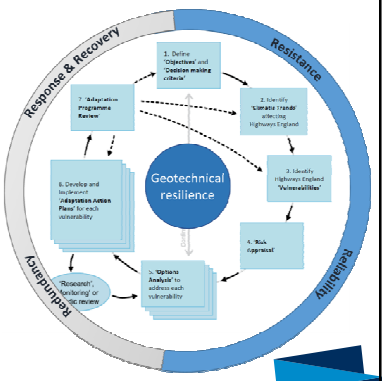
Geotechnical Asset Resilience

"the ability of assets, networks and systems to anticipate, absorb, adapt to and/or rapidly recover from a disruptive event" (Cabinet Office, 2011)

- Identification of hazards and risk assessment is key for design of a resilient system.
- However, increasing asset resilience goes beyond risk management strategies and should use risk assessments to plan adaptation, response and recovery from a severe weather event.
- Resilience should rarely be considered in isolation and is usually dependent on the resilience of services or external assets (i.e. interdependencies).



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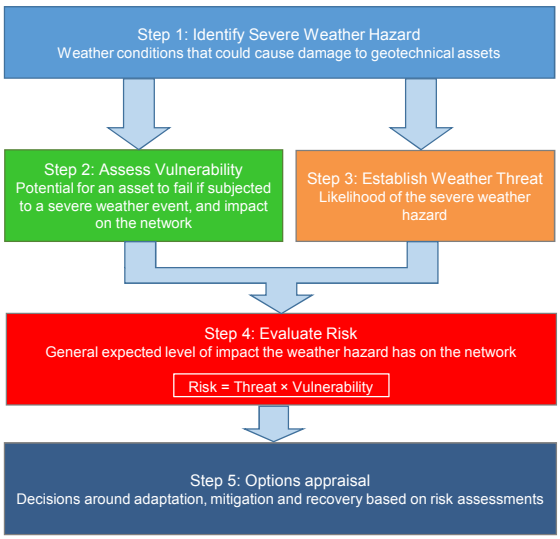
Resilience Framework for geotechnical assets



The proposed framework can be used for e.g.:
- Reactive checking to severe weather forecast
- Planning pro-active interventions

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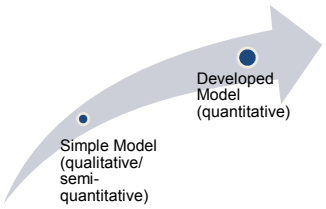
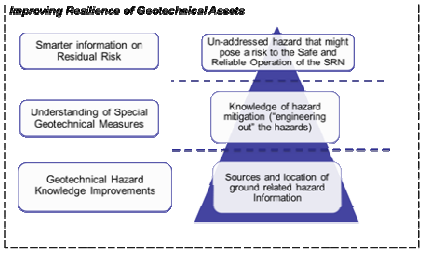
Modelling overview

The overall maturity of the vulnerability assessment will be **governed by the minimum level of sophistication** of any one part.

The findings of the Scoping Study report and a further review of available input data and related tasks has indicated that a 'simple model approach' is currently the most appropriate for the proposed framework.





This task is **aligned with other ongoing work streams** that are looking to achieve a better incorporated and more informed asset knowledge base. Once available, outputs from these related tasks will help refining the proposed model.

Step 1: Identify Severe Weather Hazard

Severe Weather Hazard

Severe or hazardous weather which has the potential to cause damage to geotechnical assets

Simple Model

Basis: Qualitative MET Office weather warnings, NHP daily assessments. Select severe weather hazard from the following list:

- Heavy and/or prolonged rainfall
- Freeze / thaw cycles
- Hot/dry periods
- Heavy snowfall

The selection is limited to simple weather scenarios, i.e. primary weather types are not combined.

Developed Model

Basis: Specified event magnitudes related to asset-based trigger levels which may include:

- Prolonged rainfall
- Heavy rainfall
- Flooding
- Freeze / thaw cycles
- Prolonged hot/dry periods
- Combined scenarios, e.g.. Prolonged hot/dry followed by intense rainfall

Different trigger levels (adverse/extreme) may also be defined within the same weather type

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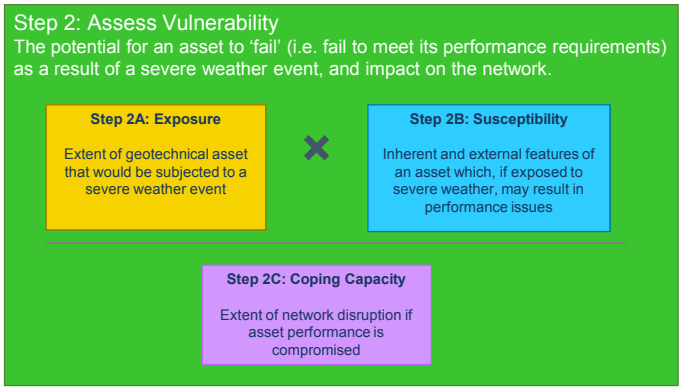
Step 2: Assess Vulnerability (1)

The purpose of a weather vulnerability assessment framework is to combine the asset and climate information to identify vulnerabilities.



Step 2: Assess Vulnerability (2)

Step 2a: Exposure

A measure of the extent of geotechnical asset that would be subjected to a severe weather event.

Simple Model	Developed Model
Asset present / not present within the area of severe weather conditions Data required: location of geotechnical assets	Physical quantity of asset present within area of weather conditions. It may be indicated by e.g. surface area of geotechnical asset, linear length, morphology class. Will allow a more granular prioritisation than a simple present/not present filter

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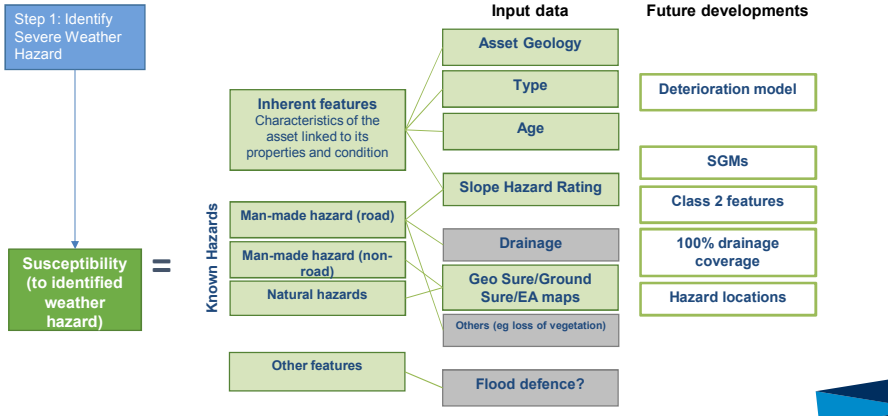
Step 2: Assess Vulnerability (3)

Step 2b: Susceptibility

Inherent and external features of an asset which, if exposed to severe weather (of a particular type), may result in performance issues



Step 2: Assess Vulnerability (4)

Step 2c: Coping Capacity

A measure of the extent of network disruption if asset performance is compromised.

Simple Model	Developed Model
Basis: Network impact is quantified by the traffic affected by the geotechnical asset's reduced performance. Proposed metric: 1 / Criticality score (as defined in Task 419)	Basis: Impact considered in multiple ways such as: • Measure of disruption to traffic (e.g. increased journey times) • Duration of disruption • Cost of remediation • Safety consequences This will follow with the development of the Criticality Score (separate Task)

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Step 3: Establish Weather Threat

Weather Threat

Likelihood of occurrence of the severe weather conditions

Simple model

For ***imminent weather threats*** (ie the threat is materialising): this can be assessed by a weather alert system and level of warning, e.g. alerts issued by MET Office, NHP daily assessment.

Qualitative

Developed model

For ***longer-term planning***, this can be assessed through a climate study reporting frequencies e.g. number of days per year of severe rainfall.

Quantitative

Weather threat allows to introduce climate change scenarios.

Model complexity will be based on:
- level of detail of the weather conditions that can be assessed e.g. 'Severe Rainfall' vs '4 day average of more than 30mm/day'.
- confidence level of the assessment e.g. 'Low likelihood' vs '100 year Return Period'

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Framework modelling: next steps

Step 1: Identify Severe Weather Hazard
Weather conditions that could cause damage to geotechnical assets

Step 2: Assess Vulnerability
Potential for an asset to fail if subjected to a severe weather event, and impact on the network

Step 3: Establish Weather Threat
Likelihood of the severe weather hazard

In the case of imminent weather threats, vulnerability becomes a proxy for risk

Likelihood of occurrence of the severe weather type cannot meaningfully be evaluated due to lack of available data.

Step 4: Evaluate Risk
General expected level of impact the weather hazard has on the network

Risk = Threat × Vulnerability

Step 5: Options appraisal
Decisions around adaptation, mitigation and recovery based on risk assessments

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Outputs – Assessment Framework

1. Severe weather warning given by e.g. HA WIS, Met Office, Natural Hazards Partnership or similar organisation.

2. Establish severe weather hazard, informing vulnerability assessment

3. Undertake vulnerability assessment

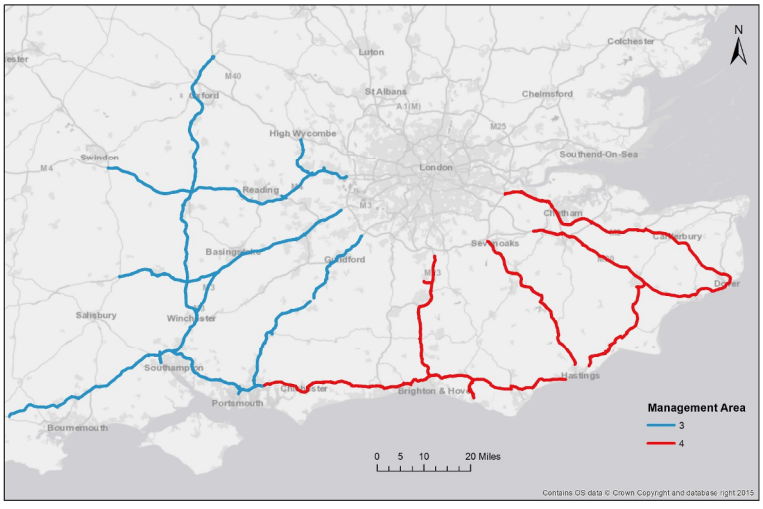
(a) Exposure – regarded as geotechnical assets exposed to severe weather event (i.e. spatial extent of severe weather event – see step 1.).

(b) Susceptibility – use layers provided within HA GDMS or data available within GAD

(c) Coping Capacity or Criticality – Information not currently available within Highways England

4. Identify those assets vulnerable or at-risk (currently **limited to vulnerability** for longer-term planning) of severe weather to **categorise them** (e.g. vulnerability bands 1 to 5).

'Proof of concept' pilot study – Areas 3 and 4



Vulnerability calculation

For pilot, assumed that a 'prolonged rainfall' event is affecting case-study area – informs…

Taken to be '1' for this assessment – i.e. asset is exposed

More factors can be added if necessary

$$Vulnerability = \frac{(1\ [exposure]\ x\ (F_1, F_2, F_3, \ldots . F_n\ [susceptibility]))}{Coping\ Capacity}$$

Inverse to user criticality index

F_1 - Geological risk
F_2 - Flood risk
F_3 - Asset age
F_4 - Slope angle
F_5 - Slope Height
F_6 - Observation (HD41/15)
F_7 - Geology (Assigned geology code)

Susceptibility factors used in analysis

Pilot study outputs

Benefits

- Usefulness - Resilience categorisation that can be used for resilience planning/management
- Flexibility - in adding new data
- Adaptability - GIS environment that can be easily incorporated in HE management systems

Next Steps

- Further refinements on methodology: validation, sensitivity checks, weightings of input factors
- Inclusion of latest (flood maps, slope hazard ratings, etc) and future datasets
- Establishment of '**tolerable**' risk

Outputs – next steps

Simple Model
Visual/semi-quantitative assessment of risk factors.
Use of HA GDMS and HA WIS/Weather reporting separately.

Developed model
Quantitative assessment using GIS.
Process automated using HA GDMS database.
Live feed from HA WIS system/weather reporting for real-time monitoring of at-risk assets during severe weather event.

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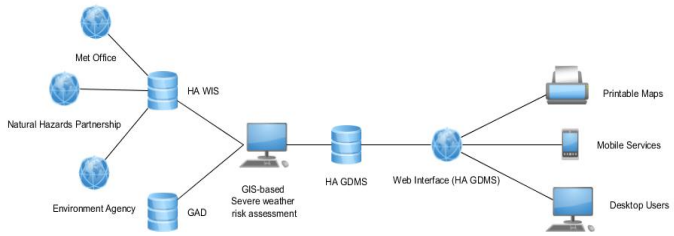

Potential GIS architecture for near real-time estimation of severe weather risk to geotechnical assets

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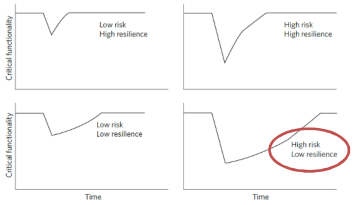
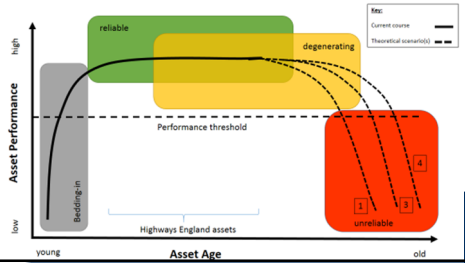
Towards a resilient approach

- Highways England's CCRA identifies geotechnical assets as low vulnerability and resultant action is 'do minimum'.
- However the following considerations should be made for geotechnical assets:
  - long design lives → can be impacted by climate change
  - ground related hazards
  - Deterioration of assets and SGMs
- **More focussed assessment** of severe weather hazards, vulnerability and risk to geotechnical assets whilst using existing asset knowledge base and incorporating work from related tasks



Adaptation options:
[1] – 'Do Minimum'
[3] –'Retro-fit solutions'
[4] – 'Develop future-proof designs'



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Towards a resilient approach

Adaptation measure		Description	Pre-event	Post-event	Suitability
1 - Do minimum		Do not implement any adaptation plans or resilience measures. Overall asset vulnerability would be low, meaning that at present they appear resilient to severe weather events. Suggest that continued monitoring of vulnerability and risk is undertaken.	N/A	N/A	Low risk assets
2 - Retro-fit solutions (proactive maintenance)	2A - Incremental adaptation	Incremental adaptation is decided and implemented over successive short timescales (10 years for instance). The advantage is to manage climate change uncertainty iteratively, based on gradually increasingly reliable climate change, reducing the risk to commit to highly expensive investment which could turn out to be inadequate	Y	N/A	Medium to high risk assets Increased resilience achieved through gradual investment
	2B - One-off adaptation	Assumes that adaptation is undertaken once to deal with long-term (e.g. over asset life). This could take the form of construction of special geotechnical measures to remediate an existing hazard. However, there is potential for the uncertainty associated with climate change projections to implement adaptation measures which are either unnecessary or inadequate, respectively.	Y	N/A	High risk assets (high vulnerability/high threat likelihood) e.g. critically important to the smooth running of the SRN Requires substantial investment
3- Develop contingency plans		This involves the development of a pre-planned response for when a severe weather risk is realised. Such cases where this might be included is where options aren't available to mitigate the risk, or where residual risks exist following mitigation measures. Such a pre-planned response may include the re-routing of traffic or closure of the hard shoulder.	N/A	Y	Medium to high risk assets Should be incorporated in organisational procedures
4 - Develop future-proof designs		This adaptation measure is aimed at construction of new assets, but also equally applicable to assets that undergo improvement measures. Knowledge of severe weather impacts on vulnerability and risk could be used to assess how climate change projections would impact on potential designs	Y	N/A	All assets Future-proof designs should be rolled out to all new built asset and renewals

Recommendations for further work

The following recommendations are aimed to **improve the categorisation of the resilience of geotechnical assets,** hence **aid resilience management**:

1. Integration of resilience assessment with severe weather plans
2. Defining 'tolerable risk' for Highways England to help focussing prioritisation of resilience enhancement interventions (pre-event adaptation/mitigation, renewals, increased maintenance and post-event response and recovery)
3. Establish weather thresholds, in particular to establish emergency response measures to forecasted severe weather events
4. Further assessment of climate change projections and return periods
5. Updating coping capacity assessment based on criticality
6. Assessment of an asset's post-event recovery, repair time and costs
7. Integration of the Weather Information with the Geotechnical Data Management System
8. Improve asset data knowledge, filling the current gaps (e.g. SGMs, drainage) to refine assessment
9. Further trial of the outputs as the modelling maturity increases

Discussion

1. Alignment and linkages

2. Feedback and agree next steps

Possible points for discussion:

- Incorporation of the 'Simple Model' in Resilience Management: use of 'triggers' as identified from NHP and/or HA WIS outputs
- Application of the model to other assets
- Alignment with planned strategy/policy development related to severe weather management, climate adaptation, etc.

AOB